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How do green finance, digital technology, trade openness, and climate change interact to shape food production in sub-Saharan Africa?

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Abstract: The promotion of sustainable food productivity through innovative technologies remains a central priority in economic development, attracting increasing attention from scholars, policymakers, and industry stakeholders. With the continuing rise in global food demand, resource-efficient solutions are essential to ensuring long-term agricultural growth and stability in food production. This study examines the impact of green finance, agricultural innovation, digital technology, trade openness, and climate change on food production in sub-Saharan Africa (SSA). Using the method of moments quantile regression (MMQR) and the generalised method of moments (GMM), it analyses a balanced panel dataset covering 46 SSA countries from 2001 to 2023. The findings highlight the positive influence of green finance, agricultural innovation, and digital technology in enhancing food production, particularly in lower production sectors, suggesting important bidirectional policy implications. Trade openness is found to promote agricultural growth but exhibits diminishing effects at higher levels of productivity, indicating the relevance of a unidirectional policy focus. In contrast, climate change has a negative effect on food production. The study also identifies key mediation pathways, including green finance stimulating research and development, digital technology improving agricultural credit and farmers' education, and trade openness attracting foreign direct investment. These results emphasise the importance of integrated policy frameworks that combine financial support, technological advancement, and trade openness to promote sustainable agricultural growth and strengthen food security across SSA.

Keywords: agricultural trade; digital agriculture; environmental change; food security; sub-Saharan Africa; sustainable finance

Food security remains a persistent challenge in sub-Saharan Africa (SSA), shaped by environmental, economic, and political factors. The region experiences some of the highest levels of food insecurity globally, with widespread hunger, malnutrition, and poverty-related health issues (Bah et al. 2025; Nkhoma et al. 2025). In 2022, approximately 868 million people

across Africa experienced moderate food insecurity, with 342 million classified as severely food insecure (FAO 2023). Over two-thirds of the population in Central, Eastern, and Western Africa lack adequate access to food (United Nations 2024), while climate-induced crises in Southern Africa have placed over 11 million people in urgent need (WVI n.d.). Countries such

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as the Democratic Republic of Congo, Nigeria, Ethiopia, and South Sudan collectively account for more than 78 million food-insecure individuals, underscoring the urgency for coordinated and sustainable responses (Africa Center for Strategic Studies 2023).

Addressing food insecurity in SSA requires significant increases in agricultural output to meet the demands of a rapidly expanding population (Abdi et al. 2024; Addai et al. 2024). The population has grown from 283 million in 1960 to over 1.5 billion in 2024 and is projected to reach 2.5 billion by 2050 (ECA 2024). This demographic pressure intensifies stress on food systems already constrained by climate change, land degradation, and inefficient supply chains (Chindasombatcharoen et al. 2024; Choruma et al. 2024). In response, sustainable agricultural strategies that enhance productivity, improve access, and build resilience are increasingly prioritised (Brenya et al. 2024; Shamshiri et al. 2024). Among the most critical strategies are green finance, technological innovation, digital technologies, and trade openness (Gharleghi et al. 2024; Bah et al. 2025).

Green finance supports environmentally sustainable practices, renewable energy adoption, and climate adaptation (Yuan et al. 2024). Investments in efficient irrigation systems, environmentally friendly fertilisers, and climate-resilient crop varieties help to reduce agriculture's environmental footprint and improve productivity (Gharleghi et al. 2024). However, limited access to finance, weak institutions, and policy gaps continue to hinder implementation (Mungai et al. 2022). When green finance combined with technological innovation and digital tools, it becomes more effective, especially for smallholder farmers (Getnet et al. 2025). Innovation in agriculture, such as the development of improved crop varieties, precision farming techniques, and integrated pest management, can boost yields and reduce post-harvest losses (Araya et al. 2024), nonetheless, uptake remains limited due to infrastructural and financial constraints (Chindasombatcharoen et al. 2024). Digital technologies offer solutions by improving access to real-time agricultural data, mobile-based financial services, and market intelligence. Innovations such as mobile payments and blockchain systems improve supply chain efficiency and transparency (Bah et al. 2025).

