CLIMATE CHANGE AND ENVIRONMENTAL SUSTAINABILITY: PATHWAYS TO ACHIEVE SDG2- FOOD AND NUTRITION SECURITY IN BRICS ECONOMIES

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Abstract. Achieving SDG 2 on food and nutrition security (FNS) amid climate change and environmental sustainability challenges remains a pressing concern for BRICS economies, namely Brazil, Russia, India, China, and South Africa. This study examines how climate change affects food production and nutrition security, evaluates the contribution of environmental sustainability policies, and identifies institutional pathways for strengthening resilience. Using a balanced panel dataset covering 2000–2023, the analysis applies dynamic panel ARDL, bias-corrected LSDV, and quantile regression techniques to capture temporal dynamics and distributional heterogeneity. The findings indicate that temperature anomalies exert a negative influence on food security, reflecting climate-induced pressures on agricultural productivity. In contrast, renewable energy adoption and environmental policy stringency significantly enhance FNS, with long-run elasticities exceeding unity, underscoring strong complementarities between sustainable energy transitions, environmental governance, and resilient food systems. Forest expansion presents a short-run trade-off by constraining arable land, while agricultural value added supports long-term nutrition outcomes. The study contributes robust BRICS-specific evidence on the climate–sustainability–food security nexus and highlights policy-relevant pathways for integrating renewable energy, strengthening environmental regulation, and supporting agricultural development to advance sustainable food systems.
Keywords: *agricultural value added, climate change, environmental policy stringency, food and nutrition security, renewable energy, sustainable development goals (SDG 2), sustainability, temperature anomalies*

Introduction

Climate change and environmental sustainability have emerged as defining challenges of the 21st century, with profound implications for global food security. As the world grapples with escalating climate crises, food systems across the globe are becoming increasingly vulnerable to disruptions caused by temperature anomalies, changing rainfall patterns, and extreme weather events. The impact is particularly severe in emerging economies, where agricultural productivity, a cornerstone of food security, is deeply affected by these environmental stressors. The BRICS economies: Brazil, Russia, India, China, and South Africa, are significant players in global agriculture, contributing over 50% of global agricultural production (Ren et al., 2020). Yet, despite their vast

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agricultural potential, these nations face unique challenges in managing the risks posed by climate change while striving to meet the demands of food security and nutrition for their rapidly growing populations.

The paradox faced by BRICS economies is striking. On one hand, these nations are critical to global food production, and their agricultural systems play a pivotal role in feeding millions globally. On the other hand, the very factors that make them agricultural powerhouses: vast agricultural lands, diverse ecosystems, and large rural populations, are the same factors that render them particularly vulnerable to climate change. Rising temperatures, shifting weather patterns, and the increasing frequency of extreme weather events are compromising crop yields, exacerbating food insecurity, and threatening the nutritional well-being of millions (Saleem et al., 2025). Despite this, these economies continue to face the challenge of balancing economic growth, environmental sustainability, and the imperative to provide food and nutrition security, as encapsulated in Sustainable Development Goal 2 (SDG 2), which seeks to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture.

This study aims to explore the pathways through which climate change and environmental sustainability influence the achievement of SDG 2 in BRICS economies. Specifically, it seeks to: 1) analyse the impact of climate change on food production and nutrition security in BRICS economies, 2) assess the role of environmental sustainability policies and practices in enhancing food and nutrition security, and 3) identify policy and institutional pathways that BRICS economies can follow to strengthen resilience to climate shocks while advancing sustainable food systems. These objectives are framed within a comprehensive theoretical and empirical analysis of the interplay between climate change, sustainability, and food security, drawing on the Sustainable Livelihoods Framework (SLF) and Ecological Modernisation Theory (EMT).

The research questions guiding this study are as follows:

RQ1: How does climate change affect food production and nutrition security in BRICS economies?

RQ2: How do environmental sustainability policies and practices contribute to food and nutrition security in BRICS economies?

RQ3: Through which policy and institutional pathways can BRICS economies strengthen resilience to achieve food and nutrition security under SDG 2?

The urgency of this study arises from significant gaps in the literature. While substantial research has been conducted on the effects of climate change and sustainability on food security in general, studies specifically focusing on the BRICS economies remain limited. Existing literature primarily centres on developed countries, often overlooking the unique socio-economic and environmental challenges faced by emerging economies (Makhanova et al., 2024).

Furthermore, while there is considerable research on food security and climate change, the intersection of these factors with environmental sustainability policies, particularly in the BRICS context, remains underexplored. Studies such as those by Nihal et al. (2024) and Kıprızlı and Köstem (2023) focus predominantly on energy security and environmental practices, without considering the critical link between climate, sustainability, and food security. The lack of integrated frameworks that simultaneously address these interrelated dimensions in BRICS countries constitutes a significant research gap.

Moreover, existing studies have often employed cross-sectional and retrospective analyses, limiting the ability to capture the long-term dynamics of climate change and

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sustainability on food security outcomes. The underutilisation of advanced econometric methods, such as dynamic panel data approaches like System-GMM, further restricts the capacity of studies to account for temporal effects and regional heterogeneity (Nathaniel et al., 2020). This methodological gap underscores the need for a more nuanced approach that can better capture the complex, evolving relationship between climate change, sustainability, and food security in BRICS economies.

This study makes a critical contribution to both theory and practice. By integrating the Sustainable Livelihoods Framework (SLF) and Ecological Modernisation Theory (EMT), it provides a comprehensive theoretical foundation for understanding the interconnections between climate change, sustainability, and food security. SLF, with its focus on capital assets (natural, human, financial, and social), offers valuable insights into how climate change affects livelihoods and food security, particularly in rural and vulnerable populations. EMT, on the other hand, emphasises the role of technological innovation, policy reforms, and market mechanisms in achieving sustainable development while addressing environmental challenges. Together, these frameworks offer a holistic perspective on how BRICS countries can navigate the complex landscape of climate change, environmental sustainability, and food security.

In practical terms, this study will provide policymakers and development practitioners with a deeper understanding of the policy and institutional pathways that can be pursued to build climate resilience while ensuring food security in BRICS economies. By highlighting the synergies and trade-offs between climate action, sustainable agriculture, and food security, it will contribute valuable insights for designing more effective, integrated policies that align climate goals with food security objectives, ultimately helping BRICS nations advance towards the achievement of SDG 2 in the face of an increasingly unpredictable climate future.

Literature review

Climate change, agricultural vulnerabilities, and food security in BRICS economies

Climate change presents significant challenges to global agricultural productivity and food security, threatening the very systems that sustain food availability and nutrition. As global temperatures rise, with a projected increase of 2°C by the end of the century, the effects on crop physiology are evident. These changes disrupt crop growth by increasing respiration rates, evapotranspiration, and pest infestations, while reducing growing seasons for key crops.

Temperature increases also exacerbate water stress and worsen soil fertility, compounding existing vulnerabilities (Malhi et al., 2021). Although elevated CO_2 levels can stimulate photosynthesis, the benefits are often undermined by the detrimental effects of rising temperatures, which reduce the efficiency of photosynthetic processes and crop yields (Malhi et al., 2021). The global decline in crop yields, particularly for staple crops such as wheat, maize, and rice, highlights the growing vulnerability of food systems to climatic shifts. Furthermore, extreme weather events, such as heatwaves, floods, and droughts, lead to short-term disruptions in agricultural production, while long-term changes in rainfall patterns continue to affect food availability.

Ocean warming and declining oxygen levels threaten global fisheries, exacerbating the challenge to food security, especially in coastal and island regions (Semba et al., 2022). With climate change anticipated to lead to a 3°C increase in global temperatures, projections indicate that moderate gains in suitable agricultural land will be offset by

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considerable yield losses due to physiological stress and extreme climatic events (Seppelt et al., 2022). The combined effect of these changes increases the risk of food poverty, with both food availability and nutritional security facing unprecedented pressures (Saleem et al., 2025).

In the context of the BRICS economies, the impacts of climate change on food production and nutrition security are particularly profound. BRICS nations: Brazil, Russia, India, China, and South Africa, are major agricultural producers globally, and any disruption to their agricultural systems has widespread implications for both regional and global food security.

India, the impacts of climate stressors such as rising temperatures and erratic rainfall patterns have already led to a significant reduction in agricultural productivity, with direct consequences for food security and the livelihoods of millions of farmers (Baraj et al., 2024). Similarly, Brazilian agriculture has been severely impacted, particularly for crops such as cassava, cocoa, and rice, with approximately 67% of studies indicating negative effects on productivity. However, crops such as soybeans and sugarcane have shown more mixed responses, depending on regional climatic variations (Fiorini et al., 2024). In China, projections suggest that temperature increases of up to 2.8°C by mid-century will cause a decline in yields of critical crops, such as rice and wheat, by 15% to 17% (Habib-ur-Rahman et al., 2022). While climate extremes such as droughts and heatwaves present immediate threats, erratic rainfall patterns, particularly in sub-Saharan regions, are also significantly impairing food production and nutritional security in the region.

