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SDG-2: Food and Nutrition Security in BRICS Countries: Do GVC Participation and Carbon Footprints Matter?

SDG-2: Bezpieczeństwo żywnościowe w krajach BRICS: Czy udział w globalnym łańcuchu wartości i ślad węglowy mają znaczenie?

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Abstract
This study explores the complex interplay between global value chain (GVC) participation, environmental sustainability, proxied by carbon footprints and food and nutrition security (FNS) across BRICS economies (Brazil, Russia, India, China, and South Africa) from 2000 to 2023. Anchored in the sustainable development theoretical framework, the analysis incorporates structural variables such as agricultural productivity, GDP per capita, government expenditure on agriculture, and access to clean energy and electricity. Employing a balanced panel dataset, we estimated both pooled and country-specific Ordinary Least Squares (OLS) regressions to assess aggregate effects and country-level heterogeneity. A temporal decomposition contrasts pre-pandemic (2000–2018) and pandemic-era (2019–2023) dynamics. Findings reveal that agricultural productivity and GDP per capita are consistently significant and positive drivers of FNS, reinforcing their foundational roles. However, GVC participation demonstrates a negative association with FNS in the pooled sample, particularly significant in India, suggesting trade-induced vulnerabilities. Carbon footprints show no effect in the aggregate model but are positively associated with FNS in India and South Africa, possibly reflecting industrialisation-driven improvements in food systems. The COVID-19 pandemic altered several relationships, dampening the impact of GVC participation and agricultural productivity while reinforcing the role of GDP per capita. Notably, an interaction effect indicates that the positive marginal impact of GVC participation on FNS increases with higher carbon intensity, raising concerns about potential trade-offs between nutrition gains and environmental degradation. These results underscore the need for differentiated policy strategies in BRICS countries that enhance domestic resilience, balance trade integration with ecological priorities, and promote inclusive food systems. Future research should investigate non-linearities in the trade–environment–nutrition nexus to inform sustainable development planning.

Key words: food and nutrition security, Global Value Chains, carbon footprint, BRICS, sustainable development

Streszczenie
Niniejsze badanie analizuje złożoną interakcję między udziałem w globalnym łańcuchu wartości (GVC), zrównoważonym rozwojem środowiska, reprezentowanym przez ślad węglowy, oraz bezpieczeństwem żywnościowym i żywieniowym (FNS) w gospodarkach BRICS (Brazylia, Rosja, Indie, Chiny i RPA) w latach 2000–2023. Oparta na teoretycznych ramach zrównoważonego rozwoju analiza uwzględnia zmienne strukturalne, takie jak produktywność rolnictwa, PKB per capita, wydatki rządowe na rolnictwo oraz dostęp do czystej energii i energii elektrycznej. Wykorzystując zbilansowany zestaw danych panelowych, oszacowaliśmy zarówno zbiorcze, jak i krajowe regresje metodą najmniejszych kwadratów zwyczajnych (OLS), aby ocenić efekty zagregowane i heterogeniczność na poziomie kraju. Dekompozycja czasowa kontrastuje dynamikę sprzed pandemii (2000–2018) i w okresie pandemii (2019–2023). Wyniki wskazują, że produktywność rolnictwa i PKB per capita są konsekwentnie istotnymi i pozytywnymi czynnikami napędzającymi FNS, wzmacniając ich fundamentalną rolę. Jednakże udział w globalnych łańcuchach wartości (GVC) wykazuje negatywny związek z FNS w próbie zbiorczej, szczególnie istotny w Indiach, co sugeruje podatność na zagrożenia wywołaną handlem. Ślad węglowy nie wykazuje wpływu w modelu zagregowanym, ale jest pozytywnie powiązany z FNS w Indiach i Republice Południowej Afryki, co

może odzwierciedlać usprawnienia systemów żywnościowych spowodowane industrializacją. Pandemia COVID-19 zmieniła kilka relacji, osłabiając wpływ udziału w globalnych łańcuchach wartości (GVC) i produktywności rolnictwa, jednocześnie wzmacniając rolę PKB na mieszkańca. Co istotne, efekt interakcji wskazuje, że pozytywny marginalny wpływ udziału w globalnych łańcuchach wartości (GVC) na FNS rośnie wraz ze wzrostem intensywności emisji dwutlenku węgla, co budzi obawy dotyczące potencjalnych kompromisów między korzyściami żywieniowymi a degradacją środowiska. Wyniki te podkreślają potrzebę zróżnicowanych strategii politycznych w krajach BRICS, które wzmocnią odporność wewnętrzną, zrównoważą integrację handlu z priorytetami ekologicznymi i będą promować inkluzywne systemy żywnościowe. Przyszłe badania powinny zbadać nieliniowości w powiązaniach handel-środowisko-żywienie, aby wspomóc planowanie zrównoważonego rozwoju.

Słowa kluczowe: bezpieczeństwo żywności, globalne łańcuchy wartości, ślad węglowy, BRICS, zrównoważony rozwój

1. Introduction

Food and nutrition security (FNS) have become a cornerstone of sustainable development, encompassing not only the availability and accessibility of food but also its utilisation, stability, and sustainability across spatial and temporal scales (Simelane & Worth, 2020; Kenney et al., 2024). Anchored in the ambitions of Sustainable Development Goal 2 (SDG 2) – to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture, FNS represents a multidimensional objective that integrates social welfare, economic resilience, and environmental stewardship (Swaminathan & Kesavan, 2018; Cohen, 2019). SDG 2's sub-targets underscore the interconnectedness of these priorities: from ensuring universal access to safe and nutritious food (SDG 2.1) and eliminating all forms of malnutrition (SDG 2.2), to doubling agricultural productivity and incomes of small-scale producers (SDG 2.3), fostering sustainable and resilient food systems (SDG 2.4), and preserving genetic diversity in food production systems (SDG 2.5) (Fanzo, 2019; Bongaarts, 2021; Smale & Jamora, 2020).

Within the BRICS economies – Brazil, Russia, India, China, and South Africa, the relevance of SDG 2 is particularly pronounced, given their demographic significance, economic influence, and diverse agro-ecological contexts. These nations simultaneously host significant proportions of the global population facing food and nutrition insecurity and wield considerable agricultural capacity and policy leverage (Udmale et al., 2020; Atukunda et al., 2021). Despite notable progress, persistent challenges remain, including disparities in nutritional outcomes, hidden hunger, and rising dual burdens of undernutrition and obesity, as well as environmental stresses such as land degradation, water scarcity, and climate-induced shocks (Gonçalves et al., 2019; Malta et al., 2024). For instance, India continues to grapple with high rates of stunting among children, while Brazil, despite being a leading food exporter, faces growing internal nutritional inequalities linked to socio-economic disparities (Fanzo, 2019; Canella et al., 2019). These vulnerabilities have been further exacerbated by the COVID-19 pandemic, which disrupted supply chains, induced price volatility, and deepened food insecurity among low-income and vulnerable populations (Newell et al., 2022; Ihle et al., 2020; Udmale et al., 2020).

Recent scholarship increasingly adopts a systems-oriented approach to FNS, recognising that food outcomes are shaped by the complex interplay of economic, environmental, and institutional factors (McGreevy et al., 2022; Nyström et al., 2019). Within this context, global value chain (GVC) participation has emerged as both an opportunity and a challenge for achieving SDG 2's multidimensional targets. While integration into GVCs can enhance market access, productivity, and incomes (SDG 2.3) through technology diffusion and investment (Ndlovu et al., 2022; Hlatshwayo et al., 2023; Raimondi et al., 2023), it can also expose domestic food systems to external shocks, create dependencies, and potentially divert resources away from local consumption towards export markets (Stojčić & Matić, 2023; Scoppola, 2022). Moreover, GVC participation does not automatically guarantee improvements in nutritional outcomes, especially when price volatility or export-oriented priorities undermine local food availability and affordability (Montalbano & Nenci, 2022).

Environmental sustainability, captured through measures such as carbon footprints, has become equally central to assessing the viability of food systems, particularly in the pursuit of SDG 2.4, which emphasizes sustainable food production and resilient agricultural practices (Michel-Villarreal et al., 2019; Liu, 2023). The tension between economic integration and ecological resilience raises significant questions about trade-offs and synergies, as intensified agricultural practices can boost yields yet simultaneously contribute to soil degradation, biodiversity loss, and elevated greenhouse gas emissions (Pingali & Plavšić, 2022; Ngarava et al., 2019; Valin et al., 2021). These sustainability considerations intersect critically with efforts to preserve genetic diversity (SDG 2.5), as global trade and industrial agriculture increasingly favour uniform, high-yield cultivars over traditional, diverse varieties that are essential for resilience against pests, diseases, and climate variability (Smale & Jamora, 2020; Long et al., 2021).

The COVID-19 pandemic further illuminated the fragility of globally interconnected food systems, revealing vulnerabilities that threaten progress toward SDG 2's holistic objectives. Disruptions in supply chains, shifts in consumption patterns, and the reallocation of public resources have exposed structural weaknesses in reaching vulnerable populations and achieving equitable nutritional outcomes (Newell et al., 2022; Ihle et al., 2020; Udmale et al., 2020). These disruptions underscore the necessity of understanding the dynamic nature of food systems and the robustness or fragility of traditional development levers under conditions of crisis.

This study contributes to this growing field by empirically examining how GVC participation and environmental sustainability, proxied by carbon footprints, affect food and nutrition security across BRICS countries, thus engaging directly with several sub-targets of SDG 2. It further explores the roles of structural determinants including agricultural productivity (SDG 2.3), GDP per capita, government expenditure on agriculture, and access to clean energy and electricity in shaping FNS outcomes. Employing a panel dataset and applying both pooled and country-specific ordinary least squares (OLS) regressions, the study investigates the heterogeneous nature of these relationships. A temporal decomposition facilitates comparative analysis between the pre- and during-COVID-19 periods, offering insights into the pandemic's impact on the structural and economic drivers of FNS.

Theoretically, this study is grounded in emerging frameworks on food system resilience, climate-smart agriculture, and the complex trade–environment–nutrition nexus (Liu et al., 2023; Shabir et al., 2023; Zurek et al., 2022). It aligns with recent calls for integrated approaches that reconcile trade facilitation, environmental sustainability, and equitable food access (Berthet & Fusacchia, 2024; Scoppola, 2022). While GVC integration, accompanied by infrastructure development and climate accountability, may yield synergistic outcomes, insufficient attention to environmental impacts, structural preparedness, and local food system resilience could exacerbate existing disparities in food and ecological security (Righi et al., 2023; Zhu et al., 2021; Cohen, 2019). By addressing these questions through a multidimensional lens informed by the SDG 2 framework and its sub-targets, this study offers policy-relevant insights into balancing global trade participation with national FNS objectives, particularly in the Global South. It further contributes to the evidence base for designing environmentally sustainable, resilient, and socially inclusive food systems capable of withstanding the uncertainties of an increasingly complex global landscape.

2. Literature review

2.1. Conceptual foundations and theoretical perspectives

Food and Nutrition Security (FNS) occupies a central place in global development discourse, underpinned by its multidimensional nature that integrates availability, accessibility, utilisation, and stability of food. These dimensions, as articulated by Simelane and Worth (2020), encapsulate not merely the presence of food but its nutritional adequacy, cultural appropriateness, and long-term reliability. FNS extends beyond the traditional scope of food security to incorporate nutrition security, which is concerned with ensuring the availability and access to foods that support adequate dietary intake and health outcomes (Kenney et al., 2024). This broadened conceptualisation has elevated FNS as a pivotal social determinant of health with implications for both human development and planetary health (Pérez-Escamilla, 2024). Measurement of FNS has evolved through experience-based food insecurity scales that have proven instrumental in shaping policies and interventions at various governance levels. Nevertheless, FNS remains elusive in many developing regions, where rural populations continue to face significant deficits in access and nutrition (Arnés et al., 2018).

The food systems perspective offers a comprehensive framework to understand the interdependencies within agri-food chains, from production and processing to distribution and consumption. McGreevy et al. (2022) argue for the reconfiguration of food systems based on sufficiency, regeneration, and care, acknowledging the complexity and dynamism of global food networks. This systems approach recognises that food is not merely an end product but is embedded in a web of socio-economic and environmental relations. The homogenisation and hyper-connectivity of the global food production ecosystem, as noted by Nyström et al. (2019), have heightened systemic risks, making food systems more susceptible to disruption. Informal food economies, especially prevalent in low- and middle-income countries, are indispensable for food access but remain vulnerable to challenges such as regulatory incoherence and safety standards (Alarcón et al., 2021). The COVID-19 pandemic starkly exposed these vulnerabilities, prompting a renewed interest in localised food systems as mechanisms for enhancing food sovereignty and resilience (Vittuari et al., 2021). Strategies such as supporting community-level food innovations and leveraging institutional platforms like schools are increasingly being promoted as part of integrated urban-rural food policy solutions.