Trade openness enhances regional and international market access, facilitates technology transfer, and contributes to price stability. It also supports income generation among rural producers through greater market integration (Dithmer and Abdulai 2017). Nevertheless, its benefits depend on the presence of strong institutions and protective policies to shield

domestic producers from external shocks. The combined influence of green finance, innovation, digital technology, and trade constitutes a mutually reinforcing framework for improving food production (Lee and Song 2024; Bah et al. 2025). For instance, solar-powered storage units financed through green investments, supported by digital logistics systems and facilitated by cross-border trade, demonstrate the value of integration.

Despite the clear benefits of integrating green finance, innovation, digital technology, and trade openness, significant research and policy gaps remain. Existing studies often examine these factors in isolation (Koppenjan 2015; Parlasca et al. 2022; Zhou and Li 2022; Bah et al. 2025), overlooking their combined impact on food production. While researchers have explored the role of green finance in climate adaptation (Hossain et al. 2024; Omri et al. 2025), its potential to drive technological innovation and facilitate trade in food production in SSA remains largely unexamined. Similarly, although the effects of digital technology on market access and productivity are well-documented (Chandio et al. 2023; Shamshiri et al. 2024; Bah et al. 2025), its interactions with broader financial and policy ecosystems require further investigation.

This study seeks to bridge these gaps by developing a comprehensive framework that examines how green finance, agricultural innovation, digital technology, trade openness, and climate change influence food production in SSA. It addresses the following research questions: (i) How do these factors interact to influence food production in SSA? (ii_a) Is there a causal relationship between these variables and food production? (ii_b) If so, what is the direction of this relationship? (iii) Through which mechanisms do green finance, digital technology, and trade openness improve food production in SSA? The findings from this study will provide actionable insights for policymakers, investors, and stakeholders, contributing to the development of resilient and sustainable food production systems across the region.

The contributions of this research are outlined as follows:

First, the study adopts a holistic framework to analyse the interconnections between green finance, agricultural innovation, digital technology, and trade openness in food production, while recognising climate change as a moderating factor. This integrated approach moves beyond fragmented research (Lee and Song 2024; Shamshiri et al. 2024), providing a deeper understanding of their combined impact on agricultural productivity and food security.

Second, the study explores the relatively underexamined role of green finance in driving agricultural innovation and sustainability. It examines the mechanisms through which green finance significantly enhances food production and the interactive impact of green finance in supporting technological advancements and facilitating digital tools to improve food production.

Third, unlike previous studies that rely solely on mobile phone ownership as a proxy for digital technology (Khan et al. 2022; Parlasca et al. 2022), this research develops a more comprehensive ICT index using Principal Component Analysis (PCA). This methodological advancement allows for a more accurate assessment of the role of digital technology in enhancing food security. In addition, the study examines the mechanisms through which digital technology improve food production.

Fourth, the research makes a significant contribution to the literature by empirically examining the mechanisms through which trade openness influences food security in SSA. It highlights how trade openness attracts foreign direct investment, facilitates agricultural exports and imports, and fosters a resilient and inclusive food system.

Fifth, the study employs method of moments quantile regression (MMQR) and generalised method of moments (GMM) to ensure robust empirical validation. These econometric techniques enhance the reliability of the findings by addressing issues such as heterogeneity and endogeneity, thereby strengthening causal inferences about the relationships between green finance, agricultural innovation, digital technology, trade openness, climate change, and food production.

Literature review

Empirical literature review. Empirical studies highlight the increasing role of green finance in advancing sustainable agriculture through environmentally sound investments and climate-resilient technologies. Financial instruments such as green bonds and sustainability-linked loans have facilitated funding for renewable energy, efficient irrigation systems, and the use of organic agricultural inputs (Lee and Song 2024; Yuan et al. 2024). These financing mechanisms often support technological innovations in agriculture, including precision farming, mechanisation, and biotechnology such as gene-edited seeds and improved soil management practices, which collectively enhance productivity while minimising chemical inputs (Ke et al. 2021; Hamdan and Tan 2024). The integration of digital technologies further strengthens these initiatives by enabling real-time, data-driven decision-making and expanding access to markets, credit,

and extension services (Bah et al. 2025). Empirical evidence supports the positive role of mobile applications, satellite imagery, and financial platforms in improving farm efficiency, resilience, and overall productivity (Khan et al. 2022; Choruma et al. 2024; Shamshiri et al. 2024).