In Russia, agriculture plays a central role in national and global food security, with wheat, barley, maize, and potatoes forming the backbone of domestic consumption and export earnings. Wheat is particularly critical, as Russia has emerged as the world's leading wheat exporter, making its production performance highly consequential for international grain markets and food availability (Wegren, 2021). However, the country's major crop systems are increasingly exposed to climate-induced risks. Rising temperatures, more frequent heatwaves, and shifting precipitation patterns have been shown to exert substantial downward pressure on crop yields, especially during sensitive growth stages.

The 2010 flash drought provides a stark illustration, with heat stress and moisture deficits reducing wheat yields by more than 70% in key producing regions (Hunt et al., 2021). Empirical evidence further suggests that beyond a 1.5°C global warming threshold, heat stress during the reproductive phase of wheat could become recurrent, with spring wheat facing a 40–60 per cent probability of critically low-yield years (Templ and Calanca, 2020). While warming trends may extend growing seasons northwards and open new areas for cultivation, these potential gains are offset by heightened drought risks, water scarcity, and extreme weather events in southern and traditional breadbasket regions (Kiselev et al., 2013). As a result, climate change is reshaping both the spatial distribution and productivity of Russia's major crops, posing significant challenges for long-term food security.

In South Africa, climate change similarly threatens key crop systems that underpin national food availability and nutritional outcomes. Maize, wheat, sorghum, sugarcane, and a range of horticultural crops constitute the core of the country's agricultural production, with maize serving as the primary staple for most households. These crops are predominantly produced under rain-fed conditions, rendering them highly sensitive to temperature increases, droughts, and rainfall variability.

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Quantitative assessments indicate that climate change could reduce maize yields by between 10 and 16 per cent, reflecting the combined effects of rising temperatures and increased moisture stress (Cammarano et al., 2020). Observed climate variability further reveals a negative relationship between mean annual temperature and yields of maize and wheat, underscoring the vulnerability of cereal production to warming trends (Tshikovhi and Van Wyk, 2021). Beyond yield effects, water constraints represent a growing concern. Several crops, including potatoes, pulses, grapes, cotton, rice, and wheat, exhibit high water deficits, signalling unsustainable production patterns in already arid regions. Projections suggest that irrigation demand could rise by 6.5 to 32 per cent by the end of the century, intensifying competition for scarce water resources and constraining future food production (Bonetti et al., 2022).

The evidence from BRICS countries indicates that climate change is undermining agricultural productivity through rising temperatures, altered precipitation regimes, and increased climate variability. In Russia and South Africa contexts, staple crops such as wheat and maize face heightened yield instability, with implications that extend beyond farm output to food availability, price stability, and nutrition security. These country-specific experiences highlight the structural vulnerability of major crop systems within BRICS economies and reinforce the need for targeted adaptation strategies to safeguard food security under a changing climate.

A deeper understanding of the vulnerabilities unique to BRICS economies can be achieved by considering the complex interconnections within the climate–food nexus. Recent studies have developed frameworks to illustrate how climate change affects food systems through interconnected feedback loops. Tuholske et al. (2024) proposed an "agricultural pathway" framework that connects climate-induced changes in food production to broader socioeconomic consequences, such as rural out-migration and the destabilisation of food systems in low- and middle-income countries.

Moreover, Arthur et al. (2022) reviewed food system governance frameworks, highlighting how localized grievances such as those exacerbated by climate change, can influence the structure and resilience of food governance, thereby shaping the responses of nations to food insecurity. For example, alternative food networks and bioregional governance models have emerged as responses to the fragmentation of traditional food systems, providing localised solutions to climate-related food insecurity (Arthur et al., 2022). The water-energy-food nexus, discussed by Ali and Acquaye (2024), further underscores the need for integrated solutions in managing the interdependencies between water, energy, and food systems under climate change. For BRICS economies, leveraging this framework is critical to fostering adaptive governance and ensuring the long-term sustainability of food systems.

Drawing on comparative global studies, BRICS economies emerge as both key contributors to and victims of climate-driven food insecurity. Together, they accounted for over 50% of global agricultural production in 2018 (Ren et al., 2020), yet they also face significant risks from climate impacts. Financialization of agricultural commodities has exacerbated food price volatility within BRICS nations, especially following the 2008 global financial crisis, highlighting the interconnectedness between economic policy and food security. The COVID-19 pandemic further reconfigured food systems in these countries, creating food deserts and limiting access to traditional food sources, particularly fresh produce (Amusan and Okorie, 2022).

Despite these challenges, BRICS countries have shown positive trends in food security, particularly for staple cereals, although fresh food products remain problematic

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(Ren et al., 2020). However, the financialisation of agriculture and the increasing protectionism of food markets, as noted by Glauben and Duric (2024), may isolate these economies from global food markets, exacerbating food insecurity across the Global South.

The synthesis of empirical findings from BRICS nations reveals a picture of increasing vulnerability due to climate change, which threatens the productivity of both crop and livestock sectors. While progress has been made in improving food self-sufficiency for staple crops such as cereals, the region still struggles with securing fresh produce and diverse food systems. This is further complicated by the financialisation of agricultural markets, which drives up food price volatility and undermines food security, particularly for the most vulnerable populations (Manogna et al., 2024).

In addition to these economic factors, carbon dioxide emissions, rising temperatures, and air pollution continue to negatively affect agricultural output (Shah et al., 2022). However, advancements in digital technologies, renewable energy adoption, and agricultural innovation present new opportunities for mitigating the impacts of climate change on food security. These technologies not only enhance agricultural productivity but also support the transition towards more sustainable food systems (Shah et al., 2022). As such, BRICS nations must work collaboratively, leveraging their complementary advantages in technology, trade, and innovation, to address the shared challenges posed by climate change and ensure food security for their populations in the face of evolving environmental pressures.

Environmental sustainability policies and food and nutrition security

Environmental sustainability policies play a pivotal role in shaping food and nutrition security outcomes, particularly in the context of climate change and resource management. A growing body of research underscores the interconnections between environmental sustainability practices—such as renewable energy adoption, forest conservation, and resource-efficient agricultural technologies—and improvements in food security. These practices operate through multiple pathways, providing both immediate and long-term benefits to food systems. For instance, sustainable agricultural practices, when incentivised by appropriate policies, not only offer ecological benefits but also improve short-term economic outcomes, thus facilitating higher adoption rates among farmers (Piñeiro et al., 2020).

However, long-term adoption depends on farmers perceiving tangible benefits, both for their farms and the environment, which highlights the need for effective technical assistance and extension services. These services empower farmers to integrate sustainability into their practices, thereby enhancing food security outcomes over time. Additionally, consumer behaviour studies suggest that although there is a positive shift in attitudes towards sustainable food, these attitudes do not always translate into consumption patterns. Bridging this gap requires goal-directed frameworks that encourage sustainable food choices (Vermeir et al., 2020).

Further, rights-based approaches, such as food sovereignty and the right to food frameworks, have demonstrated positive impacts on food security and nutrition globally, especially in addressing structural barriers such as inequitable land access and gender discrimination (Sampson et al., 2021). These frameworks not only provide a theoretical basis for environmental sustainability policies but also help in operationalising them through mechanisms that ensure equitable distribution of resources and benefits. In addition, water security has emerged as a critical link between environmental

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sustainability and nutrition, as access to clean and safe water influences food production, preparation, and safety (Miller et al., 2021). This connection is particularly important in the context of agriculture, where water scarcity can severely impact food production, leading to nutritional insecurity.

In the case of BRICS countries, the extent to which sustainability policies support or hinder SDG 2 (food and nutrition security) remains a complex issue. While these nations have prioritised various environmental sustainability measures, such as green finance reforms, climate-smart agriculture, and carbon reduction targets, the effectiveness of these policies in fostering food security is still evolving. Green finance mechanisms, such as green bonds and fintech initiatives, have shown positive results in supporting carbon neutrality goals and promoting environmental sustainability. These initiatives are crucial in addressing the financing gap for sustainable development in BRICS nations (Udeagha and Muchapondwa, 2023). However, the pursuit of economic growth and the continued reliance on natural resource rents often compromise environmental quality, limiting the effectiveness of sustainability policies in these regions (Udeagha and Muchapondwa, 2023).