The susceptibility of food systems to environmental degradation and market fluctuations is increasingly documented in empirical literature. Fault tree analyses reveal numerous critical failure points in the supply chain, each posing unique risks to food security (Chodur et al., 2018). UK farmers, for instance, identify climate change, shifting trade dynamics, and ecosystem decline as significant threats to food system stability (Jones et al., 2024). Furthermore, the pandemic amplified structural vulnerabilities by disrupting food access pathways and exacerbating pre-existing inequities in food distribution (Newell et al., 2022). The environmental sensitivity of aquatic food

systems, particularly blue foods, further complicates the security equation. Capture fisheries in marine settings and freshwater aquaculture operations are differentially impacted by environmental stressors, demanding nuanced policy responses to maintain nutritional contributions from aquatic sources (Cao et al., 2023). These vulnerabilities underscore the imperative of resilience-building across all nodes of the food system.
Environmental externalities associated with agricultural systems have gained prominence, particularly through the lens of carbon emissions and sustainability. Agriculture remains a significant source of greenhouse gases, with specific practices such as conventional tillage contributing heavily to atmospheric carbon release. Alternatives such as conservation tillage, no-till farming, and mulching have demonstrated potential in sequestering soil carbon and reducing emissions (Abbas et al., 2020; Ozlu et al., 2022). Crop diversification and limited mechanical intervention further bolster soil health while lowering carbon intensity. Despite global increases in agricultural emissions, certain economies have achieved relative decoupling, reducing emissions per unit of agricultural GDP through innovations and efficiency gains (Bajan & Mrówczyńska-Kamińska, 2020). Renewable energy utilisation within agrifood systems also emerges as a critical lever for reducing ecological footprints, with demographic pressures compounding the urgency of such interventions (Luo et al., 2024). Robust carbon accounting methodologies, both spatially and temporally disaggregated, are essential for aligning agricultural practices with international climate commitments and sustainability goals.
Taken together, these theoretical and empirical insights advance a holistic understanding of food and nutrition security within the broader food systems paradigm. They underscore the need for integrative frameworks that align environmental sustainability with socio-economic equity, and call for cross-sectoral policies that are adaptive to both chronic stressors and acute shocks in food systems.

2.2. Global challenges: climate change and economic globalisation

The intersection of climate change and economic globalisation presents profound challenges for food security, influencing not only the availability and accessibility of food but also the stability and nutritional quality of food systems worldwide. Climate change exerts direct and indirect pressures on agricultural productivity through shifting temperature patterns, increasing frequency and intensity of extreme weather events, and elevated atmospheric CO_2 concentrations. These changes disrupt the phenology and physiological processes of staple crops, often leading to yield reductions and volatility in food production (Khurshid & Abid, 2024; Javadi et al., 2022). Particularly in regions such as sub-Saharan Africa and South Asia, where food systems are heavily reliant on rain-fed agriculture, the consequences are especially severe, exacerbating food insecurity among already vulnerable populations (Hasegawa et al., 2018; Omotoso et al., 2023).
Recent empirical studies underscore the geographic variability of climate change impacts. In sub-Saharan Africa, erratic rainfall patterns and rising temperatures have been linked to diminishing agricultural outputs and surging food prices, placing additional strain on household food security (Omotoso et al., 2023). Similar trends are observed across parts of Asia, where projections indicate heightened variability in precipitation and escalating thermal stress, further compounding risks to agricultural sustainability (Habib-ur-Rahman et al., 2022). Moreover, climate models may overestimate productivity in certain regions, failing to account for the compounding effects of soil degradation, pest proliferation, and declining water availability (Guo et al., 2022). To counter these challenges, scholars advocate for climate-smart agricultural approaches – emphasising adaptive crop management, the use of early warning systems, and increased agrobiodiversity as critical strategies for enhancing resilience (Habib-ur-Rahman et al., 2022; Yuan et al., 2024). These measures not only support productivity but also contribute to the broader goals of sustainability and ecosystem health.
Concurrently, economic globalisation introduces a complex web of influences on food distribution and market dynamics. While global trade liberalisation and investment flows can enhance the efficiency and reach of food distribution networks, they also render local food systems more susceptible to external shocks and market fluctuations. Globalisation facilitates the widespread availability of energy-dense, nutrient-poor food commodities, often to the detriment of public health outcomes, particularly in low- and middle-income countries (An et al., 2019). Furthermore, the structural characteristics of agricultural trade reflect persistent home bias effects, whereby physical distance continues to significantly influence trade in primary agricultural goods, despite advancements in transport and communication (Luckstead, 2023). This underscores the limitations of globalisation in equitably distributing agricultural produce across regions.
The socio-economic repercussions of economic globalisation are further mediated by contextual factors such as institutional quality and social fragmentation. In ethnically fractionalised societies, financial globalisation has been shown to negatively affect income redistribution, suggesting that global economic integration may exacerbate inequality under certain conditions (Pleninger & Sturm, 2019). Moreover, global crises such as the COVID-19 pandemic have revealed the fragility of global food distribution systems. Disruptions to cross-border supply chains led to increased market concentration at the local level, strengthening the market power of domestic retailers and altering price dynamics to the detriment of both consumers and producers (Ihle et al., 2020). These shifts highlight the dual-edged nature of globalisation: while it may enhance availability and economic efficiency, it can also engender structural vulnerabilities that undermine equitable access and resilience.

Climate-related policies themselves may contribute to these dynamics. Although essential for long-term sustainability, stringent climate mitigation policies can inadvertently raise production costs and consumer prices, disproportionately impacting food-insecure regions (Hasegawa et al., 2018). Export restrictions and protectionist trade measures, often introduced in response to climatic stress, can further distort global food markets and deepen inequalities between food-exporting and food-importing nations (Liu et al., 2022). Hence, achieving food security in the era of climate change and economic globalisation necessitates a balanced policy framework – one that promotes sustainable agricultural practices, strengthens adaptive capacity, and safeguards against the externalities of market liberalisation. Overall, the combined effects of climate change and economic globalisation on food systems call for integrated and inclusive governance approaches. These must address the ecological constraints of agricultural production while navigating the intricacies of global market forces, ensuring that food security remains a central priority in development and environmental policy agendas.

2.3. Global Value Chain Participation and food security outcomes

The integration of food and agriculture sectors into global value chains (GVCs) has emerged as a critical driver of food and nutrition security, particularly in developing economies. GVC participation facilitates access to international markets, introduces innovation, and enhances productivity, with implications for household food access and dietary quality. Empirical evidence from South Africa demonstrates that smallholder farmers who participate in markets through GVCs exhibit improved nutritional outcomes, with household wealth and social support systems serving as enabling factors (Hlatshwayo et al., 2023). Similarly, research from KwaZulu-Natal indicates that value chain participation substantially reduces food insecurity among smallholder vegetable farmers, reinforcing the link between market integration and nutritional well-being (Ndlovu et al., 2022).

The structure of GVC participation – specifically backward and forward linkages, shapes the extent and nature of its benefits for food and nutrition security. Backward linkages, which involve the sourcing of inputs from foreign suppliers, can enhance the productivity of domestic agriculture through technology transfer and improved inputs. Forward linkages, on the other hand, entail the export of domestic products to foreign markets and may generate income gains and employment opportunities across the food system. In the context of Sub-Saharan Africa, substantial participation in agricultural GVCs has been documented, challenging the long-held assumption of marginalisation in global trade (Balié et al., 2018). The evolution from backward to forward linkages is contingent upon national development capacities and innovation ecosystems, and is shaped by the prevailing trade policy environment (Stojčić & Matić, 2023). Trade policy thus emerges as a key determinant of value chain dynamics, mediating the distribution of benefits and risks across participants (Balié et al., 2018).

Trade openness, as an enabler of GVC integration, has consistently been linked with positive food security outcomes. Studies across diverse geographies – Africa, Asia, Latin America, and the European Union, show that trade liberalisation improves the availability and diversity of food, contributing to healthier diets (Ge et al., 2020; Fusco et al., 2020). In Indonesia, reductions in tariffs have been associated with improved nutritional intake, with industrial tariffs yielding greater effects than those on agricultural goods (Montolalu et al., 2022). However, the relationship is not uniformly linear. For example, in Central Asia, a U-shaped association between trade openness and food security has been observed, suggesting that benefits emerge more clearly beyond certain thresholds of openness (Sun & Zhang, 2021). This non-linearity underscores the need for nuanced trade strategies that promote openness while safeguarding against external vulnerabilities. While global trade can bolster food access, it also necessitates maintaining a degree of food self-sufficiency to mitigate exposure to global market disruptions.

Sustainability is an increasingly important dimension in the discourse on GVCs and food security. While GVC integration can enhance food access and modernise domestic supply chains, especially through innovations and efficiency gains, it may also introduce sustainability trade-offs. The case of aquaculture highlights this duality: production is largely concentrated in developing countries, while consumption is driven by developed markets, resulting in asymmetric regulatory burdens and environmental concerns (Ababouch et al., 2023). The pursuit of GVC participation in such contexts must reconcile market demands with local ecological capacities. In broader terms, the complexity of GVCs necessitates a multidisciplinary approach to ensure that gains in food security do not come at the expense of environmental and social sustainability (Berthet & Fusacchia, 2024). In developing economies, resource competition and socio-economic displacement are potential risks when integrating into global supply chains without adequate regulatory oversight (Scoppola, 2022).

Ultimately, while GVC participation presents a pathway for enhancing food access, generating employment, and modernising food systems, its success in achieving food and nutrition security hinges on policy coherence, equitable trade structures, and sustainable value chain governance. The strategic alignment of trade, agriculture, and social policies is essential to maximise the developmental gains from GVC integration while mitigating associated risks.

2.4. Environmental sustainability and carbon footprints in the food system

The intricate relationship between environmental sustainability, carbon footprints, and food and nutrition security (FNS) has become central to contemporary debates on agricultural and food system transformation. Carbon footprints not only represent a metric of environmental burden but also reflect broader socioeconomic dynamics influencing access to nutritious food. Emerging research suggests that food insecurity concerns, whether driven by health or poverty, shape consumer dietary choices, which in turn affect carbon emissions. For example, health-motivated choices often correlate with reduced carbon footprints, while poverty-induced consumption patterns may elevate them due to reliance on cheaper, carbon-intensive staples (Righi et al., 2023). These findings underscore the necessity of integrating environmental indicators into food security frameworks, recognising that sustainability and nutrition are increasingly co-dependent.

Agriculture and food systems account for nearly one-third of global anthropogenic greenhouse gas (GHG) emissions, positioning them as both significant contributors to and victims of climate change (Tubiello et al., 2021). Emissions are generated not only from on-farm activities and land-use change but increasingly from pre- and post-production processes, such as food processing, transportation, and retail. This expansion in emission sources, particularly prominent in high-income nations, has prompted calls for a comprehensive re-evaluation of food system configurations (Zurek et al., 2022). While past agricultural subsidies have often incentivised high-emission practices, their current role in shaping global emissions is more nuanced and relatively constrained (Laborde et al., 2020). Nonetheless, reforming agricultural support structures remains vital for promoting low-emission, climate-resilient practices.

Climate-smart agriculture (CSA) has emerged as a key strategy to balance productivity, adaptation, and mitigation in food systems. CSA practices can increase crop resilience against climatic shocks and yield variability, particularly in regions prone to environmental stress (Liu et al., 2023). The implementation of CSA is mediated by a complex interplay of economic incentives, institutional frameworks, and personal motivations, while financial and technological constraints often serve as limiting factors (Pedersen et al., 2024). Policy instruments such as targeted subsidies and carbon taxes can incentivise the uptake of low-carbon agricultural methods, aligning environmental and economic goals (Hamidoğlu & Weber, 2024). Beyond on-farm techniques, CSA encompasses broader systemic transformations including improved weather forecasting, reduced food loss and waste, and more efficient supply chains each contributing to a recalibrated, climate-resilient agri-food system (Zougmoré et al., 2021).

Low-carbon supply chains are also crucial for reducing emissions across the food system continuum. Efforts to curtail food processing-related carbon footprints have focused on the integration of renewable energy sources, improved logistics, and adoption of resource-efficient technologies (Shabir et al., 2023). In irrigation agriculture, technological reforms have led to measurable reductions in crop-level carbon footprints, highlighting the role of innovation in achieving climate goals without compromising food production (Niu et al., 2023). Environmental footprints, encompassing carbon, water, and land use metrics, are increasingly used to assess dietary sustainability and inform shifts toward more ecologically viable consumption patterns (Hatjiathanassiadou et al., 2023). This multi-dimensional assessment framework reinforces the imperative of embedding sustainability into FNS discourse.

The globalisation of food systems through global value chains (GVCs) adds another layer of complexity to the sustainability equation. GVCs facilitate international trade in agricultural commodities, often reducing trade barriers and enhancing market integration (Raimondi et al., 2023). However, the environmental implications of GVC participation are less straightforward. While trade liberalisation can promote efficiency and innovation, it may also externalise environmental costs, particularly if carbon emissions generated by multinational enterprises in host countries are underreported (Zhu et al., 2021). The integration of carbon accounting within GVC analysis is therefore critical to ensuring that economic benefits do not obscure ecological consequences.

Furthermore, the interaction between GVC participation and food security requires careful calibration. While GVCs can expand food access and generate income, they must also support environmental goals to remain sustainable in the long term. The potential for synergistic outcomes lies in linking global supply chains with local food systems, promoting inclusive growth while minimising ecological degradation (Scoppola, 2022). Trade in value-added data now allows for a more granular understanding of country-level engagement in agri-food GVCs, providing essential insights into the trade-environment nexus and its implications for food system governance (Nenci et al., 2022). In sum, integrating carbon footprints and sustainability metrics into the discourse on food and nutrition security is no longer optional but imperative. A holistic approach that embeds climate-smart practices, low-carbon supply chains, and GVC environmental accountability into agricultural policy and trade governance is essential for building resilient food systems capable of addressing both ecological imperatives and human development goals.

2.5. Empirical evidence and policy-relevant drivers of food and nutrition security

Food and nutrition security (FNS) in low- and middle-income countries is shaped by a constellation of interrelated drivers, with empirical evidence pointing to the critical influence of agricultural, infrastructural, economic, and policy dimensions. At the macroeconomic level, per-capita final consumption expenditure has consistently emerged as one of the most robust predictors of food security, accounting for a substantial share of observed variation across countries (Allee et al., 2021). This underscores the role of household purchasing power in determining access to adequate and nutritious food, reinforcing the importance of pro-poor economic growth strategies. Additionally, agricultural diversity has proven essential at multiple scales – individual, household, and farm – in enhancing food security, though its effectiveness is moderated by local socio-economic and biophysical conditions (Waha et al., 2022). Sociocultural and psychological drivers, including individual perceptions of health and food choice motivations, further complicate the food security landscape, necessitating context-specific interventions that consider both behavioural and structural dimensions (Karanja et al., 2022).