Trade openness has also been identified as a complementary factor, fostering regional market integration, facilitating technology transfer, and contributing to price stabilisation. However, it may increase vulnerability to external shocks if not supported by robust regulatory frameworks (Shamshiri et al. 2024). At the same time, climate variability poses a growing threat to agricultural systems across SSA, disrupting crop yields, livestock, and water availability. In response, various adaptation strategies have gained prominence, including conservation agriculture, advanced irrigation techniques, and the cultivation of climate-resilient crop varieties, often supported by both national policies and international frameworks (IPCC 2021; Thornton et al. 2022). These interlinked dimensions; green finance, innovation, digital technology, trade, and climate change, shape the trajectory of food systems in SSA, as illustrated in the conceptual framework (Figure 1). Moreover, [Table S1 \(Electronic Supplementary Material – ESM\)](#) presents a summary of the relevant empirical literature reviewed in the study.

Theoretical framework. The theoretical framework guiding this study integrates sustainable development theory, innovation diffusion theory, climate resilience theory, and trade liberalisation theory to explore the structural mechanisms through which green finance, digital technology, trade openness, and climate change influence food production in SSA. Sustainable development theory frames green finance as a means of promoting long-term agricultural productivity by aligning environmental sustainability with economic growth (Yuan et al. 2024; Omri et al. 2025). This perspective emphasises the allocation of financial resources to enhance resource efficiency and resilience within agricultural systems. Innovation diffusion theory provides a lens for understanding how new technologies, particularly digital tools, are adopted and scaled within farming communities (Rogers 1962; Chandio et al. 2023; Bah et al. 2025). It highlights the role of communication channels, social structures, and perceived benefits in accelerating the uptake of innovations that improve productivity and decision-making.

Climate resilience theory positions climate change as a systemic challenge that requires anticipatory and adaptive responses (IPCC 2021; Samarasinghe et al. 2025). It underscores the importance of structural transformations in agricultural systems, including