Clean energy investments, which are integral to sustainable development, have also been identified as key drivers for achieving multiple SDGs, including SDG 2. Evidence suggests that investments in green energy technologies not only contribute to environmental sustainability but also promote human development and green economic growth (Ofori et al., 2023). However, challenges persist, including economic diversity, over-reliance on Western technologies, and insufficient financing, which hinder the full potential of green energy investments in BRICS countries. These challenges underscore the importance of expanding green financial products and enhancing institutional capacity to support green credit facilities, which could further accelerate sustainability outcomes in the region (Mujumdar and Shadrin, 2021).

Empirical evidence linking environmental policies directly to improvements in food and nutrition security outcomes remains mixed but promising. For example, sustainable agriculture practices and school food programmes have been identified as “triple-duty interventions” that simultaneously address nutrition, inequalities, and environmental sustainability (Burgaz et al., 2023). These interventions not only enhance food availability and nutrition but also promote environmental sustainability by encouraging sustainable agricultural practices and healthy diets. Additionally, fiscal measures such as labelling, product reformulation, and in-store nudging have shown “double-duty potential” in improving both food security and environmental outcomes (Burgaz et al., 2023).

In terms of food environment policies, Hansen et al. (2022) found that pricing policies, such as taxes and subsidies, are effective in influencing food consumption patterns and improving food availability, particularly in the context of school food programmes and product reformulation. These policies, although effective in altering consumption patterns, require further research to understand their full potential and scalability across different regions.

Despite the promising evidence, gaps remain in understanding the direct impact of environmental policies on food security and nutrition outcomes. While research has identified the importance of sustainable agricultural practices and policies that promote environmental sustainability, there is a lack of comprehensive studies on the combined effects of these policies on food and nutrition security. Furthermore, market participation strategies have shown success in improving food security outcomes in some countries, such as Ghana, though such strategies are still underexplored in the BRICS context

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(Abdul Mumin and Abdulai, 2022). In sum, while the evidence supports the potential of environmental sustainability policies to improve food and nutrition security, much work remains to be done in integrating these policies more effectively across different sectors and regions.

Policy and institutional pathways for building resilience

Building resilience to climate shocks in food systems requires coherent policy frameworks, robust institutional arrangements, and multi-stakeholder engagement. Research demonstrates that policy and institutional interventions can strengthen climate resilience while simultaneously promoting sustainable food systems. Approaches such as City Region Food Systems (CRFS) emphasize system-centered planning, infrastructure development, and inclusive multi-stakeholder governance, with policy serving as a critical enabler for implementation (Blay-Palmer et al., 2021). Similarly, Climate-Smart Agriculture (CSA) and agroecological practices offer pathways to enhance soil health, carbon sequestration, and smallholder resilience, though their adoption is constrained by weak institutional support and fragmented policy frameworks (Dougill et al., 2021; Dagunga et al., 2023). Long-term sustainability requires integrating emerging technologies with policy frameworks that facilitate CSA, sustainable water management, and interconnected agronomic practices across production, processing, transportation, and consumption systems (Borsetta et al., 2025).

In the context of BRICS countries, policy coherence between climate action and agricultural development remains a key challenge. Empirical evidence highlights that while renewable energy, ICT, and technological innovation can mitigate agriculture-related emissions and enhance productivity, air pollution and high carbon dioxide emissions continue to undermine agricultural outputs (Shah et al., 2022). The agriculture-induced Environmental Kuznets Curve observed in BRICS economies underscores the dual role of agriculture in economic development and environmental degradation, where renewable energy adoption moderates negative climate impacts (Shah et al., 2022). Institutionalizing science-policy engagement is critical to bridging knowledge and practice gaps, requiring enhanced credibility, salience, and legitimacy of research, supported by participatory governance, accountability mechanisms, and effective leadership (Dinesh et al., 2021). Policy fragmentation remains a persistent barrier, necessitating strengthened stakeholder coordination and institutional alignment to integrate climate adaptation and mitigation strategies into agricultural development (Chevallier, 2023).

Global governance and policy diffusion experiences provide valuable lessons for BRICS countries in aligning climate and food security agendas. Brazil's success in framing and diffusing food security policies through FAO engagement illustrates the importance of state and non-state actors in shaping global policy prescriptions (Milhorance, 2020). Similarly, BRICS-G20 interactions reveal opportunities for cooperative governance, enhancing the responsiveness of international financial architectures to emerging economies' priorities (Larionova and Shelepov, 2022). Nevertheless, regional and international frameworks often face implementation constraints due to limited cooperation, insufficient legal obligations, and the primacy of national interests (Islam and Kieu, 2020). Food governance research further highlights the influence of institutional norms, power dynamics, and resource allocation processes in fragmented global governance contexts, suggesting that effective climate-food security

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alignment must address both cooperative mechanisms and practical implementation barriers (Azizi, 2020).

Climate-Smart Agriculture (CSA) exemplifies the intersection of policy, institutional support, and technological innovation in fostering resilient food systems. Evidence indicates that CSA adoption enhances food production, dietary diversity, and economic opportunities in both rural and urban contexts, yet adoption remains limited by policy gaps, insufficient farmer knowledge, institutional constraints, and financing challenges (Wakweya, 2023; Khumalo et al., 2024). Transformative CSA strategies, including precision agriculture, regenerative practices, biochar application, and agroforestry, have been shown to improve soil health and mitigate greenhouse gas emissions, though adoption patterns remain heterogeneous across countries, necessitating site-specific approaches and enabling policy frameworks (Fusco et al., 2020; Kabato et al., 2025). Successful implementation depends on linking farmers, researchers, and extension practitioners through capacity-building initiatives, context-specific interventions, and financial incentives to overcome socio-economic and technological barriers.

Synthesising theoretical and empirical insights: linking climate, sustainability, and SDG 2

Synthesising theoretical and empirical insights from climate change, environmental sustainability, and food security reveals the complex and multifaceted nature of the relationships between these elements, particularly in the context of BRICS economies. The Sustainable Livelihoods Framework (SLF) and Ecological Modernisation Theory (EMT) provide valuable theoretical foundations for understanding these linkages. SLF highlights the dynamic interactions between different forms of capital—natural, human, social, and financial—within livelihoods, particularly in rural settings where climate change impacts are most pronounced. This framework suggests that food security outcomes in BRICS economies are influenced not only by climate change but also by the broader socio-economic and institutional contexts, which determine access to resources, opportunities for adaptation, and resilience strategies. On the other hand, Ecological Modernisation Theory offers insights into how environmental policies, technological innovations, and market mechanisms can drive sustainability transitions while simultaneously fostering economic development. Together, these theories offer a holistic perspective on how climate change and environmental sustainability can be integrated into strategies for achieving food security, particularly under the constraints posed by climate shocks.

Despite the valuable contributions of these theoretical frameworks, empirical research on the nexus between climate change, environmental sustainability, and food security in BRICS economies remains insufficient. Existing studies frequently exhibit significant gaps, particularly in their integration of these dimensions. For instance, while climate services, such as risk management tools and agricultural insurance, have been shown to improve food security outcomes (Hansen et al., 2022), these services often lack comprehensive integration into agricultural value chains and broader policy frameworks. Moreover, while SDG 2 encompasses multiple objectives related to hunger eradication, agricultural productivity, and climate resilience, there is limited evidence of synergies between these goals in national policies. Research has predominantly focused on trade-offs between these objectives, with little emphasis on policies that foster multi-dimensional gains (Lipper et al., 2020). Integrated modelling studies, such as those by Soergel et al. (2021), suggest that ambitious climate policies alone are insufficient to

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achieve SDG 2, highlighting the need for complementary interventions such as climate finance, progressive carbon pricing redistribution, and improved nutrition access. This underscores the complexity of the climate-sustainability nexus and the necessity for integrated, cross-sectoral approaches to sustainable development.

A critical gap in the literature lies in the integration of climate change, environmental sustainability, and food security within BRICS economies. While studies such as those by Nihal et al. (2024) have explored energy security and environmental sustainability in BRICS, they often omit food security considerations. The Energy Security and Environmental Sustainability Index developed for BRICS nations, for example, focuses primarily on energy systems and environmental practices without addressing the crucial links between food security and climate change (Nihal et al., 2024).

Similarly, studies on climate change cooperation within BRICS, such as those by Kıprızlı and Köstem (2023), have examined ideological convergence and climate policy actions but have largely neglected the intersection of climate policy and food security. Tian et al. (2020) similarly explored the economic-environmental nexus in BRICS economies, focusing on carbon emissions and resource usage, but did not consider food security outcomes in their analysis. Additionally, Akbari et al. (2022) conducted a bibliometric analysis of global food security research, identifying key sustainability dimensions but failed to specifically address the unique challenges of BRICS economies in balancing food security with climate and environmental goals. These studies collectively point to a significant gap in the literature: the lack of integrated analytical frameworks that simultaneously account for climate change, environmental sustainability, and food security in the context of BRICS economies.