Agricultural productivity remains a cornerstone of FNS strategies, though its influence is nuanced. While improvements in productivity have been associated with increased food availability and enhanced dietary diversity (Villacis et al., 2022; Sibhatu et al., 2022), the nature of these gains is subject to the type of intervention and its alignment with broader food system goals. For instance, Zambia's Smallholder Productivity Promotion Programme has shown that productivity-enhancing interventions can yield positive nutrition outcomes when coupled with income growth (Sibhatu et al., 2022). However, the narrow focus on productivity and market liberalisation, especially through input subsidies, has sometimes led to unintended trade-offs such as the proliferation of calorie-dense but nutrient-poor food and heightened environmental degradation (Benton & Bailey, 2019). These concerns call for a shift in policy emphasis from sheer output increases to systemic food system efficiency that incorporates nutritional adequacy, ecological sustainability, and social inclusion as core metrics of success.

Infrastructure plays a pivotal yet often underappreciated role in shaping FNS outcomes, particularly through its impact on post-harvest losses (PHLs). In sub-Saharan Africa, poor transport networks and substandard storage facilities contribute substantially to mechanical damage, nutrient degradation, and spoilage across a wide range of crops (Kuyu et al., 2019). Crop-specific studies further illuminate the severity and location of losses along the value chain. For instance, the majority of bush bean losses occur during post-harvest handling, while nightshade losses are more concentrated at the consumption stage (Strecker et al., 2022). Groundnut production in Africa experiences significant losses during pod stripping, shelling, and storage, ranging from 8.9% to 31% depending on the conditions (Daba et al., 2023). In addition to quantity losses, nutritional post-harvest losses (NPHLs) compromise the bioavailability of essential nutrients, particularly in highly perishable or nutrient-dense crops (Bechoff et al., 2022). These insights highlight the critical need for investments in post-harvest technologies and value chain infrastructure to preserve both the quantity and quality of food available to low-income populations.

Government spending on agriculture and social protection also exerts a significant influence on FNS outcomes. Empirical studies from across Africa reveal that increased public expenditure in agriculture, especially in research, extension, and nutrition-sensitive programmes, is correlated with improvements in food availability and dietary outcomes (Kamenya et al., 2022; Sers & Mughal, 2019). In Nigeria, for example, deliberate investments in nutrition-sensitive agriculture have led to notable increases in budget allocations for related programmes, demonstrating the capacity of targeted policies to reshape sectoral priorities (Adeyemi et al., 2023). However, the effectiveness of such investments is contingent upon both the scale and strategic focus of funding. Agricultural input subsidies, while common, have yielded mixed results; their impact varies based on implementation quality and the degree to which they are aligned with inclusive and sustainable productivity goals (Walls et al., 2018). Hence, government interventions must go beyond short-term inputs to embrace comprehensive food system reforms that balance productivity, equity, and resilience.

Taken together, the empirical literature affirms that achieving sustainable food and nutrition security in low- and middle-income countries requires multifaceted policy approaches. These must integrate economic empowerment, productivity enhancements, infrastructural investments, and targeted social spending. Crucially, future interventions must account for the dynamic interplay of structural, behavioural, and institutional drivers to ensure that food systems evolve in a manner that supports both human and planetary health.

2.6. Global undernourishment trends and implications for food and nutrition security

An analysis of global undernourishment from 2005 to 2022 as depicted by figure 1, provides critical insights into the trajectory of food and nutrition security and the structural vulnerabilities of global food systems. Data reveal a substantial decline in both the prevalence and absolute number of undernourished people between 2005 and 2014, reflecting global progress in improving food access and availability. The proportion of undernourished individuals dropped from 12.1% in 2005 to 8.6% in 2014, while the absolute number decreased from 793.4 million to 597.8 million. These improvements can be attributed to gains in agricultural productivity, poverty alleviation, and the cumulative benefits of sustained economic growth and development interventions, particularly in low- and middle-income countries.

However, from 2015 to 2019, the rate of progress slowed significantly. The prevalence of undernourishment stagnated around 7.7% to 8.4%, and the number of undernourished individuals hovered between 588.9 million and 656.6 million. This plateau suggests that existing strategies had begun to reach their limits in the face of deepening inequalities, escalating conflict, environmental degradation, and the increasingly evident effects of climate change.

The persistence of food insecurity during this period underscores the need for more inclusive and resilient food system policies that extend beyond production-based interventions.

The onset of the COVID-19 pandemic in 2020 marked a critical inflection point. Both indicators sharply reversed, with the prevalence of undernourishment spiking to 10.1% and the number of undernourished individuals rising dramatically to 796.9 million—levels not seen since the early 2000s. These trends illustrate the profound vulnerability of globally integrated food systems to systemic shocks. Disruptions to supply chains, shifts in labour mobility, inflation in food prices, and constraints in public expenditure compounded the effects of the pandemic, disproportionately affecting marginalised and low-income populations. While 2022 estimates suggest a slight decline to 9.2% in prevalence and 735.1 million in absolute terms, these figures remain well above pre-pandemic levels, indicating an uneven and fragile recovery.

The divergence between the prevalence rate and the absolute number of undernourished individuals in recent years further reflects demographic pressures and uneven spatial distribution of food insecurity. Even when prevalence rates stabilise, population growth in vulnerable regions can lead to a continued increase in the total number of affected individuals. This underscores the importance of disaggregated analysis and context-specific policy responses in designing effective interventions.

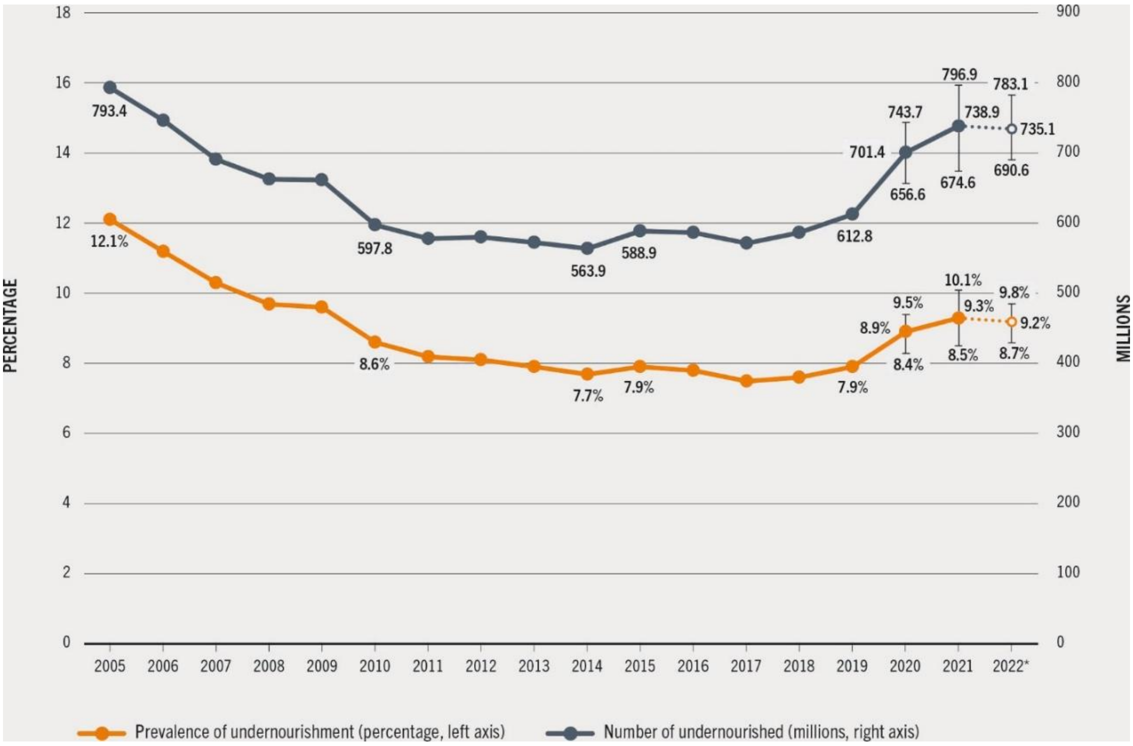

Figure 1. Global Undernourishment Trends, 2005–2022, source: (FAO, 2023)

The implications of these trends for food and nutrition security are profound. First, they highlight the urgency of strengthening the resilience of food systems through investments in local agriculture, infrastructural development, and adaptive social protection mechanisms. Second, they reveal the limitations of global food trade reliance in ensuring consistent and equitable access to food during global crises. Third, they call for a recalibration of development strategies towards more integrated, sustainable, and shock-responsive frameworks that can buffer future disruptions and ensure continued progress toward Sustainable Development Goal 2.

In sum, the global trajectory of undernourishment over the past two decades demonstrates that while gains can be made through targeted economic and agricultural policies, these advances are highly susceptible to reversal in the absence of systemic resilience. As this study reveals, any assessment of food and nutrition security must incorporate the dynamic interplay between structural determinants, environmental change, and global health emergencies to produce robust, long-term strategies for inclusive and sustainable development.

2.7. The overarching goal of SDG 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture

The Sustainable Development Goal 2 (SDG 2) to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture, represents a multidimensional aspiration central to global development. As articulated by the United Nations, SDG 2 encapsulates interrelated objectives that span social welfare, economic resilience, and environmental sustainability. The goal not only aims to eliminate chronic hunger and undernourishment but also to enhance nutritional outcomes, bolster agricultural productivity, and ensure the long-term viability of food systems. This ambition acknowledges that food security is not merely a matter of production but is deeply embedded in issues of access, equity, environmental stewardship, and political will (Swaminathan & Kesavan, 2018). However, achieving SDG 2 remains elusive due to persistent challenges such as policy incoherence, unmet international commitments, and the prioritisation of short-term interventions over structural reforms (Cohen, 2019). These issues are compounded by a fragmented approach to food governance and a *Missing Middle* between production and consumption systems, as well as between global agendas and local implementation strategies (Veldhuizen et al., 2020).

The relevance of SDG 2 to BRICS countries (Brazil, Russia, India, China, and South Africa), is particularly pronounced in light of their demographic weight, economic influence, and diverse agro-ecological systems. These countries collectively host significant portions of the world's population facing food and nutrition insecurity, yet they also wield substantial agricultural capacity and policy-making leverage. For instance, India continues to grapple with high rates of undernourishment and child stunting despite its large-scale food subsidy programs, while Brazil, a major food exporter, faces internal nutritional inequalities exacerbated by socio-political instability. China has made impressive strides in reducing hunger but now contends with the environmental consequences of intensive agricultural practices and a growing nutrition transition. South Africa's food security is undermined by deep-seated income inequality and structural unemployment, even as it plays a key role in regional agricultural markets. In each of these contexts, the pursuit of SDG 2 intersects with complex socio-economic inequalities, rapid urbanisation, and mounting environmental stressors such as land degradation, water scarcity, and climate-induced shocks (Fanzo, 2019; Udmale et al., 2020). These conditions have been further exacerbated by the COVID-19 pandemic, which disrupted global supply chains, triggered cereal price spikes, and deepened household food insecurity, particularly among low-income populations (Udmale et al., 2020).

Efforts to operationalize SDG 2 in the BRICS countries must therefore reckon with these multifaceted challenges. Literature highlights that progress towards the goal has been uneven, and in many cases, stagnant, especially in addressing hidden hunger and malnutrition in vulnerable sub-populations (Atukunda et al., 2021). Achieving SDG 2 also entails managing potential trade-offs with other SDGs such as responsible consumption (SDG 12) and climate action (SDG 13) since agricultural intensification can result in unsustainable resource use and elevated carbon emissions (Valin et al., 2021). Moreover, while mechanisms such as ISO standards may offer pathways toward improving agricultural sustainability and productivity, their limited uptake among small-scale farmers, who dominate food production in the Global South, undermines their transformative potential (Zhao et al., 2020). The literature further emphasises that bridging the gaps between global strategies and local realities will require robust investment in agricultural infrastructure, transparent and equitable food markets, and behavioural shifts in dietary consumption (Valin et al., 2021). In this regard, BRICS nations occupy a dual role: they are both sites of urgent food security concerns and critical actors in reshaping the future of global food systems.

2.8. Understanding and contextualizing SDG 2 sub-targets: a thematic review of food and nutrition security dimensions

Achieving universal access to safe, nutritious, and sufficient food remains a central pillar of the 2030 Agenda for Sustainable Development, as articulated in SDG 2.1. This sub-target emphasises not merely the availability of food, but equitable access to a diet that supports human health, productivity, and development across all life stages. Despite global efforts, nearly 690 million people were undernourished in 2019, and projections suggest that the world remains off course in meeting both SDG 2.1 and 2.2 by 2030 (Bongaarts, 2021). The shortcomings in global food security are not only a matter of aggregate supply but also reflect profound disparities in distribution, affordability, and nutritional quality. Studies suggest that while improvements in food availability are projected under shared socio-economic pathways (SSPs), substantial regional disparities remain, particularly in Sub-Saharan Africa and South Asia, where issues of access and utilisation are most pronounced (Van Meijl et al., 2020). The complexity of food security demands a multidimensional approach that includes calorie sufficiency alongside the intake of proteins, essential amino acids, fats, and critical micronutrients (Ritchie et al., 2018). Agricultural interventions, though important, require tailored program designs that consider local needs, policy environments, and implementation capacity to ensure sustainable outcomes (Bizikova et al., 2020).

Complementing this goal, SDG 2.2 aims to end all forms of malnutrition by 2030. This includes undernutrition in the form of stunting and wasting, as well as micronutrient deficiencies and rising levels of overweight and obesity. The global nutrition landscape is marked by alarming disparities in progress, with many countries falling short of the required pace to meet 2030 targets (Scott et al., 2020). Strategies such as infant feeding education, iron and folic acid supplementation, and malaria prevention during pregnancy have demonstrated cost-effectiveness and scalability, yet implementation gaps persist. Moreover, malnutrition is not solely about caloric deficits but requires a deeper analysis of nutrient quality and bioavailability (Ritchie et al., 2018). Innovations such as biofortification through gene stacking and metabolic engineering offer promising avenues for addressing hidden hunger and micronutrient deficiencies (Straeten et al., 2020). Nonetheless, nutrition-specific interventions must be complemented by broader, nutrition-sensitive policies that target the underlying social determinants of health such as income, education, gender equity, and access to healthcare, to produce meaningful change (Scott et al., 2020).