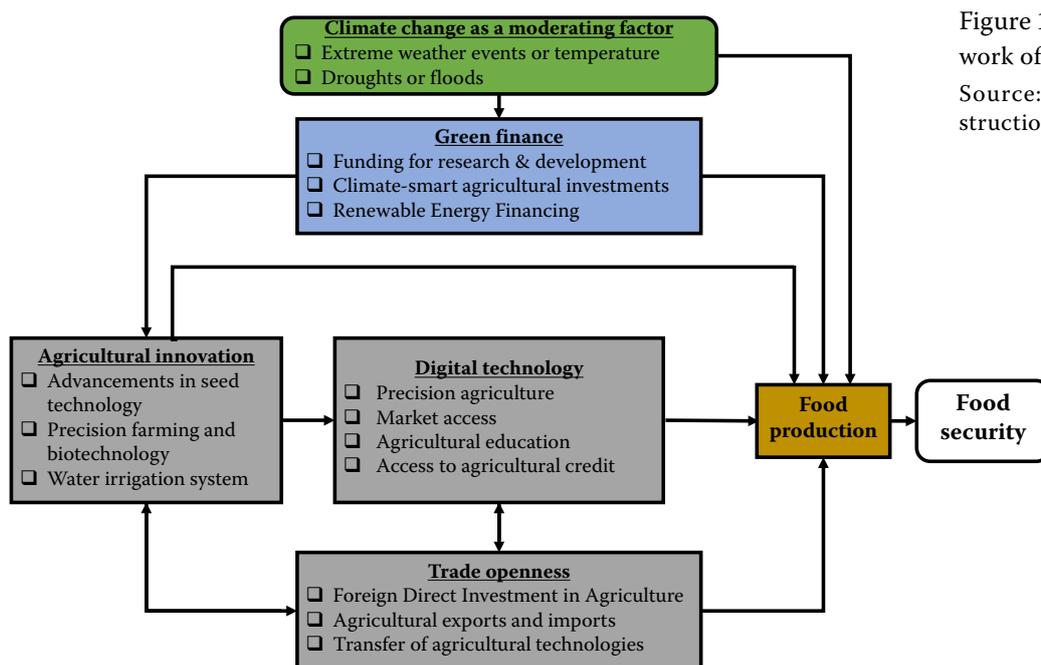


Figure 1. Conceptual framework of the research

Source: Authors' own construction

the adoption of stress-tolerant crops and ecosystem-based management approaches to ensure stability under climatic variability. Trade liberalisation theory, meanwhile, views trade openness as a mechanism that facilitates access to external markets, capital, and knowledge (Ricardo 1817; Dithmer and Abdulai 2017). However, it also recognises that the gains from trade depend on the quality of domestic institutions and the degree of policy alignment. The integration of these theoretical strands offers a comprehensive foundation for analysing the interplay among financial, technological, environmental, and trade-related factors in shaping food production. The framework posits that these variables are not isolated influences but interact dynamically, forming reinforcing pathways that collectively determine agricultural outcomes in the region.

MATERIAL AND METHODS

Study area and data sources

This study analyses 46 SSA countries across the Western, Eastern, Central, and Southern regions from 2001 to 2023, focusing on low and middle income economies. The study period was selected based on data availability and significant changes in food security, including the growth of green finance, the adoption of digital tools such as mobile money services like M-Pesa, and the expansion of trade through the African Continental Free Trade Area (AfCFTA). These developments have enhanced market access and financial inclusion, while climate change,

reflected in rising temperatures, irregular rainfall, and extreme weather events, continues to threaten agriculture. The study provides insights into how financial and technological progress interacts with environmental challenges within the context of key policy frameworks such as the Comprehensive Africa Agriculture Development Programme (CAADP), the Sustainable Development Goals (SDGs), the Paris Agreement, and the AfCFTA. Data from the Organisation for Economic Co-operation and Development (OECD), the World Development Indicators (WDI), the Food and Agriculture Organisation (FAO), and the Emergency Events Database (EM DAT) underpin the analysis. Table 1 presents the data sources, and Table S2 (ESM) lists the countries included in the study.

Dependent variables

This study uses *food production* as the main dependent variable, defined as the total amount of food, including crops, livestock and processed goods, produced in a country over time. It is a key variable of food security, agricultural policy performance and the impact of environmental and economic factors. As most of the rural population in SSA depends on agriculture, food production is considered the best reflection of overall food security. To capture the multidimensional nature of food security, three additional dependent variables are included: *per capita food supply* (kilocalories per person per day) as a proxy for availability, *average dietary energy supply adequacy* to reflect accessibility, and *cereal yield* (kilograms per hectare) as a measure of stability.

Table 1. Variables units of measurement, data sources, summary statistics and variable inflation factor (VIF) results

Variables	Units of measurement	Data source	Obs.	Mean	SD	Min	Max	VIF	1/VIF
<i>Food production</i>	metric tonnes	WDI	1 058	94.756	22.555	33.02	183.45	–	–
<i>Green finance</i>	thousand USD	OECD	1 058	33.054	27.642	0.015	176.789	1.35	0.739
<i>Agricultural innovation</i>	water withdrawal (e.g. irrigation) (%)	WDI	1 058	66.044	26.261	0.700	98.300	2.08	0.481
<i>Digital technology</i>	digital technology index	Author construction	1 058	1.612	1.000	0.808	3.924	1.58	0.633
<i>Trade openness</i>	percentage of GDP	WDI	1 058	76.704	50.19	20.964	347.997	1.75	0.570
<i>Climate change</i>	droughts, floods, and extreme weather events	EM-DAT	1 058	8.682	12.471	0.012	196.984	1.05	0.951
<i>Rural population</i>	percentage of rural population	WDI	1 058	12 066 354	18 517 465	40 045	1.023×10^8	2.97	0.337
<i>Urban population</i>	percentage of urban population	WDI	1 058	7 441 784.5	13 603 276	41 126	1.215×10^8	3.60	0.277
<i>R&D</i>	R&D expenditure (% of GDP)	WDI	1 058	10 301.665	61 019.841	0.003	1 090 050.4	2.40	0.417
<i>Agricultural credit</i>	million USD	FAO	1 058	1 026 721.2	2 832 447.3	0.464	24 996 116	2.35	0.425
<i>Education</i>	enrolment of primary education	WDI	1 058	2 840 180.8	4 505 726	0.000	30 455 582	4.36	0.229
<i>Foreign direct investment (FDI)</i>	FDI (% of GDP)	WDI	1 058	4.975	7.971	0.001	103.337	1.22	0.819
Mean VIF								2.25	