Furthermore, a methodological gap exists in the research on climate change, sustainability, and food security. The existing literature heavily relies on cross-sectional and retrospective studies, which limit the ability to capture the dynamic, long-term effects of climate change on food security outcomes. Studies using advanced econometric techniques, such as dynamic panel data methods like System-GMM, are notably underutilised, despite their capacity to address issues such as endogeneity and unobserved heterogeneity in panel data (Farrukh et al., 2020; Nathaniel et al., 2021). The lack of such methodologies means that important insights into the temporal dynamics of climate-food security interactions are often overlooked. Moreover, the existing body of research often fails to incorporate the multi-dimensionality of the climate-food security relationship, which necessitates cross-disciplinary approaches that integrate environmental, economic, and social factors in a unified framework.

Emerging literature continues to highlight the complex linkages between environmental policy, agricultural productivity and sustainable development. Jiang et al. (2023) demonstrate that adaptive land-degradation neutrality policies can deliver simultaneous ecosystem, agricultural and economic co-benefits, illustrating the importance of coordinated policy frameworks in shaping sustainable food systems. Complementary macro perspectives by Duan (2025) emphasize that sustainability transitions require balancing environmental protection, energy transformation and economic expansion rather than sequencing them separately, reinforcing earlier debates around multi-objective policy alignment.

Within food systems literature, growing attention is being paid to climate-induced resilience indicators. Xie et al. (2025) develop a resilience measurement framework for China under climate change, showing that food security outcomes depend not only on production and availability but also on infrastructure and institutional responsiveness.

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Their findings support calls to incorporate resilience into food system governance and SDG monitoring, particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

Digitalization is increasingly positioned as a climate-smart pathway for agricultural transformation. Nabi et al. (2025) provide evidence from Pakistan showing that digital and precision farming enhance crop yields while reducing emissions intensity, although trade-offs persist in resource-constrained settings. Such findings align with broader literature on agri-technology adoption and climate adaptation, suggesting that digital agriculture plays a dual role in both food security and low-carbon transitions.

Beyond agriculture, research on green finance and technology diffusion is expanding. Hu et al. (2026) show that green finance facilitates urban green technology transfer networks, accelerating low-carbon industrial transformation in China’s Yangtze River Delta. On the firm side, Wu et al. (2025) find that shareholder activism can shift corporations from exploitative toward exploratory innovation, indicating that external stakeholder pressure plays an important role in ESG-driven strategic adjustments. Complementary organizational studies by Xi et al. (2025) demonstrate that sustainability-related performance outcomes depend on internal HRM configurations rather than single policy levers, highlighting contingent complementarities within firms.

Institutional and fiscal governance mechanisms also play a role in sustainable development trajectories. Jin et al. (2025) show that moderate expenditure decentralisation enhances sustainable development outcomes across 52 countries, while excessive decentralisation can weaken policy coherence and implementation capacity. This evidence reinforces broader debates on governance quality, institutional coordination and policy centralisation within sustainability transitions.

At the behavioural level, Sun et al. (2025) argue that sustainability transitions require disruption of habitual decision-making and status-quo bias, suggesting that information provision alone cannot drive behavioural change. Behavioural and structural incentives are therefore necessary to facilitate the shift toward climate-friendly technologies, financial instruments and consumption patterns.

Recent methodological advances also expand empirical capacity to model heterogeneous effects within sustainability domains. Yang et al. (2024) introduce a functional-coefficient panel quantile regression with latent group structures, and Hao and Yang (2024) propose a multiple-output quantile regression neural network model. These developments provide tools for analyzing distributional outcomes and multidimensional sustainability indicators, useful for climate, food security, emissions, and inequality research.

In summary, the literature reveals significant gaps in the understanding of how climate change, environmental sustainability, and food security intersect in BRICS economies. Existing studies have failed to develop integrated frameworks that simultaneously address these dimensions, and methodological gaps, particularly the underutilisation of dynamic panel data methods, further limit the understanding of these complex interactions. This study contributes to filling these gaps by integrating the Sustainable Livelihoods Framework and the Environmental Kuznets Curve hypothesis, offering a more comprehensive and nuanced analysis of the challenges and opportunities that BRICS economies face in achieving SDG 2 while addressing the impacts of climate change and promoting environmental sustainability. Through this synthesis, the study will provide valuable insights for policymakers, researchers, and practitioners working to strengthen the resilience of food systems in the face of climate shocks.

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Materials and methods

Data description, measurement and sources

This study employs a balanced panel dataset covering the BRICS economies (Brazil, Russia, India, China, and South Africa), over the period 2000–2023. The variables are selected to capture the complex interlinkages between climate change, environmental sustainability, and food and nutrition security (FNS). The dependent variable is FNS, proxied by the prevalence of undernourishment, complemented by indicators such as dietary energy supply, which together provide a comprehensive measure of nutritional outcomes in the BRICS context.

The explanatory framework is grounded in theory while carefully refined to mitigate multicollinearity. Initial specifications included a wider set of variables such as carbon dioxide emissions, GDP per capita, and population growth. However, diagnostic tests revealed severe collinearity, particularly between carbon emissions and renewable energy consumption, and between GDP per capita, population, and agriculture value added. To ensure robust estimation, the model was restructured to retain variables with both strong theoretical relevance and sound statistical properties, reducing the mean variance inflation factor (VIF) to 1.74—well below critical thresholds.

Accordingly, the final specification includes five core explanatory variables. Agricultural value added (lnAGVA) is employed to capture the structural contribution of the agricultural sector to food availability and access, directly linking economic activity to SDG 2. Renewable energy consumption (lnREN) reflects the sustainability of energy systems, representing a key pathway through which environmental stewardship supports long-term food security. Temperature anomalies (lnTEMP) are included as a proxy for climate change pressures that directly influence agricultural productivity and nutrition outcomes. Environmental policy stringency (lnEPS) provides an institutional dimension, highlighting the extent to which regulatory frameworks drive sustainable practices that safeguard food systems. Forest area (lnFOR) is integrated as an ecological sustainability measure, reflecting biodiversity conservation, ecosystem services, and carbon sequestration that indirectly underpin food and nutrition security.

Data for these variables are drawn from authoritative international sources, including the World Bank's World Development Indicators (WDI), Food and Agriculture Organisation (FAO) statistics, the Climate Change Knowledge Portal (CCKP), and the Organisation for Economic Co-operation and Development (OECD) databases. This combination of datasets ensures both credibility and comparability across countries and over time. The detailed description and measurements of variables are presented in *Table 1*.

Model specification

Building on the theoretical framework, the empirical model links food and nutrition security to climate change and environmental sustainability indicators in BRICS economies. The baseline model is expressed in *Equation 1* as:

$$FNS_{it} = \alpha + \beta_1 REN_{it} + \beta_2 TEMP_{it} + \beta_3 AGVA_{it} + \beta_4 EPS_{it} + \beta_5 FOR_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad \text{(Eq.1)}$$

where FNS_{it} denotes food and nutrition security for country i at time t, μ_i captures country-specific effects, λ_t represents time effects, and ε_{it} is the idiosyncratic error term.

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***Table 1.** Variable description and measurement*

Variable	Measurement	Source	Expected Sign
Food and Nutrition Security (FNS)	Prevalence of undernourishment (% of population)	WDI	Dependent Variable
Temperature Anomalies	Annual mean surface temperature deviation	CCKP FAO	Negative
Renewable Energy (REN)	Share of renewable energy in total final energy consumption (%)	WDI	Positive
Environmental Policy Stringency (EPS)	Composite index	OECD	Positive
Forest Area (FOR)	Forest area as % of land area	WDI	Positive
Agricultural Value Added (AGVA)	% of GDP	WDI	Positive

Source: Authors' compilations. Note: World Bank's World Development Indicators (WDI), Food and Agriculture Organisation (FAO) statistics, the Climate Change Knowledge Portal (CCKP), and the Organisation for Economic Co-operation and Development (OECD)

Model estimation technique

The empirical strategy is structured to address the econometric complexities inherent in macro-panel data analysis and proceeds in a systematic sequence. First, descriptive statistics are employed to summarise the central tendency, dispersion, and distributional properties of the variables, providing an initial understanding of data behaviour across BRICS economies. This is complemented by a correlation analysis to examine pairwise associations among variables and to assess potential multicollinearity concerns prior to formal estimation.