The burden of malnutrition in BRICS countries vividly illustrates the global shift toward a dual burden of disease, where undernutrition and overnutrition coexist within populations, communities, and even households. In Brazil, a country long regarded as a model in food and nutrition policy, the prevalence of stunting among children under five declined by 53% between 1982 and 2015. Yet this success is increasingly overshadowed by a surge in overweight and obesity rates, which rose by 88% over the same period (Gonçalves et al., 2019). By 2019, the burden of disease attributed to undernutrition had fallen by 75%, while deaths linked to high body mass index had increased by nearly 140% (Malta et al., 2024). Inequities in malnutrition distribution remain entrenched, with undernutrition more prevalent among the poor and less educated, but emerging data suggest that obesity is rapidly increasing in these same groups, effectively eroding prior socioeconomic gradients (Canella et al., 2019; Watanabe et al., 2022). In India, the persistence of stunting and underweight among children particularly in rural and low-income populations, continues to pose a significant barrier to achieving SDG 2.2. These patterns signal that nutrition inequality is not simply a matter of resource scarcity but also reflects structural issues in health, education, and food environments that must be addressed through coordinated public policy and multisectoral interventions.

Global value chain (GVC) integration represents both an opportunity and a challenge in achieving food and nutrition security. As countries become more embedded in international trade networks, the structure and performance of their domestic food systems are increasingly shaped by global market dynamics. Evidence suggests that GVC participation can improve food availability and affordability by reducing trade barriers, lowering tariffs, and enhancing agricultural productivity through technology diffusion and investment (Raimondi et al., 2023; Montalbano & Nenci, 2022). For instance, increased GVC participation is positively associated with agricultural value added per worker, although countries positioned further upstream in the value chain may not enjoy the same gains in food system resilience. In low and middle-income countries, including some BRICS nations, GVCs have also facilitated access to inputs, finance, and export markets. However, the benefits are not uniformly distributed. The development of export-oriented global food value chains can divert resources, such as land, water, and labour from local food production systems, potentially undermining domestic food availability and access (Scoppola, 2022). Moreover, participation in GVCs does not automatically translate into improved nutritional outcomes, especially where food exports are prioritized over local consumption or where price volatility in global markets affects food affordability. The influence of GVCs on food security is thus context-dependent, shaped by governance structures, trade policy, infrastructure, and domestic institutions. In the BRICS context, this complexity is magnified by large internal markets, diverse agricultural systems, and varying degrees of policy coherence in integrating trade and nutrition agendas.

Taken together, the goals of universal access to safe and nutritious food and the eradication of malnutrition are deeply interlinked with the broader dynamics of globalisation, structural inequality, and policy integration. For BRICS countries, which sit at the nexus of emerging economic power and persistent development challenges, meeting SDG 2.1 and 2.2 will require not only scaling effective interventions but also transforming food systems to be more inclusive, equitable, and resilient in the face of evolving global pressures.

2.9. Agricultural productivity and incomes

Achieving Sustainable Development Goal 2.3, which seeks to double the agricultural productivity and incomes of small-scale food producers, remains a central yet formidable objective in global development discourse, particularly within the diverse agricultural landscapes of the BRICS nations. The structural challenges faced by smallholders in these economies are deeply intertwined with both socioeconomic and environmental complexities, necessitating nuanced and multidimensional strategies. Among these challenges, institutional limitations, resource constraints, and environmental vulnerabilities coalesce to hinder sustained productivity growth and equitable income distribution. Pingali and Plavšić (2022) underscore the delicate balance between reducing hunger and safeguarding environmental sustainability, cautioning that rapid strides in agricultural intensification, while effective in addressing food insecurity, may simultaneously precipitate ecological degradation. This paradox is vividly apparent in regions where intensified agricultural practices have delivered substantial yield gains but at the cost of soil degradation, water stress, and biodiversity loss, thereby undermining the very foundations of sustainable productivity.

Innovative institutional arrangements have emerged as potential avenues for overcoming these entrenched barriers. In India, Farmer Producer Companies (FPCs) have been identified as critical mechanisms for strengthening smallholder bargaining power, facilitating access to inputs, credit, and markets, and fostering knowledge exchange among producers (Mourya & Mehta, 2021). However, the practical implementation of FPCs often encounters significant hurdles, including governance challenges, heterogeneous member interests, and limited financial resources, which constrain their transformative potential. Parallel to institutional innovations, biophysical constraints also loom large over smallholder productivity prospects. Langhans et al. (2021) identify phosphorus deficiency as a persistent and severe impediment to agricultural productivity in tropical regions, where low native soil fertility necessitates targeted nutrient interventions. Yet, the economic feasibility and environmental sustainability of increased phosphorus application remain contentious, underscoring the complex trade-offs that define efforts to boost productivity while safeguarding ecological integrity.

Advancements in analytical methodologies have contributed to a more refined understanding of the pathways through which productivity and income gains might be achieved sustainably. Nozaki et al. (2023) highlight the pivotal role of robust indicators and modelling tools in tracking the progress of small-scale producers towards SDG 2.3, revealing the substantial benefits of climate adaptation measures in mitigating productivity risks. These insights underscore the importance of integrating climate resilience into productivity enhancement strategies, particularly given the escalating variability in weather patterns and the heightened exposure of smallholder systems to climatic shocks.

The pursuit of higher productivity is further complicated by the environmental implications of carbon-intensive agricultural practices, which often generate significant greenhouse gas emissions while delivering variable productivity outcomes. The relationship between productivity and environmental sustainability is far from linear, revealing a complex interplay of biophysical, technological, and economic factors. Plassmann et al. (2014) observe that extensive, low-yield farming systems, despite offering lower per-unit carbon footprints, frequently entail expanded land use, heightening the risk of deforestation and associated carbon emissions. By contrast, Johnson et al. (2014) argue that selective agricultural expansion, strategically prioritising areas with both high productivity potential and significant carbon storage capacity, could mitigate up to 6 billion metric tons of carbon emissions relative to uniform expansion approaches. Such findings highlight the necessity for spatially differentiated strategies that align productivity objectives with climate mitigation goals.

Moreover, contemporary farming practices often accelerate soil carbon depletion, diminishing soil health and productivity while fostering dependency on external inputs, a feedback loop that jeopardises both economic viability and environmental sustainability. Lal et al. (2004) propose conservation agricultural practices such as no-till farming combined with residue mulching as viable interventions for enhancing soil carbon sequestration and improving agronomic outcomes. Nevertheless, the efficacy and adoption of such practices vary widely across farm sizes, geographies, and crop systems, reflecting the heterogeneous nature of agricultural landscapes. Baldoni et al. (2017) further elucidate that high-productivity farms often exemplify best practices in greenhouse gas mitigation, suggesting that environmental benefits and productivity gains need not be mutually exclusive. Instead, targeted innovations and sustainable intensification can reconcile productivity imperatives with environmental stewardship, provided they are tailored to the specific socioecological contexts of smallholder agriculture.

2.10. Food production sustainability and resilience agricultural practices

The pursuit of Sustainable Development Goal 2.4, which aims to ensure sustainable food production systems and implement resilient agricultural practices, has become increasingly urgent amidst the escalating threats posed by climate change, environmental degradation, and global economic volatility. Sustainable food production hinges on fostering economic resilience within agri-food systems, underpinned by technological innovation, institutional support, and interdisciplinary collaboration. Michel-Villarreal et al. (2019) underscore the importance of economic resilience in safeguarding agricultural livelihoods against external shocks, a view echoed by Liu (2023), who emphasizes the necessity of integrative scientific approaches to navigate the complexities of sustainable agriculture. Advances in climate-informed agricultural practices, such as weather forecast-based advisory systems, have demonstrated notable efficacy, offering substantial yield advantages and environmental benefits, as evidenced in rice cultivation (Rahman et al., 2023). Such practices are critical in enhancing both productivity and adaptive capacity, particularly in regions where climatic variability exerts profound impacts on food systems.

Agroecological strategies, including poly-cropping, agroforestry, and integrated crop-livestock systems, have emerged as viable pathways towards sustainable intensification, delivering benefits that extend beyond food security to encompass biodiversity conservation and ecosystem services (Akanmu et al., 2023). These approaches foster ecological balance and resource efficiency, contributing simultaneously to multiple Sustainable Development Goals, including zero hunger, poverty alleviation, and climate change mitigation. However, their broader adoption remains hindered by institutional, financial, and knowledge barriers, coupled with the complexities inherent in measuring progress towards sustainability, necessitating the continued refinement of robust indicators and evaluative frameworks (Liu, 2023; Michel-Villarreal et al., 2019).

Climate change introduces profound challenges to food security, disproportionately affecting vulnerable regions such as sub-Saharan Africa and South Asia. Richardson et al. (2018) highlight the stark vulnerability of agricultural systems in these regions, where climatic variability exacerbates food insecurity and erodes rural livelihoods. South Africa exemplifies the precarious intersection of climate vulnerability and food security, with provinces like Limpopo and the Eastern Cape frequently facing climate-induced disruptions (Mthethwa & Zegeye, 2022). The 2007 drought in Lesotho and South Africa vividly illustrates how climate perturbations can ripple through interconnected trade relationships, amplifying food insecurity where national food systems depend heavily on climatically linked partners (Verschuur et al., 2021). Complicating the sustainability discourse further, Ngarava et al. (2019) observe that in South Africa, economic gains in agriculture have not been accompanied by reductions in carbon emissions, highlighting the persistent tension between growth and environmental stewardship. Addressing these intertwined challenges necessitates a dual strategy of mitigation and adaptation, as Richardson et al. (2018) contend that meaningful reductions in climate vulnerability require the highest levels of mitigation coupled with robust adaptive measures.

The carbon footprint of agricultural production systems is intrinsically linked to food security outcomes, given that high-emission agricultural practices contribute to climate change, which, in turn, undermines food system stability. This dynamic necessitates innovative practices that minimize carbon emissions while sustaining yields and preserving ecosystem integrity. The imperative for low-carbon agricultural pathways is underscored by the realisation that resilience and sustainability are inseparable in securing future food supplies, particularly in regions experiencing escalating climate risks.

Complicating the sustainability landscape further are the intricate dynamics of global value chains (GVCs), which simultaneously offer avenues for sustainability enhancement and present significant risks of environmental and social externalities. Agostino et al. (2023) highlight the role of GVCs in facilitating the diffusion of clean energy technologies and sustainable practices, particularly within developed economies. However, these benefits are counterbalanced by the potential for environmental degradation and social inequities embedded within complex transnational supply networks (Berthet & Fusacchia, 2024). The integration of sustainable business models into GVCs is essential for mitigating negative impacts, yet the asymmetric distribution of influence and responsibility among GVC participants complicates collective action (Yuan & Mähönen, 2024). Sustainability management has increasingly become a strategic asset in global markets, resulting in what Ponte (2020) terms *green capital accumulation.* While this phenomenon suggests a growing alignment between market competitiveness and sustainability, it also raises concerns about superficial commitments to environmental objectives that may obscure continued exploitative practices under the guise of green branding.

The interplay between GVCs and sustainability demands multifaceted governance solutions, necessitating coordinated interventions from public authorities, civil society organizations, and international regulatory frameworks to ensure that sustainability ambitions translate into substantive action rather than symbolic gestures (Ponte, 2020; Yuan & Mähönen, 2024). Future research is called upon to develop integrated perspectives capable of addressing the systemic sustainability challenges embedded within GVCs, ensuring that global trade contributes to, rather than undermines, sustainable and resilient food production systems (Berthet & Fusacchia, 2024).

Collectively, the literature illustrates that achieving sustainable food production and resilient agricultural practices requires harmonizing productivity goals with environmental imperatives, mitigating climate risks, and reconfiguring global trade networks to support rather than erode sustainability. This endeavour remains central not only to the realisation of SDG 2.4 but also to the broader stability and security of global food systems in an era defined by climate uncertainty and economic interdependence.

2.11. Genetic diversity in food

Maintaining genetic diversity in food production stands as a cornerstone of global food security and sustainable agriculture, an imperative explicitly articulated in Sustainable Development Goal Target 2.5, which seeks to safeguard plant and animal genetic resources for food and agriculture. The conservation of plant genetic diversity underpins the resilience of food systems by enabling the development of new crop varieties capable of withstanding evolving biotic and abiotic stresses, thereby ensuring adaptability to climatic variability and changing consumer demands. Smale and Jamora (2020) underscore the strategic role that genetic diversity plays in sustaining agricultural productivity and mitigating the risks posed by genetic uniformity, which can leave crops susceptible to pests, diseases, and environmental fluctuations. Gene banks have emerged as vital repositories for preserving this genetic wealth, with institutions like the CGIAR gene banks significantly enhancing their performance in the acquisition, conservation, and distribution of plant genetic resources over the past decade, notwithstanding the complexities introduced by international access and benefit-sharing regulations (Halewood et al., 2020; Lusty et al., 2021). These collections serve as invaluable reservoirs of genetic traits, which can be harnessed through breeding programmes to develop crops with enhanced yield, nutritional quality, and resilience to climate-induced stresses.

Technological advancements have markedly transformed the landscape of genetic conservation and utilisation, offering powerful tools to characterise, evaluate, and deploy plant genetic resources more effectively. Salgotra and Chauhan (2023) highlight the potential of next-generation sequencing and molecular marker technologies to unravel the genetic architecture of both cultivated and wild species, facilitating the precise identification of valuable alleles associated with traits such as drought tolerance, disease resistance, and nutrient use efficiency. Such genomic insights are crucial for the strategic introgression of beneficial traits into modern cultivars, enabling breeders to accelerate the development of varieties tailored to specific agroecological contexts and future climatic scenarios. The preservation of rare and underutilized species through genomic characterization not only secures genetic resources for breeding but also sustains cultural and culinary diversity, contributing to dietary diversity and nutrition security.