OECD – Organisation for Economic Co-operation and Development; WDI – World Development Indicators; FAO – Food and Agriculture Organisation; EM-DAT – Emergency Events Database; Obs – observations

Source: Authors' own estimation

Independent variables

The first independent variable, *green finance*, is measured as total mitigation-related development finance (thousand USD) received per country, using OECD data. It is associated with efforts to reduce investment risk, attract green investment, and promote climate-smart agriculture (Addai et al. 2024). The second variable, *water withdrawal* (% for irrigation), from the WDI, serves as a proxy for agricultural innovation, reflecting irrigation efficiency and its potential effects on yields and production stability. The third variable, *digital technology*, is represented by an index constructed through

Principal Component Analysis (PCA), incorporating mobile subscriptions, secure internet servers, internet access and usage, with data from the WDI. This index relates to aspects such as market access, financial inclusion and precision farming. The fourth variable, *trade openness*, measured as total trade (% of exports and imports to GDP) from WDI, captures exposure to inputs, technology, markets and external shocks (Brewer et al. 2023). The fifth variable, *natural disasters*, used as a proxy for climate change, includes droughts, floods and extreme weather events, based on EM-DAT data, which may affect agriculture and food supply chains.

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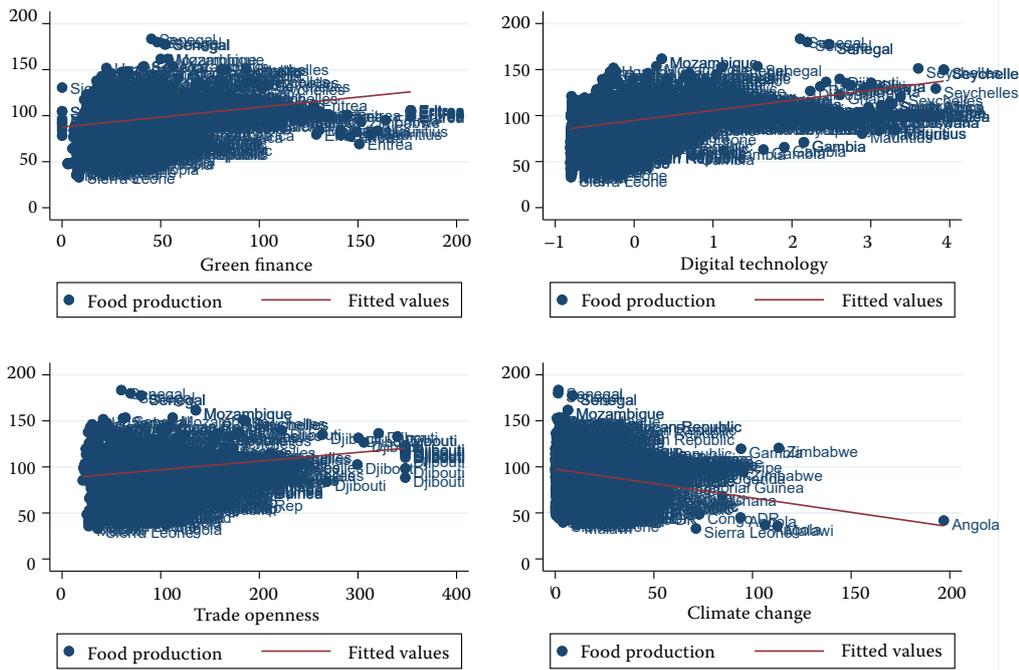


Figure 2. Fitted scatter plots depicting the relationship between the food production and independent variables
Source: Authors' own construction

The study explores these variables' relationships with food security. Figure 2 presents scatter plots of the variables, while Figure 3 shows quantile–quantile (Q–Q) plots assessing data normality.