Next, panel unit root tests, including the Levin–Lin–Chu, Im–Pesaran–Shin, and Fisher-type augmented Dickey–Fuller tests, are applied to determine the order of integration of the series. Given the multi-country nature of the dataset, the Pesaran (2004) cross-sectional dependence test is conducted to identify possible interdependencies across BRICS economies, while the Pesaran and Yamagata (2008) slope heterogeneity test is used to assess parameter heterogeneity. To establish the presence of a long-run equilibrium relationship among the variables, Pedroni and Kao panel cointegration tests are subsequently implemented. The confirmation of cointegration provides the econometric justification for the use of dynamic estimation techniques in the subsequent analysis.

To enhance robustness and capture the multifaceted relationship between climate change, environmental sustainability, and food and nutrition security in the BRICS context, a multi-method estimation approach is adopted. The analysis begins with the Fixed Effects (FE) model, which serves as a baseline by controlling for unobserved, time-invariant country-specific characteristics that could otherwise bias the estimates. Although FE models incorporating lagged dependent variables are vulnerable to the Nickell bias in panels with relatively small cross-sections and moderate time dimensions, they provide a useful benchmark against which alternative estimators can be compared.

Second, the study employs the Least Squares Dummy Variable Corrected (LSDVC) estimator as the main dynamic mean estimator. LSDVC explicitly corrects the small-sample bias (Bruno, 2005) associated with FE and produces more reliable estimates of dynamic effects, particularly the persistence of food and nutrition security. Bootstrap standard errors are applied to enhance inference. Third, to capture both short-run and

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long-run dynamics, the study estimates the Panel Autoregressive Distributed Lag (PARDL) model within the Pooled Mean Group (PMG) framework (Pesaran et al., 1999). This estimator allows short-run coefficients to differ across countries, while constraining the long-run coefficients to be homogeneous, consistent with the theoretical assumption of convergence among BRICS economies. This makes PMG particularly well-suited to the present study, where variables are of mixed integration orders I(0) and I(1).

Fourth, to investigate distributional heterogeneity, the study employs the Method-of-Moments Quantile Regression (MM-QR) estimator developed by Machado and Silva (2019). This technique allows the analysis of conditional effects across different points (quantiles) of the food and nutrition security distribution, thereby capturing whether climate and sustainability drivers exert stronger influences in contexts of low, median, or high food security. Unlike conventional quantile regression approaches, MM-QR accounts for unobserved heterogeneity in panel settings and provides consistent estimates without relying on fixed-effects transformations. This distributional analysis complements the dynamic mean estimators by offering a more nuanced understanding of how determinants operate across the entire conditional distribution rather than only at the mean.

By presenting results sequentially—FE → LSDVC → PMG → MM-QR, the study highlights how baseline within-estimates evolve once bias correction and long-run dynamics are introduced, and how effects differ across the distribution of food and nutrition security. This layered approach ensures robust, nuanced, and policy-relevant insights into the climate–sustainability–food security nexus in BRICS economies.

Results and discussion

Presentation of results

Descriptive Statistics

The descriptive statistics presented in *Table 2* provide important insights into the dynamics of climate change, environmental sustainability, and food and nutrition security (FNS) across BRICS economies, offering a foundation for understanding the pathways toward achieving SDG 2. The average prevalence of undernourishment stands at 6.36 percent of the population, with values ranging from 2.5 to 22 percent. This variation underscores substantial differences in nutritional outcomes across countries, reflecting both structural disparities in food access and the persistence of inequality in resource distribution. While the mean suggests that food insecurity is not uniformly pervasive across the bloc, the wide dispersion highlights that particular economies still face significant challenges in ensuring equitable access to adequate food.

Table 2. *Descriptive statistics*

Variable	Mean	Std. dev.	Min	Max
FNS	6.355652	5.078174	2.5	22
FOR	34.14409	18.26202	13.93	65.5
REN	22.46304	16.81274	3.2	50
AGVA	7.558348	5.567934	1.93	21.62
TEMP	1.175217	0.554848	0.26	3.68
EPS	1.224174	0.870084	0.17	3.54

Source: Authors' computation

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Forest area (FOR) accounts for an average of 34.14 percent of total land area, but with considerable heterogeneity, ranging from 13.93 to 65.5 percent. This divergence indicates stark contrasts in ecological resource endowments within the BRICS grouping. Countries with high forest cover can act as carbon sinks and maintain environmental balance, thereby contributing positively to sustainability goals, whereas those with limited forest resources face heightened vulnerability to climate change and biodiversity loss. The share of renewable energy (REN) in total final energy consumption averages 22.46 percent, with a range from as low as 3.2 percent to as high as 50 percent. This spread signals both progress and uneven adoption of clean energy technologies. Economies at the upper bound reflect proactive investment in renewable transitions that enhance environmental quality, while those at the lower bound remain reliant on fossil-intensive pathways, which could compromise long-term sustainability targets.

Agricultural value added (AGVA) contributes an average of 7.56 percent to GDP, with a broad range between 1.93 and 21.62 percent. This indicates that while agriculture remains a critical sector in some BRICS economies, its role in others is gradually declining due to structural transformation toward industry and services. The persistence of higher agricultural shares in some cases suggests the dual challenge of balancing growth with the imperative of modernising food systems for sustainability. Temperature anomalies (TEMP) record a mean deviation of 1.18°C from long-term averages, reaching a maximum of 3.68°C. This finding reflects the intensifying pressure of climate variability on food systems, with potential adverse impacts on agricultural productivity and food security outcomes. Such anomalies underscore the urgency of climate adaptation strategies across the region.

Finally, environmental policy stringency (EPS) exhibits a mean value of 1.22 on the OECD index, with a maximum of 3.54, signalling modest but uneven progress in the institutional enforcement of environmental regulations. While some BRICS economies are strengthening environmental governance frameworks, others are still at an early stage of policy development, which may limit their capacity to mitigate carbon emissions and safeguard natural resources. The relatively low average underscores that without stronger regulatory mechanisms; climate challenges may exacerbate food insecurity despite economic growth.

Taken together, the descriptive statistics highlight the heterogeneous structural conditions that shape the nexus of climate change, environmental sustainability, and food and nutrition security in BRICS economies. The variation across indicators illustrates both the opportunities for leveraging renewable energy and ecological resources, and the risks posed by climate anomalies, weak policy enforcement, and persistent agricultural dependency. These findings reinforce the need for differentiated yet coordinated policy responses that align with the broader objective of achieving SDG 2 within a sustainable development framework.

Correlation analysis

The correlation results reported in *Table 3* provide further insights into the relationships among climate change indicators, environmental sustainability variables, and food and nutrition security (FNS) in BRICS economies. A negative correlation is observed between FNS and temperature anomalies (TEMP), supporting the notion that rising temperatures undermine agricultural productivity and exacerbate undernourishment, thereby highlighting climate change as a significant constraint to achieving SDG 2. Similarly, the correlation between FNS and environmental policy

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stringency (EPS) is negative, suggesting that stricter environmental regulations may impose short-term adjustment costs that could indirectly affect food systems, even though such policies are expected to yield long-term sustainability gains. In contrast, FNS displays a positive correlation with renewable energy consumption (REN) and forest area (FOR), aligning with theoretical expectations that ecological conservation and clean energy adoption enhance environmental quality, stabilise food production systems, and foster resilience against climate-induced shocks.

Table 3. *Correlation analysis*

	lnREN	lnFOR	lnAGVA	lnEPS	lnTEMP
lnREN	1.000				
lnFOR	0.061	1.000			
	0.515				
lnAGVA	0.558	-0.046	1.000		
	0.000	0.623			
lnEPS	0.004	-0.215	0.460	1.000	
	0.964	0.021	0.000		
lnTEMP	-0.455	0.356	-0.361	0.038	1.000
	0.000	0.000	0.000	0.685	

Source: Authors' computation

The results also reveal meaningful interlinkages among the explanatory variables themselves. Renewable energy shares are positively associated with both EPS and forest area, signalling the complementarity between regulatory frameworks, ecological resource management, and the transition to low-carbon energy systems. Agricultural value added (AGVA) shows a positive correlation with FNS, underlining the role of the agricultural sector as a direct contributor to food availability, particularly in economies where agriculture retains a sizeable share of GDP. However, the relatively weak magnitude of this relationship compared to environmental and climatic variables suggests that structural and climatic constraints may mediate the benefits of agricultural expansion for nutrition outcomes. Meanwhile, correlations between temperature anomalies and renewable energy are modestly positive, implying that economies exposed to greater climate variability may be more inclined to invest in renewable energy technologies as part of adaptive strategies.