Yet, despite these scientific advances and institutional efforts, the conservation of genetic diversity faces formidable threats from the prevailing structures of industrial agriculture and the dynamics of global trade. The expansion of industrial agricultural systems has precipitated a profound shift in seed systems and cropping patterns, fostering the replacement of traditional, locally adapted varieties with a narrow selection of high-yielding, commercially bred cultivars (de Mévius, 2022). This transition has significantly eroded on-farm crop diversity, diminishing the genetic heterogeneity that historically buffered agricultural systems against environmental and economic shocks. Crossley et al. (2020) document this phenomenon starkly in the United States, where spatial concentration of crop types has intensified dramatically, with thirteen of eighteen major crops experiencing a fifteen-fold increase in concentration within counties since 2002. Such consolidation exacerbates the vulnerability of agricultural systems, rendering them more susceptible to emerging pests, diseases, and extreme weather events, thereby posing significant risks to food security and ecosystem stability.

The influence of international trade on crop diversity further complicates the landscape of genetic conservation. While Aguiar et al. (2020) report that crop supply diversity within countries has increased owing to diversified imports, this diversification often masks a stagnation or decline in domestic production diversity, driven by the homogenising effects of export-oriented agriculture. Trade dynamics can thus inadvertently reinforce monoculture practices, incentivising the cultivation of a limited set of commercially viable crops at the expense of local varieties and underutilised species. Long et al. (2021) emphasize that intensive monoculture systems, while contributing to increased food supply, also engender profound environmental consequences, including soil degradation, loss of biodiversity, and heightened greenhouse gas emissions. Such environmental degradation further undermines the sustainability of agricultural systems and erodes the resilience conferred by genetic diversity.

Moreover, global policy incoherence and unmet commitments continue to impede progress toward sustaining genetic diversity in food systems. Caron et al. (2018) argue for a profound transformation of agri-food systems, aligning policies with the 2030 Agenda to prioritise nutrition, sustainability, and climate resilience. Yet, as Cohen (2019) observes, fragmented policy environments, underfunded agricultural sectors, and conflicting trade priorities often undermine coherent action toward these goals. Borsellino et al. (2020) further highlight that while global trade offers opportunities for sustainable development, its benefits remain unevenly distributed, and its mechanisms often lack safeguards to preserve genetic resources critical for future food security.

2.12. Recent evidence on energy, environment and sustainable development as relate to food security

Emerging empirical and theoretical work continues to deepen the understanding of the complex interlinkages between clean energy adoption, sustainability, and food security, particularly relevant for developing and transition economies. Luan et al. (2025) employ a system GMM approach to show that clean energy adoption significantly drives industrialization and sustainable development, emphasizing the critical role of renewable technologies in achieving lower carbon footprints without compromising economic growth. This complements findings by Osabohien et al. (2025), who establish that renewable energy expansion in Africa contributes positively to economic growth while mitigating natural resource depletion and reducing carbon footprints, a crucial insight for balancing environmental and developmental priorities.

The interconnection of economic growth, climate change, and clean energy in the post-COVID era is further illuminated by Osabohien et al. (2025), demonstrating that clean energy investments not only foster economic recovery but also support long-term climate resilience strategies. Similarly, Sahan et al. (2025) highlight that green human resource management practices significantly enhance organizational environmental performance, underlining the human capital dimension in sustainability transitions. Corporate governance dimensions have also attracted scholarly attention. Abd Majid et al. (2025) reveal that national gender policies can moderate the impact of women directors on carbon disclosure practices in global energy companies, emphasizing the intersection of governance, gender, and environmental transparency. In the same corporate sustainability discourse, Jaaffar et al. (2024) find that CEOs' and board directors' environmental experience, as well as corporate age and financial performance, strongly influence the adoption of green management practices in Malaysia's energy-intensive industries.

Technological advancement is pivotal in achieving sustainability targets. Imandojemu et al. (2025) apply quantile regression to OECD countries and find that renewable energy technologies contribute unevenly across the carbon neutrality distribution, indicating that technology benefits are context-dependent and not uniformly realized. He et al. (2024) focus on Sub-Saharan Africa, revealing that green economic growth and renewable energy adoption can simultaneously promote food security, thus reinforcing the food–energy–environment nexus critical for sustainable development goals. Sector-specific analyses have also enriched the literature. Osabohien (2024) investigates soil technologies in Nigeria, identifying their significant role in reducing post-harvest losses, thus enhancing food system resilience.

Further exploring the food-energy interface, Osabohien et al. (2024) show that electricity consumption in Malaysia is intricately linked to food production and SDG 2, suggesting that sustainable energy policies have direct implications for agricultural outcomes. Nutrition and biodiversity connections emerge in Osabohien (2024), who discusses how sustainable land management underpins SDG 15 and broader ecosystem services essential for food

and nutrition security. This aligns with Li et al. (2024), who document that clean energy adoption can substantially enhance food security in Africa, emphasizing technological adoption's spillover into agrifood systems.
Mohamed et al. (2024) revisit the environmental Kuznets curve (EKC), finding that renewable energy in power generation mitigates both carbon emissions and the ecological footprint, providing fresh insights into environmental sustainability in the energy sector. Sectoral studies such as Oteh et al. (2023) demonstrate that marketing capabilities and market orientation improve the food security of biofortified cassava producers in Nigeria, underscoring the critical role of market dynamics in agricultural sustainability. Large-scale agricultural land investments and their consequences for food security are examined by Edafe et al. (2023), highlighting potential risks and benefits for local communities in Nigeria. Moreover, Osabohien et al. (2023) address how green environment-social protection interactions enhance food security outcomes across Africa, reinforcing the relevance of policy coherence in sustainable development strategies.
Earlier studies, including Adeleye et al. (2021), emphasize the dual challenge of increasing agricultural productivity amidst environmental degradation in Nigeria, while Anser et al. (2021) and Khalid Anser et al. (2021) investigate how ICT, governance, and social inclusion shape food security in West Africa, revealing that technological and institutional dimensions remain pivotal for sustainable food systems. Finally, complementary studies outside the African context enrich the understanding of sustainability dynamics. Cai et al. (2025) explore sustainability spillovers between circular economy practices, environmental development, and social conditions, suggesting integrative frameworks for sustainable development planning. Xu et al. (2025) demonstrate that green finance reforms in China promote inclusive green growth, offering a financial policy lens for environmental transitions. Wang et al. (2025) discuss the health risks associated with the life cycle of construction waste in developing countries, broadening the sustainability discourse to urban environments. Wang (2025) reflects on foundational perspectives for sustainable futures, underscoring the need for transdisciplinary approaches in energy and environmental sustainability research.

3. Theoretical framework and methodology

This study is anchored on the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), which emphasize the need to ensure universal access to adequate and nutritious food while promoting sustainable agricultural practices and reducing environmental degradation (United Nations, 2015). These goals collectively highlight the multidimensional nature of food and nutrition security and the importance of aligning economic and environmental priorities in development planning.
Grounded in Sustainable Development Theory, the study adopts an integrated framework that recognizes the interdependence between economic growth, environmental sustainability, and human well-being (Brundtland Commission, 1987; Sachs, 2015). The theory posits that development must balance current socio-economic needs with ecological preservation to ensure the well-being of future generations. Within this context, food and nutrition security is a development outcome and a central pillar for achieving sustainable livelihoods, poverty reduction, and resilience to climate change (FAO, 2017).
Participation in Global Value Chains (GVCs) is theorized to influence national food systems through improved access to agricultural technologies, international markets, and production inputs, which may lead to enhanced food availability and dietary diversity (Gereffi & Lee, 2016; World Bank, 2020). However, increased GVC integration can also result in adverse environmental externalities, particularly through expanded production, transportation, and energy consumption that elevate carbon emissions (OECD, 2021). This creates a potential trade-off between the economic benefits of global integration and the environmental costs it may entail.
Thus, this study's theoretical framework supports a holistic analysis of how GVC participation and environmental sustainability interact to influence food and nutrition security. It aligns with the core principles of sustainable development, which demand policy coherence and institutional responses that advance inclusive growth while safeguarding ecological integrity.

3.1. Variable description

This study employs a strongly balanced panel dataset encompassing five BRICS countries—Brazil, China, India, Russia, and South Africa over the period 2000 to 2023. Data were sourced from reputable international databases, including the United Nations Sustainable Development Goals (SDG) Global Database, the World Bank's World Development Indicators (WDI), the EORA Global Supply Chain Database, and FAOSTAT. The dependent variable in this analysis is food and nutrition security, operationalised through Sustainable Development Goal 2 (Zero Hunger). The model incorporates several explanatory variables: Global value chains participation (GVCs), carbon footprint, agricultural productivity, GDP per capita, and government expenditure on agriculture. Additionally, two infrastructure-related variables were included to capture the critical role of infrastructural development in enhancing food and nutrition outcomes.

Table 1 provides a detailed summary of the variables employed in the analysis, including their definitions, measurement metrics, and expected signs based on theoretical and empirical literature.

Table 1. Variables description, expectations and sources, source: Authors' compilation

Variable	Description	Measurement/Indicator	Source	Expected Sign
SDG 2	Zero Hunger - serves as a proxy for food and nutrition security.	Captures prevalence of undernourishment, food insecurity, malnutrition, and sustainable agriculture productivity.	UN SDG Global Database (SDR)	Dependent Variable
GVC Participation (GVC)	Degree of participation in global value chains	Foreign value added (% of exports), GVC Index	World Bank EORA Database	+
Carbon Footprints (CFP)	Environmental impact of economic activities	CO_2 emissions per capita	World Bank WDI	–
Agricultural Productivity (AGRI)	Value of Agricultural Production	Farm gate value of production (excluding post-farm costs)	FAOSTAT	+
GDP per capita (GDP)	Economic development level	Constant 2015 USD	World Bank WDI	+
Government Spending on Agriculture (GEXP)	Public investment in agriculture	Agriculture expenditure as % of total government expenditure	FAOSTAT	+
Clean_Energy	Access to clean fuels	% of population with access to clean fuel and technology	World Bank WDI	+
Acc_Elect	Access to electricity	% of the population with reliable and affordable access to electricity	World Bank WDI	+

3.2 Model specification and estimation strategy

This study investigates the determinants of Food and Nutrition Security, using SDG 2 (Zero Hunger) as a proxy for the dependent variable. The empirical model draws from the multidimensional concept of food security, incorporating economic, environmental, agricultural, and infrastructural drivers. The specified model is presented in a log-linear functional form to address potential heteroscedasticity and to facilitate elasticity interpretation of the coefficients. The baseline model is specified as follows:

$$lnFNS_{it} = a_0 + \alpha_1 lnFNS_{it-1} + \alpha_2 lnGVC_{it} + \alpha_3 lnCFP_{it} + \alpha_4 lnAGRI_{it} + \alpha_5 lnGOVT_{it} + \alpha_6 lnClean\_Energy_{it} + \alpha_7 lnAcc\_Elect_{it} + \varepsilon_{it} \quad (1)$$

Where:

$SDG2_{it}$: Proxy for Food and Nutrition Security Index for country *i* in year *t*
GVC_{it} : Global Value Chain participation index
CFP_{it} : Carbon Footprints (CO_2 emissions per capita)
$AGRI_{it}$: Agricultural productivity
GDP_{it} : GDP per capita
$GEXP_{it}$: Government expenditure on agriculture
$Clean\_Energy_{it}$: Access to clean fuels
Acc_Elect_{it} : Access to electricity

In addition to the panel regression analysis, this study undertakes country-specific estimations to account for structural heterogeneity across the BRICS countries. Estimating the model individually for each country using appropriate time-series regression techniques, specifically Ordinary Least Squares (OLS), enables the analysis to capture country-specific dynamics, institutional characteristics, and policy influences on food and nutrition security.

To investigate potential temporal shifts in the determinants of food and nutrition security, the study performs a sub-period analysis, estimating the model separately for the pre-COVID period (2000–2018) and the COVID-19 period (2019–2023). The justification for this temporal segmentation arises from the significant disruptions induced by the COVID-19 pandemic, which affected global food systems, trade flows, and supply chains, thereby influencing food and nutrition security outcomes across the BRICS nations. The pandemic introduced both supply-side constraints, including interruptions in agricultural production and logistical challenges, and demand-side effects such as income reductions and altered consumption patterns. Accordingly, distinguishing between the pre-pandemic and pandemic periods facilitates a more nuanced understanding of how key determinants, including global value chain (GVC) participation and carbon footprints, may have exerted differential impacts under crisis conditions.

Furthermore, the delineation of these periods reflects the constraints imposed by data availability. Although the World Health Organization declared the end of the global COVID-19 emergency in 2023, comprehensive and harmonised datasets covering a post-pandemic period remain limited for many BRICS countries. Statistical agencies and international organisations continue to compile and validate post-2023 indicators, rendering robust empirical analysis of the post-COVID period presently impracticable. Therefore, the present study confines its empirical scope to the pre-COVID and COVID-19 periods to ensure data consistency, comparability, and analytical reliability.

4. Results and discussion

4.1. Descriptive statistics and correlation analysis

The descriptive analysis draws upon a strongly balanced panel of the five BRICS economies – Brazil, China, India, Russia, and South Africa, offering insights into the patterns and variability of key variables relevant to food and nutrition security. Summary statistics, including means, minimums, maximums, and standard deviations, are presented both for the full sample and at the country level, enabling meaningful cross-country comparisons across a range of development indicators.

An initial glance at the logged SDG 2 index values, used as a proxy for food and nutrition security, reveals notable disparities. China records the highest average score (4.371), closely followed by Brazil (4.245) and Russia (4.058), whereas India and South Africa lag behind with averages of 3.884 and 3.960, respectively. The pooled mean across the sample stands at 4.103, with relatively low standard deviations, suggesting that food and nutrition outcomes in BRICS countries tend to be stable over time, possibly due to entrenched policy frameworks or gradual improvements in food systems.