Control variables

The first control variable, *rural population*, reflects the share of people living in rural areas where agriculture is a primary livelihood. It relates to smallholder farming

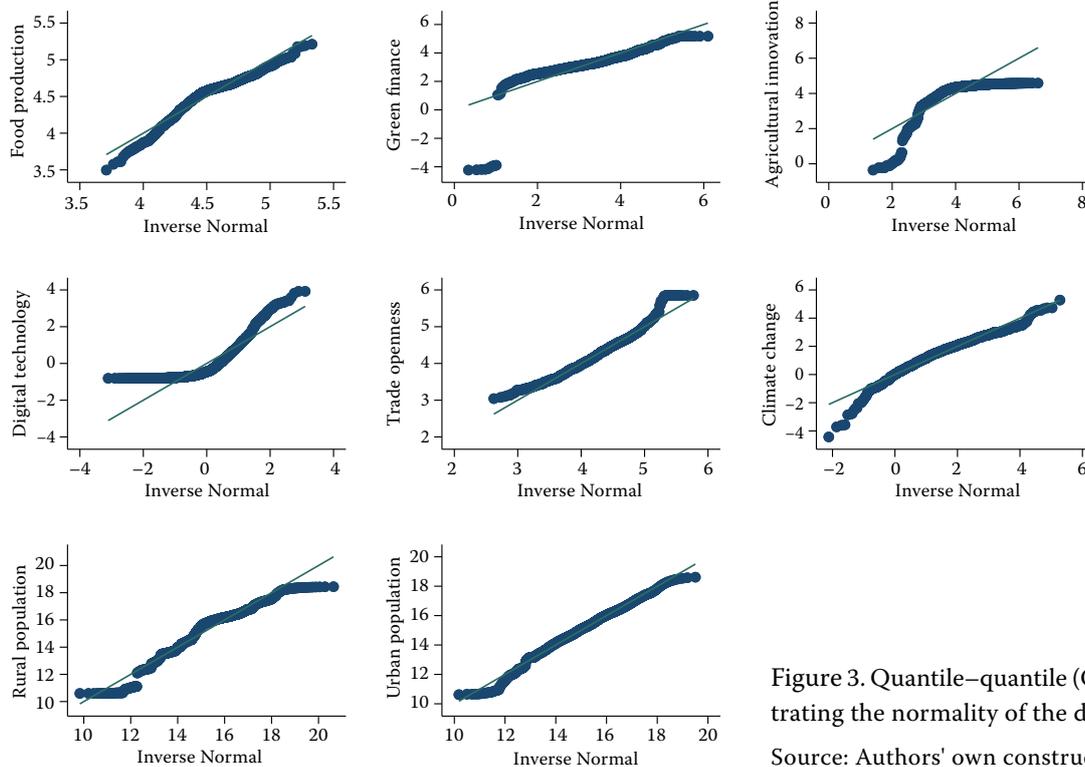


Figure 3. Quantile–quantile (Q–Q) plots illustrating the normality of the data distribution
Source: Authors' own construction

and potential infrastructure challenges affecting food security. The second variable, *urban population*, measures the percentage living in urban areas, which influences food demand, supply chains and prices. Urbanisation may affect agribusiness growth as well as food distribution and access. Both variables are included to explore their demographic effects on food security.

Mediation variables

This study considers R&DS expenditure (% of GDP) as a potential mediator between green finance and food production, given R&D's role in driving innovation, productivity and sustainability. R&D may facilitate climate resilience and adoption of green technologies. Agricultural credit and farmers' education are also examined as mediators of digital technology's impact, with digital finance platforms like mobile banking expanding credit access, and digital education supporting modern farming practices. These factors may influence whether digital technology affects food production directly or indirectly through finance and knowledge. Additionally, foreign direct investment (FDI) in agriculture is explored as a mediator between trade openness and food production, as trade openness can attract FDI, which supports modernisation, infrastructure and technology transfer.