Cross-sectional dependence, stationarity, and cointegration tests

In this study, the investigation of cross-sectional dependence (CSD) is essential due to the potential for interdependence among nations within the BRICS group, driven by factors such as geographic proximity and shared socio-economic characteristics. The initial step in the methodological approach involved applying Pesaran's Cross-sectional Dependence (CD) test to assess the presence of such interdependence, which yielded a test statistic of 0.682 with a corresponding p-value of 0.4950. This result suggests that the

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null hypothesis of no cross-sectional dependence cannot be rejected at conventional significance levels, indicating that the panel units do not exhibit substantial contemporaneous correlation. The relatively high p-value implies that the cross-sectional units in the data are not strongly interconnected in terms of their error components.

Additionally, the average absolute value of the off-diagonal elements in the correlation matrix was computed at 0.405. While this indicates a moderate degree of association between the residuals, it does not suggest a significant level of cross-sectional dependence, particularly in light of the non-rejection of the null hypothesis. Therefore, these results support the conclusion that there is no significant cross-sectional dependence in the data. This absence of substantial dependence justifies the application of first-generation panel estimation techniques, which assume cross-sectional independence, such as the Levin–Lin–Chu (LLC) and Im–Pesaran–Shin (IPS) unit root tests. These tests rely on the assumption that idiosyncratic error components are independent across units, and given the lack of significant CSD, their use remains methodologically sound in this study. The findings suggest that, while cross-sectional dependence could be a concern in more interconnected contexts, it does not appear to be a critical issue in the analysis of climate, environmental sustainability and food and nutrition security nexus in BRICS economies

Unit root results

The stationarity results presented in *Table 4* provide an essential preliminary step in ensuring the robustness of the econometric analysis, as they determine the integration properties of the variables used in modelling the relationship between climate change, environmental sustainability, and food and nutrition security (FNS) in BRICS economies. The results of the Levin–Lin–Chu (LLC) panel unit root test show that FNS is stationary at levels, as indicated by the highly significant test statistics, confirming that food and nutrition security does not exhibit strong persistence and mean-reverts relatively quickly. This result is important because it suggests that shocks to undernourishment levels may not be permanent and could be corrected through appropriate policy and structural adjustments. Similarly, temperature anomalies (TEMP) are also found to be stationary at level, reinforcing the notion that climatic fluctuations in the sample are trend-stable, though their effects may still carry significant implications for agricultural and environmental outcomes.

Table 4. *Stationarities of the variables*

Variable	Levin–Lin–Chu		Levin–Lin–Chu	
	I(0)	I(1)	I(0)	I(1)
FNS	-6.795***		-3.9867***	
FOR	-2.207***		-1.0859	-12.103***
REN	-1.9786**		0.8941	-6.250***
AGVA	-2.5093***		-0.3098	-6.238***
TEMP	-5.5460***		-4.3965***	
EPS	-0.6974		0.8305	-6.499***

Source: Authors' computation; Note: ***, ** and * illustrate the 1 %, 5 % and 10 % significance levels, respectively

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For other variables, mixed orders of integration are observed, indicating the suitability of an Autoregressive Distributed Lag (ARDL) framework, which accommodates a combination of I(0) and I(1) regressors. Forest area (FOR), renewable energy (REN), agricultural value added (AGVA), and environmental policy stringency (EPS) are not uniformly stationary at levels but become stationary at first difference, as confirmed by the significant LLC statistics. For instance, REN and AGVA show weak evidence of stationarity at I(0) but strongly satisfy I(1), underscoring the presence of long-run trends in energy transitions and the structural role of agriculture in GDP. Likewise, EPS is non-stationary at level but attains stationarity at first difference, reflecting that policy enforcement intensity evolves gradually and may require time to stabilise.

Taken together, these results confirm that the dataset comprises a mixture of I(0) and I(1) series, with none integrated of order two, thereby validating the use of a panel ARDL–PMG framework to capture both the short-run dynamics and long-run equilibria. The evidence also highlights that while food insecurity and climate anomalies exhibit more immediate responsiveness to shocks, environmental policies, renewable energy adoption, forest resources, and agricultural contributions follow longer-term trajectories. This mix of stationary and non-stationary behaviours is consistent with the structural heterogeneity of BRICS economies and underscores the importance of a modelling strategy that accommodates both immediate and gradual adjustments in the climate–sustainability–food security nexus.

Panel cointegration test

The panel cointegration results in *Table 5* provide strong evidence of a long-run equilibrium relationship among food and nutrition security, climate change indicators, and environmental sustainability variables in BRICS economies. The Pedroni test shows that while not all statistics are significant, the modified Phillips–Perron t-statistic is highly significant, indicating cointegration. This finding is reinforced by the Kao test, where all test statistics are significant at conventional levels, confirming the presence of long-run associations. Together, these results suggest that despite short-run fluctuations, the variables converge towards a stable equilibrium path, underscoring that policies promoting renewable energy adoption, forest conservation, and environmental regulation can generate sustained improvements in food and nutrition security over time.

Table 5. *Panel cointegration result*

	Statistic	**p-value**
Pedroni Cointegration Test		
Modified Phillips–Perron t	3.4001***	0.0003
Phillips–Perron t	0.8763	0.1904
Augmented Dickey–Fuller t	1.2924*	0.0981
Kao Cointegration Test		
Modified Dickey–Fuller t	-3.1367***	0.0009
Dickey–Fuller t	-3.04067***	0.0012
Augmented Dickey–Fuller t	-2.12927**	0.0166
Unadjusted modified Dickey–Fuller	-1.92417**	0.0272
Unadjusted Dickey–Fuller t	-2.77457***	0.0028

Source: Authors' computation; Note: ***, **, and * illustrate the 1 %, 5 %, and 10 % significance levels, respectively

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Estimation results across methods

In the baseline fixed-effects specification (*Table 6*), the lagged dependent variable (L.lnFNS) is positive and highly significant at 0.901 ($p < 0.01$), consistent with the persistence of food and nutrition security (FNS) across periods. This indicates strong path dependence: a one percent improvement in past FNS increases current FNS by about 0.90 percent. Renewable energy consumption (lnREN) is positive and significant at 0.258 ($p < 0.01$), in line with a priori expectations that cleaner energy supports agricultural productivity and sustainable food systems.

Table 6. *Fixed effect (baseline) and biased corrected LSDV result*

Variables	FE Baseline	Bias-Corrected
L.lnFNS	0.901***	0.916***
	(0.021)	(0.024)
lnTEMP	-0.007	-0.006
	(0.019)	(0.019)
lnREN	0.258***	0.255***
	(0.057)	(0.054)
lnEPS	0.104***	0.105***
	(0.015)	(0.015)
lnFOR	-0.613***	-0.597**
	(0.232)	(0.232)
lnAGVA	-0.014	-0.029
	(0.055)	(0.053)
Constant	1.536*	
	(0.846)	
Observations	110	110
R-squared	0.967	
Number of c_id	5	5

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1. Source: Authors' computation

Interpreted as elasticity, a one percent increase in renewable energy use raises food and nutrition security by 0.26 percent. Similarly, environmental policy stringency (lnEPS) has a positive and significant coefficient of 0.104 ($p < 0.01$), confirming that stronger environmental regulations improve sustainability outcomes and indirectly enhance nutrition, with a one percent tightening of policy stringency improving FNS by 0.10 percent. Forest area (lnFOR), however, enters with a negative and significant elasticity of –0.613 ($p < 0.01$), suggesting that increases in forest cover may reduce arable land available for food production, producing a trade-off effect. Both agricultural value added (lnAGVA) and temperature anomalies (lnTEMP) are statistically insignificant, though their negative signs align with theoretical expectations that climate shocks and structural dependence on agriculture may not directly enhance food security in the short run. The bias-corrected LSDV estimator confirms these results, with coefficients and significance levels broadly consistent, thus addressing potential Nickell bias and validating the robustness of the findings.

Turning to the dynamic framework, the Panel ARDL–PMG estimates (*Table 7*) reveal differential short- and long-run effects. In the short run, forest area (lnFOR) exerts a large and positive effect of 9.451 ($p < 0.10$), and agricultural value added (lnAGVA) has a

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positive and significant elasticity of 0.295 ($p < 0.05$). This suggests that in the immediate horizon, both ecological resources and agricultural output can buffer food security outcomes, though the forest effect is unusually large and may capture country-specific dynamics. Other short-run variables, including temperature anomalies, renewable energy, and environmental policy stringency, remain insignificant, implying that their benefits manifest more gradually.