In terms of global value chain (GVC) participation, China once again leads with an average index of 20.144, underscoring its pivotal position within global trade networks. India (18.257) and Russia (18.749) demonstrate moderate engagement, while Brazil (17.973) and South Africa (17.630) show comparatively lower participation. The pooled mean of 18.551 and a standard deviation of 1.10 indicate moderate cross-country variability, with China also recording the highest maximum, further reflecting its extensive integration into both upstream and downstream value chain activities.

Carbon footprint statistics illustrate a wide divergence in environmental performance. Russia (2.519) and South Africa (2.09) emerge as the highest per capita emitters, consistent with their energy-intensive economies and reliance on fossil fuels. In contrast, India (0.342) and Brazil (0.800) record much lower emissions. China's average (1.832) positions it between these extremes, reflecting its substantial but more distributed emissions profile. The pooled mean of 1.516 with a standard deviation of 0.85 highlights considerable variation both across and within countries over the study period.

Agricultural productivity, measured in logged terms, is also unequally distributed. China registers the highest mean value (20.831), reflecting the effectiveness of its agricultural policies and technological uptake. India follows with a mean of 19.593, while South Africa records the lowest productivity (16.71). The overall mean is 18.813, with notable dispersion (SD = 1.41), suggesting that country-specific factors such as land use, public investment, and climate conditions significantly influence productivity levels.

Regarding GDP per capita, Russia (9.04), Brazil (9.02), and China (8.66) show relatively high-income levels, whereas India remains the least affluent (7.17). South Africa's average of 8.65 is near the overall mean of 8.51, yet income disparities within and between countries remain apparent. These differences in economic capacity are likely to influence national food security efforts, particularly where affordability and access are concerned. Government expenditure on agriculture reveals substantial heterogeneity. India (2.03) and China (1.93) invest heavily in their agricultural sectors, indicating strong policy prioritisation. Conversely, Brazil (0.22) and Russia (0.24) allocate far less, with South Africa sitting moderately at 0.41. The pooled mean of 0.97 and a high standard deviation (0.88) underscore the uneven nature of fiscal support for agriculture within the BRICS bloc.

Access to clean energy, essential for both environmental sustainability and household nutrition, is similarly uneven. Brazil (4.51) and Russia (4.60) report the highest access, while India (3.71) lags significantly, pointing to a continued reliance on traditional cooking fuels. The average access score across countries is 4.25, with a moderate standard deviation, suggesting ongoing challenges in achieving energy transition goals.

Electricity access, by contrast, is nearly universal across the BRICS nations. All countries report averages above 4.37 on the logged scale, with China and Russia approaching the upper bound of 4.60. The pooled mean is 4.51, with very low variability (SD = 0.13), reflecting successful electrification efforts, particularly in urban settings. These descriptive patterns provide a useful backdrop for interpreting the dynamics of food and nutrition security in the BRICS context. China emerges as a leader in GVC integration, agricultural productivity, and food security performance, whereas India's strength lies in its substantial public investment in agriculture. At the same time, India faces environmental challenges tied to energy access and agricultural sustainability. South Africa and Russia, with higher carbon emissions, raise concerns regarding environmental sustainability. The variation observed across these indicators supports further empirical analysis to investigate how GVC participation and environmental sustainability proxied by carbon footprints, influence food and nutrition security, with a view to understanding the mediating roles of infrastructure, income, and public investment.

Table 2. Descriptive statistics, source: Authors' computation

Variable	FULL SAMPLE		BRAZIL		CHINA		INDIA		RUSSIA		SOUTH AFRICA	
	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min	Mean	Min
	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)	(SD)	(Max)
lnsdg2	4.103	3.829	4.245	4.190	4.371	4.290	3.884	3.829	4.058	3.99	3.96	3.89
	(0.18)	(4.42)	(0.03)	(4.28)	(0.04)	(4.42)	(0.03)	(3.93)	(0.03)	(4.09)	(0.03)	(4.04)
lngvc	18.551	16.622	17.973	16.747	20.144	18.619	18.257	16.779	18.749	17.26	17.63	16.62
	(1.10)	(20.90)	(0.61)	(18.57)	(0.75)	(20.90)	(0.74)	(19.01)	(0.71)	(19.43)	(0.49)	(18.08)
lncfp	1.516	(0.06)	0.800	0.651	1.832	1.066	0.342	(0.06)	2.519	2.44	2.09	1.84
	(0.85)	(2.67)	(0.10)	(1.00)	(0.37)	(2.24)	(0.26)	(0.72)	(0.06)	(2.67)	(0.11)	(2.26)
lnagri	18.813	16.440	18.837	18.388	20.831	20.502	19.593	19.184	18.093	17.83	16.71	16.44
	(1.41)	(21.09)	(0.23)	(19.20)	(0.18)	(21.09)	(0.25)	(20.00)	(0.18)	-18.40	-0.17	-16.96
lngdppc	8.51	6.63	9.02	8.83	8.66	7.69	7.17	6.63	9.04	8.58	8.65	8.46
	(0.76)	(9.41)	(0.11)	(9.14)	(0.55)	(9.41)	(0.34)	(7.71)	(0.20)	(9.25)	(0.09)	(8.73)
lngexp	0.97	-1.47	0.22	-0.34	1.93	1.29	2.03	1.87	0.24	-1.47	0.41	0.05
	(0.88)	(2.34)	(0.34)	(0.66)	(0.25)	(2.19)	(0.12)	(2.34)	(0.40)	(0.78)	(0.16)	(0.71)
lnclean_energy	4.25	3.12	4.51	3.70	4.11	3.72	3.71	3.12	4.60	4.60	4.33	4.03
	(0.40)	(4.61)	(0.17)	(4.57)	(0.26)	(4.50)	(0.41)	(4.61)	(0.00)	-4.61	-0.15	-4.50
lnacc_elect	4.51	4.10	4.591	4.548	4.596	4.572	4.375	4.099	4.594	4.56	4.41	4.25
	(0.13)	(4.61)	(0.02)	(4.61)	(0.01)	(4.61)	(0.17)	(4.60)	(0.01)	(4.61)	(0.06)	(4.50)

4.2. Correlation analysis

The correlation analysis provides preliminary empirical insights into the structural relationships among the key variables influencing food and nutrition security across BRICS countries – Brazil, China, India, Russia, and South Africa. By employing Pearson correlation coefficients, the analysis assesses the direction and strength of associations between food and nutrition security (proxied by lnSDG2) and a set of economic, environmental, and infrastructural variables, including global value chain (GVC) participation, carbon footprints, agricultural productivity, GDP per capita, public agricultural expenditure, and access to clean fuels and electricity.

For the full BRICS sample, a moderately strong positive correlation is observed between food and nutrition security and GVC participation (r = 0.594), suggesting that countries more deeply integrated into global trade networks tend to experience improved food access and availability. Although the relationship between food and nutrition security and carbon footprints (r = 0.176) is relatively weak, it may reflect the environmental trade-offs that accompany intensified production systems and industrial agricultural expansion. More robust associations are evident for agricultural productivity (r = 0.564) and GDP per capita (r = 0.576), both of which display strong and positive correlations with food and nutrition security. These findings are consistent with theoretical expectations; wherein higher agricultural output enhances food supply while rising income levels increase household access to a diverse and nutritious diet. In contrast, the correlation between government expenditure on agriculture and food and nutrition security is unexpectedly weak (r = 0.044), indicating that public spending alone may not suffice to drive improvements in food outcomes. This may be attributable to inefficiencies in fund allocation, institutional weaknesses, or inadequate targeting of vulnerable populations.

Infrastructure-related variables also display noteworthy associations. Access to electricity shows the strongest correlation with food and nutrition security (r = 0.690), underscoring its role in enabling food storage, processing, and nutritional awareness. Clean energy access (r = 0.318) is also positively correlated, reinforcing the importance of energy transition in improving household health and cooking conditions, both essential for achieving SDG 2. However, substantial heterogeneity emerges when the correlations are disaggregated by country. In Brazil, GVC participation and agricultural productivity are weakly or negatively correlated with food and nutrition security, potentially reflecting structural disparities, urban-rural imbalances, or inefficiencies in resource distribution. Nevertheless, access to clean energy in Brazil shows a moderate and positive association with food outcomes, highlighting the relevance of energy infrastructure even in contexts with uneven agricultural performance.

China demonstrates the most consistent and robust positive correlations across all variables: GVC participation (r = 0.959), carbon footprints (r = 0.962), agricultural productivity (r = 0.958), and electricity access (r = 0.956).

These results indicate a highly integrated food-energy-economic system, wherein trade openness, industrial output, and infrastructure collectively reinforce food and nutrition security. This pattern suggests that synergistic development policies in China have facilitated systemic alignment across sectors. India's profile closely mirrors that of China, with strong positive correlations between food and nutrition security and GVC participation (r = 0.798), carbon emissions (r = 0.853), agricultural productivity (r = 0.781), and access to clean energy (r = 0.686). This alignment supports the proposition that coordinated progress in economic integration, agricultural development, and energy access can yield cumulative gains in food security. However, similar to the pooled sample, public agricultural expenditure remains only weakly correlated (r = 0.131), indicating persistent concerns about the efficiency and effectiveness of fiscal interventions.

Russia exhibits moderate to strong correlations with GVC participation (r = 0.459), carbon footprints (r = 0.442), and agricultural productivity (r = 0.612), reflecting a relatively conventional development trajectory. Interestingly, the negative association with clean energy access (r = -0.421) may signal an overreliance on fossil fuels or insufficient investment in sustainable energy systems, potentially limiting the co-benefits of energy transition for nutrition outcomes. In South Africa, the data reveal a more complex and fragmented relationship. Food and nutrition security is moderately correlated with GVC participation (r = 0.369) and strongly with agricultural productivity (r = 0.679). However, carbon footprints exhibit a negative correlation (r = -0.467), possibly indicating environmental inefficiencies or inequitable industrial development. The strongest negative association arises between food and nutrition security and government agricultural expenditure (r = -0.665), raising concerns about policy misalignment, ineffective spending, or weak institutional delivery mechanisms.

Taken together, the results underscore the importance of context-specific pathways in understanding the determinants of food and nutrition security. While countries such as China and India exhibit well-integrated systems where trade, productivity, and infrastructure positively reinforce nutritional outcomes, others like Brazil and South Africa display more disjointed or even contradictory relationships. These cross-country differences highlight the need for tailored policy interventions that consider not only economic and environmental variables, but also institutional capacity and local conditions. Overall, the correlation patterns provide empirical support for the hypothesis that global value chain integration can enhance food and nutrition security, particularly when accompanied by strong infrastructure and agricultural systems. However, the varied relationships observed with carbon footprints and public spending suggest that sustainable and inclusive food systems cannot be achieved through economic growth or investment alone. Rather, a nuanced policy approach is required—one that is adaptive to national contexts and that fosters coherence between trade, energy, agriculture, and public finance.

4.3. Cross-sectional dependence, stationarity, and cointegration tests

This study investigates the influence of global value chains and carbon footprints on food and nutrition security (FNS) across BRICS countries. Given the potential for interdependence among nations, particularly due to geographic proximity and shared socio-economic characteristics. It is methodologically prudent to begin by testing for cross-sectional dependence (CSD). Failure to address such dependence could lead to biased and inconsistent estimates in panel data analysis. To evaluate this, we applied Pesaran's Cross-sectional Dependence (CD) test, which yielded a CD statistic of –0.435 (p-value = 0.6633). This result suggests that the null hypothesis of no cross-sectional dependence cannot be rejected at conventional significance levels. Moreover, the average absolute off-diagonal correlation was calculated at 0.358, indicating a moderate degree of pairwise association; however, this was not statistically significant. These findings imply that the panel units do not exhibit substantial contemporaneous correlation, thus justifying the use of first-generation panel estimation techniques.

Accordingly, the study employed the Levin–Lin–Chu (LLC) and Im–Pesaran–Shin (IPS) unit root tests. These first-generation unit root tests rest on the critical assumption of cross-sectional independence, where idiosyncratic error components are assumed to be independently distributed across units. In practical terms, this means that shocks or innovations in one country are not presumed to spill over into or correlate with disturbances in another. While this assumption streamlines estimation procedures, it does not always mirror real-world complexities, particularly in globally interconnected economies. However, given the absence of significant CSD in our data, the use of these tests remains appropriate. The unit root test results, presented in Table 3, reveal that all variables are stationary at levels I(0) or become stationary after first differencing I(1), at the 1% and 5% levels of significance, respectively. This mix of integration orders further validates the robustness of the panel framework adopted.

To explore the possibility of a long-run equilibrium relationship among the variables, the Pedroni cointegration test was conducted. This test is well-suited for heterogeneous panels, accommodating both individual-specific effects and slope heterogeneity, while also allowing for some degree of cross-sectional dependence. The test results, detailed in Table 4, provide strong evidence in support of a cointegrating relationship between food and nutrition security and the set of explanatory variables. This finding affirms the theoretical expectation of a long-term equilibrium linkage between global integration, environmental externalities, and food-related outcomes in emerging economies.

Table 3. Stationarities of the variables, source: Authors' computation

Variable	Levin–Lin–Chu		Im–Pesaran–Shin	
	I(0)	I(1)	I(0)	I(1)
lnSDG2	-2.303***	-11.473***	-2.163**	-6.611***
lnGVC	-0.642	-8.6210***	0.854	-6.066***
lnCFP	-0.391	-6.742***	0.432	-5.320***
lnAGRI	-3.326***	-11.897***	-3.879***	-6.802***
lnGDPPC	0.231	-6.296***	0.995	-5.147***
lnGEXP	-2.071***	-9.597***	-2.786***	-6.144***
lnClean_Energy	-0.517	-1.267	3.705	-2.157**
lnAcc_Elect	-1.571**	-10.619***	-1.956**	-6.266***

Note: ***, ** and * illustrate the 1 %, 5 % and 10 % significance levels, respectively.