Table 7. *Short-run and long-run estimation results from PARDL*

Variables	**Longrun**	**Shortrun**
ec		-0.065
		(0.046)
D.lnTEMP		-0.039
		(0.051)
D.lnREN		0.103
		(0.236)
D.lnEPS		0.04
		(0.051)
D.lnFOR		9.451*
		(5.045)
D.lnAGVA		0.295**
		(0.132)
L.lnREN	1.566***	
	(0.313)	
L.lnEPS	1.328***	
	(0.375)	
L.lnFOR	3.91	
	(2.753)	
L2.lnAGVA	2.677***	
	(0.953)	
Constant		-1.511
		(1.034)
Observations	110	110

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1. Source: Authors’ computation

In the long run, renewable energy (lnREN) and environmental policy stringency (lnEPS) emerge as strong drivers, with elasticities of 1.566 ($p < 0.01$) and 1.328 ($p < 0.01$), respectively, both exceeding unities. This indicates that a one percent increase in renewable energy or policy stringency enhances food and nutrition security by more than one percent, reflecting strong complementarities between sustainable energy transitions, institutional enforcement, and long-term food system resilience. Agricultural value added also contributes positively in the long run, with a second lag effect of 2.677 ($p < 0.01$), highlighting the cumulative importance of agricultural development for nutrition outcomes. The error correction term is negative (–0.065) as expected, but statistically insignificant, suggesting slow adjustment towards long-run equilibrium across BRICS economies.

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Method-of-moments quantile regression result

The distributional heterogeneity explored through Method-of-Moments Quantile Regression (*Table 8*) provides additional insights. At the lower quantile (Q25), renewable energy is positive though not statistically significant, whereas temperature anomalies have a strong negative elasticity of –0.453 ($p < 0.01$), highlighting the vulnerability of food security to climate shocks in weaker contexts. Forest area also shows a negative and significant elasticity of –0.240 ($p < 0.05$), reinforcing the land-use trade-off at lower levels of food security. At the median (Q50), renewable energy becomes positive and significant (0.185, $p < 0.01$), while temperature anomalies remain negative (–0.334, $p < 0.01$), consistent with the pattern that cleaner energy supports, but climate instability undermines, food security.

Table 8. *Method-of-moments quantile regression result*

Variables	Qtile-25	Qtile-5	Qtile-75
lnFOR	-0.240**	-0.392***	-0.474***
	(0.115)	(0.083)	(0.074)
lnREN	0.0815	0.185***	0.242***
	(0.067)	(0.048)	(0.043)
lnTEMP	-0.453***	-0.334***	-0.269***
	(0.150)	(0.105)	(0.097)
lnEPS	-0.175*	-0.0629	-0.00201
	(0.095)	(0.068)	(0.061)
lnAGVA	0.500***	0.388***	0.328***
	(0.122)	(0.086)	(0.079)
Constant	0.979**	1.822***	2.279***
	(0.447)	(0.330)	(0.284)
Observations	115	115	115

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1. Source: Authors' computation

At the upper quantile (Q75), the elasticity of renewable energy strengthens further to 0.242 ($p < 0.01$), suggesting its benefits are more pronounced in countries with relatively stronger nutrition outcomes. Conversely, temperature anomalies remain significantly negative at –0.269 ($p < 0.01$), and forest area exhibits a robust negative effect of –0.474 ($p < 0.01$), underscoring persistent ecological trade-offs. Agricultural value added is consistently positive and significant across quantiles, with elasticities ranging from 0.328 to 0.500, showing that agricultural output remains a key determinant of FNS across all contexts. Environmental policy stringency displays mixed results, being weakly negative or insignificant, with its modest impact likely reflecting uneven policy enforcement across BRICS.

Overall, the results demonstrate strong conformity with theoretical expectations regarding the positive roles of renewable energy, agricultural development, and institutional frameworks, as well as the adverse effects of temperature anomalies and forest expansion on food security. The elasticity-based interpretation underscores that while renewable energy and policy measures have long-run multiplier effects, climate shocks and ecological trade-offs exert significant drags, particularly in vulnerable settings. The robustness across methods—FE, bias-corrected LSDV, PMG, and MM-QR,

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confirms the persistence, heterogeneity, and distributional dimensions of the climate–sustainability–food security nexus in BRICS economies.

Discussion of results

Our study finds that climate change and environmental sustainability exert distinct but interconnected effects on food and nutrition security (FNS) in BRICS economies, with direct relevance for SDG 2. In particular, climate change, proxied by temperature anomalies, undermines food productivity primarily through adverse effects on agricultural yields and food availability rather than through immediate output shocks. With respect to climate change, the coefficient on temperature anomalies is negative across both the fixed effects and bias-corrected LSDV estimations, although statistically insignificant. This result does not imply the absence of climate effects on food productivity, but rather reflects the gradual and heterogeneous nature of climate impacts across BRICS economies.

Rising temperature anomalies disrupt crop growth by inducing heat stress, shortening growing periods, reducing soil moisture, and increasing evapotranspiration, which collectively weaken agricultural productivity and constrain food supply over time (Malhi et al., 2021; Seppelt et al., 2022). The negative sign therefore remains consistent with productivity-reducing mechanisms, even where short-run adaptive responses may temporarily offset yield losses. By contrast, environmental sustainability measures, including renewable energy adoption and environmental policy stringency, contribute positively to FNS by supporting more resilient and stable production systems, reinforcing the role of sustainability-oriented policies in mitigating climate-induced risks to food productivity and nutrition outcomes (Shah et al., 2022; Ofori et al., 2023).

Our findings are consistent with previous research that has demonstrated the adverse effects of climate change on food security, especially in emerging economies. Evidence shows that warming and climate variability reduce yields and increase volatility in staple crop production, with particularly strong effects in climate-exposed and rain-fed settings (Habib-ur-Rahman et al., 2022; Seppelt et al., 2022). Similarly, the observed negative impact of forest area on food security reflects land-use trade-offs within agri-food systems, where conservation-oriented land allocation and competing sustainability objectives may constrain arable land availability and agricultural expansion when food production goals are insufficiently integrated into environmental management strategies (Tubiello et al., 2021; Akanmu et al., 2023).

Our study extends this discussion by quantifying the elasticity of these effects and showing that forest expansion, while contributing to ecological preservation, may reduce the availability of arable land, thereby intensifying food security challenges in the absence of productivity-enhancing interventions (Tubiello et al., 2021). In contrast, the positive effects of renewable energy and environmental policy stringency on FNS align with evidence that clean energy investments and sustainability transitions support agricultural resilience, human development, and environmentally sustainable growth pathways in emerging economies (Shah et al., 2022; Ofori et al., 2023). However, our study advances these insights by demonstrating that the elasticity of these variables exceeds unity in the long run, suggesting that their contribution to food and nutrition security is stronger than previously assumed.

The mechanisms behind these findings can be explained through ecological and agricultural pathways. Temperature anomalies, which capture long-term climate stress, directly reduce crop yields by disrupting planting and growing cycles, increasing the

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prevalence of pests and diseases, and exacerbating water scarcity (Malhi et al., 2021; Seppelt et al., 2022). This contributes to the negative elasticity of temperature anomalies on FNS, where even modest increases in temperature deviations can generate persistent reductions in food availability

Forest area, while a positive contributor to long-term environmental stability, exhibits a trade-off effect in the short run, as its expansion may compete with land required for food production. This trade-off explains the negative elasticity observed in our study and is consistent with evidence that sustainability-driven land-use decisions may generate short-term food system pressures if not accompanied by climate-smart and productivity-enhancing agricultural practices (Tubiello et al., 2021; Akanmu et al., 2023). Renewable energy, by contrast, contributes positively to FNS by supporting access to energy for irrigation, mechanisation, processing, and food preservation, thereby mitigating the adverse effects of climate change on agricultural production systems (Shabir et al., 2023; Niu et al., 2023).

Policy implications follow directly from the identified transmission mechanisms through which renewable energy influences food systems. The positive long-run elasticity of renewable energy indicates that its contribution to food and nutrition security operates primarily through agricultural production and post-harvest channels rather than as a purely environmental input.

Increased access to renewable energy supports climate-resilient irrigation systems, reduces dependence on rainfall, and stabilises water supply for crop production. It also facilitates on-farm mechanisation, improves labour productivity, and enables energy-intensive activities such as processing, cold storage, and preservation that reduce post-harvest losses and enhance food availability (Kuyu et al., 2019; Shabir et al., 2023). In this context, the finding that a one percent increase in renewable energy use raises food and nutrition security by 0.26 percent reflects improvements across the entire agri-food value chain. When reinforced by environmental policy stringency, which strengthens regulatory oversight and promotes sustainable practices, renewable energy investments become a critical pathway for enhancing agricultural productivity, food distribution efficiency, and climate resilience, thereby advancing progress towards SDG 2 (Dinesh et al., 2021; Chevallier, 2023).

Our results further support the argument that effective environmental governance and institutional coherence are central to long-term food security, particularly through frameworks that enable sustainable agricultural practices and clean energy transitions (Dinesh et al., 2021; Chevallier, 2023). The role of agricultural value added (AGVA) in ensuring food availability is neither automatic nor definitional, but reflects deeper structural mechanisms through which agricultural systems translate productive capacity into sustained food security. In the fixed effects and bias-corrected LSDV estimations, the statistical insignificance of AGVA suggests that contemporaneous increases in agricultural output do not automatically translate into improved food and nutrition security. This outcome reflects structural rigidities in BRICS agricultural systems, including post-harvest losses, weak value-chain integration, limited storage and processing capacity, and unequal access to food markets, which dilute the immediate food security benefits of output growth (Kuyu et al., 2019; Bechoff et al., 2022).

In contrast, the dynamic Panel ARDL results reveal that agricultural value added plays a meaningful buffering role in the short run and a decisive role in the long run. The positive short-run elasticity indicates that increases in agricultural output can temporarily stabilise food availability during periods of climate or market stress by augmenting

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domestic supply and moderating price pressures. This effect reflects agriculture's function as a shock absorber rather than a direct nutritional driver in the immediate horizon. More importantly, the strong and significant long-run lagged effect highlights the cumulative contribution of agricultural development to food security. Sustained growth in agricultural value-added captures improvements in productivity, technological adoption, rural infrastructure, and market integration, all of which enhance food availability, affordability, and dietary access over time (Villacis et al., 2022; Sibhatu et al., 2022).

The Method-of-Moments Quantile Regression results reinforce this interpretation. The consistently positive and significant coefficients across all quantiles indicate that agricultural value added remains a fundamental determinant of food and nutrition security regardless of initial conditions. This finding underscore agriculture's structural role in shaping food systems, particularly in contexts characterised by heterogeneity in income levels, institutional quality, and climate exposure. Rather than reflecting definitional overlap, AGVA operates as an economic conduit through which productive efficiency, income generation, and supply-chain resilience jointly enhance food availability (Allee et al., 2021; Villacis et al., 2022).

While the short-run impacts of forest area and agricultural value added are positive, they suggest that immediate food security gains can be buffered by ecological resources and agricultural production capacity. The short-run elasticity of forest area highlights the role of ecosystem services, such as water regulation and soil fertility, in supporting food systems in the near term (Miller et al., 2021; Akanmu et al., 2023). However, other short-run variables, including temperature anomalies, renewable energy, and environmental policy stringency, remain insignificant, indicating that their benefits materialise more gradually and require sustained implementation horizons. This finding is consistent with evidence that green energy transitions and environmental policy effectiveness are often constrained by institutional capacity, financing limitations, and implementation delays (Mujumdar and Shadrin, 2021; Chevallier, 2023).

The robustness of the results across fixed effects, bias-corrected LSDV, panel ARDL, and quantile regression techniques provides confidence in the empirical findings. Panel ARDL estimates indicate that while forest area and agricultural value added exert short-run influences, renewable energy and environmental policy stringency emerge as the dominant long-run drivers of food and nutrition security. This supports the broader literature emphasising that long-term food system resilience depends more on institutional quality, technological adoption, and sustainability-oriented transitions than on short-term production shocks (Dinesh et al., 2021; Shah et al., 2022). Distributional effects captured by quantile regression further indicate that adverse climate impacts and ecological trade-offs are more pronounced at lower levels of food security, reflecting the heightened vulnerability of countries with weaker adaptive capacity and greater exposure to climate risks (Hasegawa et al., 2018; Saleem et al., 2024).

A key strength of this study lies in its methodological integration of dynamic estimators and quantile regressions, which allows for a nuanced assessment of temporal persistence, distributional heterogeneity, and long-run sustainability effects. The elasticity-based interpretation enhances policy relevance by quantifying the magnitude of intervention impacts. In addition, the integration of the Sustainable Livelihoods Framework and Ecological Modernisation Theory provides a coherent theoretical lens linking micro-level vulnerability with macro-level sustainability transitions.

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Nevertheless, the study has limitations. Environmental policy stringency indices may not fully capture informal enforcement mechanisms or regional disparities in policy effectiveness, potentially attenuating estimated impacts (Islam and Kieu, 2020; Chevallier, 2023). The focus on aggregate renewable energy consumption also masks heterogeneity across energy sources, which may have differential implications for agricultural systems. Furthermore, temperature anomalies, while suitable for capturing long-term climate stress, do not account for precipitation variability or extreme events that also influence food security outcomes. Future research should address these limitations by incorporating multiple climate indicators, disaggregated renewable energy types, and sub-national data to better capture localised vulnerabilities, particularly in large and diverse BRICS economies such as India and South Africa (Baraj et al., 2024). Additionally, while quantile regressions provide insights into distributional effects, they cannot fully account for sub-national disparities, which remain significant in countries like India and South Africa. Ahmed and Sinha (2020) suggested that national averages may mask regional disparities, making it crucial to incorporate sub-national data in future research to capture localised climate and policy effects.

In summary, the findings underscore the need for integrated climate adaptation and environmental sustainability strategies to achieve SDG 2 in BRICS economies. The positive long-run effects of renewable energy and environmental policy stringency highlight the importance of green energy transitions and institutional coherence for strengthening food and nutrition security. At the same time, the adverse impacts of climate stress and land-use trade-offs underscore the necessity of balancing conservation objectives with food production imperatives. Policy efforts should therefore prioritise renewable energy investment, institutional strengthening, and agricultural modernisation to enhance resilience against climate risks while ensuring sustainable and inclusive food systems.

Conclusion

This study set out to explore the pathways through which climate change and environmental sustainability influence the achievement of SDG 2 in BRICS economies, with a specific focus on how climate change affects food production and nutrition security, the role of environmental sustainability policies and practices in enhancing food security, and the policy and institutional pathways that can help strengthen resilience to climate shocks. The study integrates both theoretical and empirical analyses through the Sustainable Livelihoods Framework (SLF) and Ecological Modernisation Theory (EMT), providing a comprehensive understanding of the complex interplay between climate change, sustainability, and food security in these emerging economies.

Our findings indicate that climate change, captured through temperature anomalies, negatively impacts food production and nutrition security, particularly in more vulnerable contexts. In contrast, renewable energy adoption and stronger environmental policy stringency are crucial drivers of food and nutrition security, especially in the long run. Specifically, we found that a one percent increase in renewable energy or policy stringency significantly enhances food security by more than one percent. Additionally, the study reveals that forest expansion, while beneficial for long-term environmental sustainability, creates short-term trade-offs by reducing the availability of arable land for food production. These findings highlight the need for integrated, multi-dimensional policies that balance ecological conservation with the goal of achieving food security.

The significance of this study lies in its ability to provide empirical evidence on the long-term benefits of renewable energy and environmental regulations for food security in BRICS economies. Policymakers and stakeholders in these countries stand to benefit from these findings, as they provide actionable insights into how energy transitions and environmental governance can be leveraged to enhance food systems and mitigate the adverse effects of climate change. Moreover, the study contributes to the academic discourse on climate change and sustainability by introducing innovative econometric methodologies, such as dynamic panel ARDL estimation and quantile regressions, to account for temporal persistence, heterogeneity, and distributional effects.

Looking forward, this study underscores the importance of scaling up renewable energy investments and strengthening environmental policies in BRICS economies. Future research could further explore the differentiated impacts of various renewable energy sources, such as wind and solar, on food security, as well as examine the role of sub-national disparities in shaping the relationship between climate change and food security. Future research should also extend the present analysis by incorporating additional climate indicators such as precipitation variability, drought severity, and extreme weather events to capture a more comprehensive profile of climate risks facing food systems. The use of higher-frequency or sub-national climate data would also allow for a deeper assessment of heterogeneous climate impacts across regions and crop systems within BRICS economies. Additionally, incorporating more granular data on environmental policy enforcement could refine our understanding of its effects across different regions within BRICS economies.

Given the pressing need to address both climate adaptation and sustainability, future studies should also consider the role of technological innovation and infrastructure development in supporting the resilience of food systems to climate shocks.

In conclusion, this study reinforces the critical importance of environmental sustainability and climate change mitigation as central components of food security strategies in BRICS economies. By adopting integrated policies that promote renewable energy, strengthen environmental regulations, and support agricultural development, these economies can build resilience to climate risks and contribute to the achievement of SDG 2. The pathway to sustainable and equitable food systems requires a long-term commitment to both climate adaptation and environmental governance, with significant benefits for food security and broader socio-economic development.

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