Table 4. Pedroni Panel cointegration test results, source: Authors' computation

	FULL SAMPLE	BRAZIL	CHINA	INDIA	RUSSIA	SOUTH AFRICA
Pedroni Cointegration Test						
Modified Phillips–Perron t	2.188***	0.9126	1.5321*	0.8796	0.9508	0.9382
Phillips–Perron t	-2.7601***	-0.9039	-0.1257	-1.3279*	-2.9603**	-1.2941*
Augmented Dickey–Fuller t	-2.1193***	-0.999	-0.2976	-1.2156*	-1.0752	-1.1516

Note: ***, **, and * illustrate the 1 %, 5 %, and 10 % significance levels, respectively.

4.4. Presentation and discussion of results

Table 5 presents the results of ordinary least squares (OLS) estimations examining the determinants of food and nutrition security, proxied by the logarithm of SDG 2 (lnSDG2), across BRICS countries. The analysis encompasses both pooled and country-specific models, incorporating variables that reflect structural, economic, and environmental dimensions, namely global value chain (GVC) participation, carbon footprints (CO_2 emissions per capita), agricultural productivity, GDP per capita, public agricultural expenditure, and access to clean fuels and electricity. The findings reveal significant heterogeneity in both the magnitude and significance of these determinants across countries, underscoring the differentiated pathways through which national systems mediate food and nutrition outcomes.

In the pooled sample, GVC participation (lnGVC) is negatively and significantly associated with food and nutrition security ($\beta = -0.080$, $p < 0.01$), suggesting that greater integration into global value chains may introduce vulnerabilities, potentially through exposure to external shocks, volatility in international markets, or asymmetrical distribution of trade gains. However, this aggregate relationship masks considerable variation across countries. Notably, the negative and significant effect persists only in India ($\beta = -0.040$, $p < 0.01$), where the agricultural sector remains deeply embedded in domestic markets, and where disruptions in GVCs during the COVID-19 pandemic significantly affected food supply chains and rural livelihoods. This result may reflect structural characteristics such as India's extensive network of smallholder farmers and its reliance on agricultural exports, particularly in commodities like rice and spices, which faced considerable logistical challenges during periods of international trade restrictions.

Conversely, GVC participation exerts no significant effect in Brazil, China, Russia, and South Africa. In Brazil, the lack of significant impact may be attributable to the country's comparatively diversified export base, which includes both agricultural and industrial products, potentially buffering the economy from GVC volatility. In China, the absence of a significant relationship may stem from the country's strong domestic supply chains and state-led initiatives to secure food systems even during global disruptions, reflecting high levels of institutional resilience. Russia's insignificant coefficient could reflect both the pre-2022 economic structure and the substantial state intervention in agriculture and food distribution systems. In South Africa, while the economy is highly integrated into global markets, domestic policy priorities such as land reform, coupled with persistent income inequality, may mediate the benefits of GVC integration, potentially dampening the expected positive effects on food security.

Carbon footprint (lnCFP) does not exhibit statistical significance in the pooled analysis, indicating that aggregate per capita emissions may not directly correlate with national food security outcomes. However, country-specific results reveal nuanced dynamics. In India ($\beta = 0.231$, $p < 0.05$) and South Africa ($\beta = 0.289$, $p < 0.05$), higher carbon emissions are positively associated with food and nutrition security. This counterintuitive finding may indicate that increased industrial and agricultural activity, which drives emissions, simultaneously contributes to greater food production and economic activity, thereby improving food access. Nonetheless, this raises concerns about the sustainability of such growth patterns, suggesting a potential trade-off between short-term food security gains and long-term environmental degradation. In Brazil, China, and Russia, the relationship between carbon emissions and food security remains statistically insignificant or negative, reflecting differing industrial structures and the extent of environmental regulation.

Agricultural productivity (lnAGRI) consistently emerges as a significant determinant of food and nutrition security across the sample. In the pooled model, the relationship is positive and highly significant (β = 0.108, $p < 0.01$), underscoring the critical role of productivity in enhancing food availability and access. This pattern is particularly strong in India (β = 0.264, $p < 0.05$), Russia (β = 0.235, $p < 0.01$), and South Africa (β = 0.495, $p < 0.01$). In India, improvements in agricultural productivity are closely linked to policies such as the National Food Security Act and the government's investment in irrigation and rural infrastructure. In Russia, the significant relationship may reflect state support for agricultural modernisation, which has increased output and export potential in recent years. In South Africa, where food insecurity remains intertwined with socio-economic inequality, gains in productivity are essential for improving access among vulnerable populations. By contrast, Brazil and China show negative but insignificant coefficients, possibly due to market saturation, structural inefficiencies, or uneven distribution of productivity gains across rural and urban regions.

GDP per capita (lnGDPPC) shows a significant positive effect in the pooled sample (β = 0.316, $p < 0.01$), highlighting the centrality of economic capacity in securing food and nutrition outcomes. However, the significance of this relationship varies across countries. In Russia, GDP per capita retains a significant positive impact (β = 0.350, $p < 0.10$), suggesting that higher income levels translate into improved food security through enhanced purchasing power and investment in social programmes. In Brazil and South Africa, however, the coefficients are negative and statistically insignificant, reflecting persistent structural inequalities and the possibility that aggregate income growth does not uniformly translate into nutritional improvements, particularly in contexts of high income disparity and weak redistributive mechanisms.

Public agricultural expenditure (lnGEXP) is positively and significantly associated with food and nutrition security in the pooled model (β = 0.037, $p < 0.01$). Yet, the absence of significance in the country-specific estimations raises important questions regarding the effectiveness and targeting of agricultural investments at the national level. This may reflect inefficiencies in budget execution, misalignment between budget allocations and sectoral needs, or limited absorptive capacity in certain countries. For example, while India and Brazil allocate substantial resources to agricultural subsidies and support schemes, issues such as subsidy leakages and regional disparities may limit their effectiveness in achieving national food security goals.

Access to clean fuels (lnClean_Energy) exhibits a negative relationship with food and nutrition security in the pooled analysis (β = −0.240, $p < 0.01$). This seemingly counterintuitive finding may arise from transitional challenges in energy systems where populations, particularly in lower-income contexts, face increased costs during the shift to cleaner fuels, potentially diverting household expenditures away from food consumption. In India, this negative relationship persists significantly (β = −0.201, $p < 0.01$), highlighting the affordability challenges associated with energy transitions among rural and low-income communities. In contrast, Russia displays an exceptionally large and positive coefficient (β = 21.832, $p < 0.01$), which may be attributable to unique policy structures, such as state energy subsidies or distortions in domestic energy markets, although this result warrants cautious interpretation given its magnitude.

Electricity access (lnAcc_Elect) demonstrates a positive and significant association with food and nutrition security in the pooled sample (β = 0.294, $p < 0.01$), consistent with existing literature emphasising the role of energy infrastructure in enabling food storage, processing, and distribution. At the national level, significant effects are observed only in Brazil (β = 2.928, $p < 0.05$), suggesting that electrification initiatives have played a meaningful role in enhancing food system resilience, particularly in remote regions. In other countries, statistical insignificance may reflect saturation points where further improvements in access yield diminishing marginal benefits.

Overall, the empirical evidence underscores both shared and divergent dynamics shaping food and nutrition security across the BRICS countries. While agricultural productivity, economic capacity, and infrastructure remain fundamental drivers, the role of GVC integration, environmental pressures, and public expenditure varies significantly depending on local institutional structures, policy environments, and socio-economic contexts. For policy, these findings highlight the importance of country-specific strategies. In India, interventions should focus on balancing GVC engagement with support for domestic markets and addressing energy affordability for vulnerable populations. In China, reinforcing internal supply chain resilience appears crucial, while Brazil may benefit from ensuring equitable distribution of agricultural gains and improving budget execution efficiency. For South Africa, addressing deep-seated inequalities alongside agricultural investments remains critical. In Russia, future research will need to contend with data constraints and geopolitical uncertainties arising from recent conflicts, which may have profound implications for sustainable food systems. Collectively, these insights emphasise that promoting SDG 2 targets within the BRICS context requires not only broad policy frameworks but also finely tuned national strategies that account for structural differences, institutional capacities, and emerging global challenges.

4.5. Limitations and geopolitical considerations

A significant limitation of the present study pertains to the inclusion of Russia in the empirical analysis. While Russia remains a key member of the BRICS bloc, recent geopolitical developments, particularly the invasion of Ukraine in 2022, introduce considerable uncertainties regarding the reliability and availability of economic and environmental data. Reports indicate that, as of 2025, detailed economic statistics for Russia are increasingly classified or withheld from public dissemination, posing challenges for future research seeking to conduct longitudinal analyses or cross-country comparisons. Consequently, the continuation of Russia's inclusion in studies of this nature may become untenable, necessitating either the exclusion of Russian data from future updates or the adoption of alternative methodological approaches, such as scenario analysis or imputation techniques, to mitigate data gaps.

Moreover, the conflict has direct environmental implications, including large-scale pollution and ecosystem degradation resulting from military operations and infrastructure destruction. While assessing the environmental impacts of the war on sustainable development indicators, such as carbon footprints and food system resilience, lies beyond the scope of the current study, it remains an important avenue for future research. Researchers should account for the potential distortive effects of conflict-related emissions and environmental damage on sustainability metrics when interpreting findings involving Russia. These considerations underscore the need for cautious interpretation of results pertaining to Russia in the context of sustainable development and food security analyses.

Table 5. Estimated regression result, *source: Authors' estimation*

DEPENDENT VARIABLE - lnSDG 2						
	FULL SAMPLE	**BRAZIL**	**CHINA**	**INDIA**	**RUSSIA**	**SOUTH AFRICA**
Lngvc	-0.080***	0.062	0.032	-0.040***	-0.065	-0.026
	(0.012)	(0.046)	(0.034)	(0.014)	(0.051)	(0.063)
	[-6.81]	[1.35]	[0.94]	[-2.94]	[-1.27]	[-0.41]
Lncfp	0.008	0.064	-0.068	0.231***	-0.048	0.289*
	(0.013)	(0.103)	(0.100)	(0.072)	(0.108)	(0.150)
	[0.6]	[0.62]	[-0.68]	[3.18]	[-0.44]	[1.93]
Lnagri	0.108***	-0.336**	-0.3	0.264**	0.235***	0.495***
	(0.014)	(0.117)	(0.195)	(0.103)	(0.054)	(0.145)
	[7.91]	[-2.88]	[-1.54]	[2.56]	[4.33]	[3.42]
Lngdppc	0.316***	-0.178	0.079	0.087	0.350*	-0.433
	(0.019)	(0.265)	(0.145)	(0.126)	(0.194)	(0.407)
	[16.7]	[-0.67]	[0.55]	[0.69]	[1.8]	[-1.06]
Lngexp	0.037***	-0.008	-0.02	0.012	-0.004	0.01
	(0.014)	(0.03500)	(0.020)	(0.0340)	(0.011)	(0.069)
	[2.6]	[-0.24]	[-0.99]	[0.34]	[-0.39]	[0.15]
lnclean_energy	-0.240***	-0.014	0.071	-0.201***	21.832***	0.064
	(0.040)	(0.037)	(0.200)	(0.051)	(6.894)	(0.333)
	[-6]	[-0.38]	[0.36]	[-3.92]	[3.17]	[0.19]
lnacc_elect	0.294***	2.928**	3.302	-0.121	-0.579	-0.35
	(0.111)	(1.182)	(2.003)	(0.179)	(0.406)	(0.271)
	[2.65]	[2.48]	[1.65]	[-0.68]	[-1.42]	[-1.29]
Constant	0.509*	-2.363	-6.008	-0.006	-99.818***	0.558
	(0.271)	(3.720)	(9.107)	(1.588)	(32.955)	(3.499)
	[1.88]	[-0.64]	[-0.66]	[0]	[-3.03]	[0.16]
Observations	120	24	24	24	24	24
R2	0.9183	0.643	0.956	0.91	0.708	0.727

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables is Sustainable Development Goal 13 (lnSDG13). The standard errors are in parentheses, while the t-statistics are in braces.

5. Temporal dynamics in the determinants of food and nutrition security: pre- and during-COVID analysis

To examine how the COVID-19 pandemic influenced the structural and economic drivers of food and nutrition security, separate regression models were estimated for the pre-COVID and during-COVID periods, as presented in Table 6. The dependent variable in both models is the natural logarithm of SDG 2 (lnSDG2), serving as a proxy for food and nutrition security. The results indicate considerable temporal heterogeneity in both the direction and significance of key explanatory variables, highlighting the differential impact of the pandemic on national food systems.

Prior to the outbreak of COVID-19, global value chain (GVC) participation was negatively and significantly associated with food and nutrition security (β = −0.074, $p < 0.01$). This finding suggests that greater integration into global trade networks may have exposed domestic food systems to external vulnerabilities, such as reliance on volatile supply chains or the displacement of local production. However, during the pandemic, this relationship became statistically insignificant (β = −0.069), indicating that the unprecedented disruptions to global trade may have weakened the direct influence of GVC participation on food access and availability in the short term.
Carbon footprint (lnCFP), used as a proxy for environmental pressure, remained negatively associated with food and nutrition security across both periods, though the relationship was statistically insignificant. This suggests that per capita CO_2 emissions do not exert a direct or immediate effect on nutritional outcomes, or that their influence is likely mediated through broader environmental degradation or regulatory frameworks. Agricultural productivity (lnAGRI) was a statistically significant and positive determinant of food and nutrition security before the pandemic (β = 0.088, $p < 0.01$), underscoring its role in enhancing food availability. However, this relationship became statistically insignificant during the COVID-19 period (β = 0.106), possibly due to disruptions in input supply chains, labour shortages, and restricted market access, which may have weakened the transmission of productivity gains to household-level food outcomes.
GDP per capita (lnGDPPC) remained the most consistent and robust predictor across both periods. It exhibited a strong and positive relationship with food and nutrition security in both the pre-COVID (β = 0.389, $p < 0.01$) and during-COVID (β = 0.338, $p < 0.01$) models. These findings reaffirm the foundational role of household income in maintaining access to food, even amid systemic shocks. Government expenditure on agriculture (lnGEXP) demonstrated a positive association with food and nutrition security in both models, achieving marginal statistical significance in the pre-COVID period (β = 0.019, $p < 0.10$) and increasing in magnitude during the pandemic (β = 0.059). However, the lack of statistical significance in the latter period may point to implementation delays, shifts in budgetary priorities, or inefficiencies in public spending during crisis conditions.
Access to clean fuels (lnClean_Energy) showed a statistically significant and negative association with food and nutrition security prior to the pandemic (β = −0.488, $p < 0.01$), potentially reflecting the affordability challenges or transitional burdens associated with adopting modern energy sources in lower-income households. During the pandemic, this relationship turned positive (β = 0.021) but remained statistically insignificant, suggesting that access to clean energy, while important, may not have been sufficient to buffer nutritional vulnerabilities under emergency conditions.

Table 6. Estimated regression result with COVID-19 dynamics, source: Authors' estimation

DEPENDENT VARIABLE - lnSDG 2		
	PRE-COVID	DURING-COVID
	1	2
lngvc	-0.074***	-0.069
	-0.008	-0.114
	[-8.86]	[-0.61]
lncfp	-0.013	-0.028
	-0.01	-0.084
	[-1.32]	[-0.34]
lnagri	0.088***	0.106
	-0.011	-0.074
	[7.89]	[1.44]
lngdppc	0.389***	0.338***
	-0.018	-0.057
	[21.75]	[5.96]
lngexp	0.019*	0.059
	-0.011	-0.056
	[1.8]	[1.06]
lnclean_energy	-0.488***	0.021
	-0.046	-0.036
	[-10.53]	[0.58]
lnacc_elect	0.664***	-1.038***
	-0.101	-0.403
	[6.56]	[-2.58]
Constant	-0.407*	5.105***
	-0.218	-1.578
	[-1.87]	[3.24]
Observations	95	25
R^2	0.965	0.9807

***, **, * denotes significance levels at 1%, 5%, and 10% respectively. The dependent variables is Sustainable Development Goal 13 (lnSDG13). The standard errors are in parentheses, while the t-statistics are in braces.

A marked reversal was observed in the association between electricity access (lnAcc_Elect) and food and nutrition security. In the pre-COVID period, electricity access had a strong and positive influence ($\beta = 0.664$, $p < 0.01$), aligning with literature that emphasises the role of electrification in reducing food spoilage, enhancing cooking capabilities, and supporting information dissemination. However, during the pandemic, the relationship became significantly negative ($\beta = -1.038$, $p < 0.01$), potentially indicating that affordability constraints, supply interruptions, or unequal distribution of energy access limited its protective effects during the crisis. The intercept term also shifted significantly across periods, from a negative and marginally significant value in the pre-COVID model ($\beta = -0.407$, $p < 0.10$) to a large and positive value during the pandemic ($\beta = 5.105$, $p < 0.01$). This may reflect unobserved macro-level adjustments, including emergency relief measures, food subsidies, or international aid interventions that helped stabilise food access during the pandemic.

Both models demonstrate strong explanatory power, with R^2 values of 0.965 (pre-COVID) and 0.981 (during-COVID), suggesting that the included variables account for a substantial proportion of the variance in food and nutrition outcomes. Taken together, these findings highlight the temporal fragility of traditional development levers in times of systemic crisis. While GDP per capita remained a stable and significant determinant of food and nutrition security, the roles of agricultural productivity, energy access, and public expenditure were significantly altered during the pandemic period. The evidence underscores the importance of adaptive and context-responsive strategies that can safeguard food system resilience amid external shocks. Such strategies should consider not only economic capacity, but also structural vulnerabilities and institutional readiness to respond to crises.

6. Interaction effects of GVC Participation and carbon footprints on food and nutrition security

Figure 2 presents the estimated marginal effects of global value chain (GVC) participation (measured as the natural logarithm of GVC, lngvc) on food and nutrition security (FNS), conditional on varying levels of carbon footprint intensity (lncfp). The figure illustrates four predictive margins plots with 95% confidence intervals, corresponding to lncfp values of 0.5, 1.0, 1.5, and 2.0. Each panel captures how the predicted value of FNS changes across a range of lngvc (from 16 to 20) for a fixed level of carbon emissions.

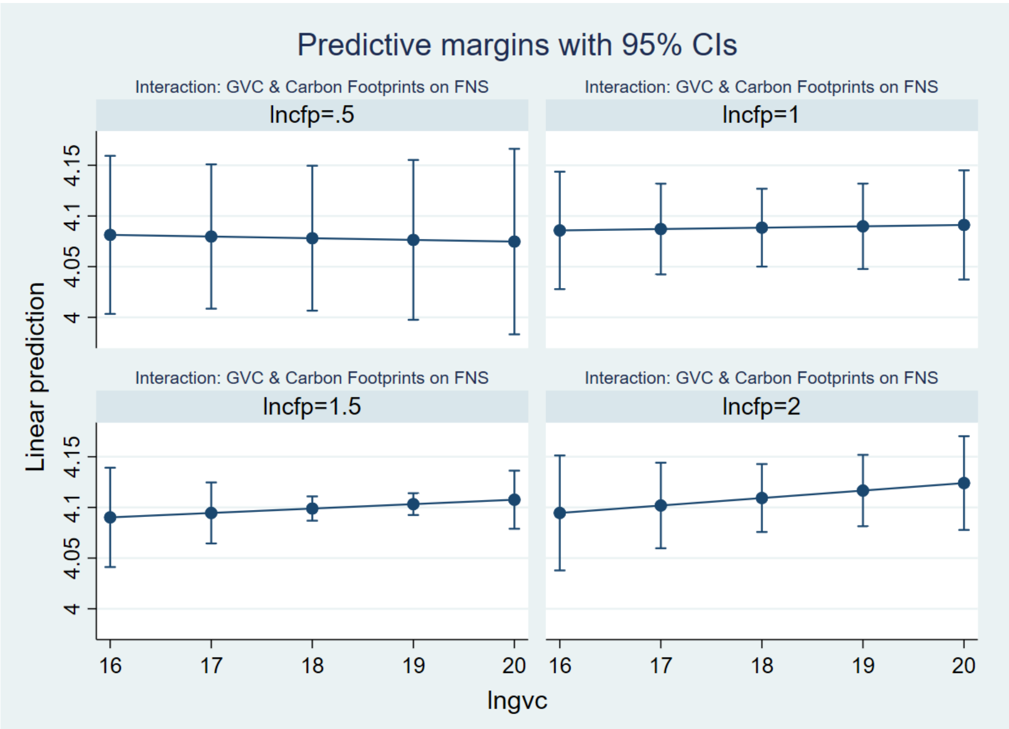

Figure 2. Marginal Effect of GVC Participation and Carbon Footprints on Food and Nutrition Security, source: Authors' computation

The upper-left panel (lncfp = 0.5) indicates a relatively flat and imprecise relationship between GVC participation and FNS. The predicted values of FNS remain largely unchanged across the range of lngvc, and the wide confidence intervals, particularly at lower levels of GVC participation, suggesting high uncertainty in the estimated effect. This finding implies that, when carbon emissions are low, GVC engagement alone may not substantially influence food and nutrition outcomes, or that the estimates are not statistically robust in this range. As lncfp

increases to 1.0 (upper-right panel), a slight positive trend in FNS predictions emerges with increasing GVC participation. However, the confidence intervals remain relatively wide, indicating that while the marginal effect becomes more discernible, it is not yet precise enough to confirm statistical significance across the observed range.
A more defined and statistically credible trend becomes apparent in the lower-left panel (lncfp = 1.5). Here, the slope of the relationship between lngvc and FNS is visibly positive, and the confidence intervals are narrower particularly around mid-range values of GVC participation (e.g., lngvc = 18 to 19). This suggests that at moderate levels of carbon emissions, increased participation in GVCs is more reliably associated with improvements in food and nutrition security. The narrowing uncertainty bands imply greater estimation precision, supporting the hypothesis that trade integration can be synergistic with moderate environmental intensity in achieving nutrition outcomes.
The strongest effect is observed in the lower-right panel (lncfp = 2.0). In this case, the positive association between GVC participation and FNS is clearly evident, and the confidence intervals, though slightly wider than those in the previous panel, largely support the upward trend. This suggests that in contexts with higher carbon footprints, possibly indicative of more industrialised or energy-intensive economies for which the nutritional benefits of GVC integration may be more pronounced. The pattern could reflect the role of greater production and processing capacity, enhanced logistics, or improved access to fortified and diversified food supplies enabled through GVCs.
These findings reveal a statistically heterogeneous relationship between GVC participation and food and nutrition security, contingent upon the level of environmental intensity. Specifically, the effect of GVC participation on FNS is attenuated or imprecise at lower levels of carbon emissions but becomes progressively stronger and more precisely estimated as environmental intensity increases. This interaction underscores the importance of contextualising the trade–nutrition nexus within broader production and energy-use patterns.

7. Implications for Policy and Research

From a policy perspective, these results suggest that GVC integration strategies are likely to be more effective in improving nutrition outcomes in countries or regions characterised by moderate to high levels of productive and energy capacity. For economies with low carbon intensity, often reflecting limited industrialisation, the benefits of trade participation on food systems may be marginal without parallel investments in infrastructure, energy access, and agricultural productivity.
The observed interaction further points to the importance of aligning trade policy with environmental and nutrition strategies. While GVC participation may contribute positively to food security, the environmental conditions under which such participation occurs play a critical role in shaping its effectiveness. Policymakers should therefore consider integrated interventions that combine trade facilitation with sustainable energy and environmental management to maximise nutrition gains. Finally, the increasing marginal returns observed at higher carbon intensity levels may also raise sustainability concerns. Future research should explore non-linear dynamics, potential thresholds, and the trade-offs between nutrition improvements and environmental degradation to inform balanced, long-term development strategies.

8. Conclusions

This study investigated the multifaceted relationship between global value chain (GVC) participation, carbon footprints, and food and nutrition security (FNS) across the BRICS economies, employing panel OLS and country-specific regression analyses. The results reveal both convergences and stark divergences in the structural, economic, and environmental determinants of FNS, offering nuanced insights into how these drivers operate under different national contexts and during systemic crises, such as the COVID-19 pandemic.
At the aggregate level, increased GVC participation was found to be negatively associated with food and nutrition security, suggesting that deeper integration into global trade may introduce vulnerabilities—particularly in the form of supply chain disruptions, reduced local food self-sufficiency, and uneven distribution of trade gains. However, this effect was not uniform. While India exhibited a significant negative association, other BRICS countries, such as Brazil and China, recorded statistically insignificant results. This heterogeneity points to the importance of domestic absorptive capacity, institutional frameworks, and policy readiness in mediating the effects of global integration on national food systems.
Agricultural productivity and GDP per capita emerged as robust and positive determinants of FNS across most model specifications, reaffirming the foundational role of economic development and sectoral output in enhancing food access and availability. Yet, the impact of government agricultural expenditure and access to clean energy was found to be more context-specific. While public investment in agriculture yielded positive effects in the pooled model, its influence dissipated in the country-level regressions, raising concerns about implementation efficiency and policy targeting. Likewise, access to clean fuels was associated with a decline in FNS in low-income settings, possibly due to affordability constraints or transitional challenges during the shift from traditional to modern energy sources.

Temporal analysis across pre- and during-COVID periods further revealed significant shifts in the relevance and magnitude of key drivers. GVC participation, for instance, ceased to be a statistically significant determinant of FNS during the pandemic, likely due to widespread trade disruptions and protectionist responses. Similarly, agricultural productivity and energy infrastructure, while significant pre-pandemic, became less effective in cushioning the food system against shocks, highlighting the fragility of conventional development levers under crisis conditions. By contrast, GDP per capita remained a consistently significant and positive determinant, underscoring the protective role of economic capacity even during periods of systemic stress.

The interaction analysis between GVC participation and carbon footprints adds another dimension to the policy discourse. The findings demonstrate that the marginal effect of GVCs on FNS is statistically heterogeneous, improving with higher levels of environmental intensity. This suggests that in economies with greater industrial and energy-use capacity, the nutritional benefits of trade integration may be more tangible, although such gains may come at the cost of increased environmental pressure.

These findings carry several important implications for policymakers and development practitioners. First, trade integration must be pursued with caution and complemented by robust domestic policy frameworks that mitigate potential external vulnerabilities. Second, efforts to boost agricultural productivity should remain central, particularly in countries where food insecurity is acute. However, productivity gains alone are insufficient without parallel investments in equitable distribution and market access. Third, public spending in agriculture needs to be better aligned with food system priorities, ensuring that allocations translate into measurable nutritional outcomes. Fourth, energy transitions, especially in cooking and food preparation should be designed to be socially inclusive, ensuring affordability and access for vulnerable populations. Finally, the temporally unstable nature of certain determinants during the COVID-19 pandemic calls for adaptive policy instruments that can be rapidly deployed in response to crises. Governments should prioritise resilience-building strategies that integrate economic growth, environmental sustainability, and social protection in order to safeguard food and nutrition security under both stable and adverse conditions.

In conclusion, the relationship between GVC participation, carbon footprints, and food and nutrition security are complex and context-dependent. While some structural drivers exert consistent influence across time and space, others are contingent upon environmental intensity, policy effectiveness, and the presence of enabling institutions. As countries seek to advance SDG 2 under conditions of global uncertainty and climate volatility, a nuanced, evidence-informed, and locally grounded policy approach is essential to building sustainable, inclusive, and shock-resilient food systems.

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