Model specification

Baseline model. In this research, we analyse the following factors to determine the long-term impact of green finance, agricultural innovation, digital technology, trade openness, climate change, rural population, and urban population on food production, as represented in Equation (1).

$$FP = f(GF, AI, DT, TO, CL, RP, UP, \varepsilon) \quad (1)$$

where: *FP* – food production; *GF* – green finance; *AI* – agricultural innovation; *DT* – digital technology; *TO* – trade openness; *CL* – climate change; *RP* – rural population; *UP* – urban population; ε – the error term.

To ensure a more accurate interpretation of the data and address concerns related to heteroscedasticity and multicollinearity, we have transformed all indicators using their natural logarithms which is shown in Equation (2).

$$\begin{aligned} \ln FP_{i,t} = & \beta_0 + \beta_1 \ln GF_{i,t} + \beta_2 \ln AI_{i,t} + \\ & + \beta_3 \ln DT_{i,t} + \beta_4 \ln TO_{i,t} + \beta_5 \ln CL_{i,t} + \\ & + \beta_6 \ln RP_{i,t} + \beta_7 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (2)$$

where: *i* – the 46 SSA countries; *t* – the time period

(2001–2023); β_0 – the intercept; $\beta_1, \beta_2, \beta_3, \dots, \beta_7$ – the coefficient of the independent and control variables, respectively.

Mediation model. To further investigate the underlying mechanisms of key variables, we first examine the mediating role of green finance in food production, as presented in Equations (3 and 4). Second, we assess the mediating effect of digital technology on food production, as outlined in Equations (5–8). Lastly, we explore the mediating role of trade openness in food production, as specified in Equations (9 and 10). Additionally, we analyse the interactions between green finance, digital technology, trade openness, and other key variables in our study.

$$\begin{aligned} \ln RD_{i,t} = & \beta_0 + \beta_1 \ln GF_{i,t} + \beta_2 \ln RP_{i,t} + \\ & + \beta_3 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (3)$$

$$\begin{aligned} \ln FP_{i,t} = & \beta_0 + \beta_1 \ln GF_{i,t} + \beta_2 \ln RD_{i,t} + \\ & + \beta_3 \ln RP_{i,t} + \beta_4 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (4)$$

$$\begin{aligned} \ln AC_{i,t} = & \beta_0 + \beta_1 \ln DT_{i,t} + \beta_2 \ln RP_{i,t} + \\ & + \beta_3 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (5)$$

$$\begin{aligned} \ln FP_{i,t} = & \beta_0 + \beta_1 \ln DT_{i,t} + \beta_2 \ln AC_{i,t} + \\ & + \beta_3 \ln RP_{i,t} + \beta_4 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (6)$$

$$\begin{aligned} \ln EDU_{i,t} = & \beta_0 + \beta_1 \ln DT_{i,t} + \beta_2 \ln RP_{i,t} + \\ & + \beta_3 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (7)$$

$$\begin{aligned} \ln FP_{i,t} = & \beta_0 + \beta_1 \ln DT_{i,t} + \beta_2 \ln EDU_{i,t} + \\ & + \beta_3 \ln RP_{i,t} + \beta_4 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (8)$$

$$\begin{aligned} \ln FDI_{i,t} = & \beta_0 + \beta_1 \ln TO_{i,t} + \beta_2 \ln RP_{i,t} + \\ & + \beta_3 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (9)$$

$$\begin{aligned} \ln FP_{i,t} = & \beta_0 + \beta_1 \ln TO_{i,t} + \beta_2 \ln FDI_{i,t} + \\ & + \beta_3 \ln RP_{i,t} + \beta_4 \ln UP_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (10)$$

where: *RD* – research and development; *AC* – agricultural credit; *EDU* – education; *FDI* – foreign direct investment.

Econometric estimation procedures

In this study, we use the normality test, cross-sectional dependence (CSD), slope heterogeneity test, unit root tests, and cointegration tests to validate the robustness of the empirical analysis concerning the selected variables,

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the results are shown in Tables S3–S7 (ESM) respectively. These statistical techniques ensure that our findings are reliable and accurately reflect the underlying relationships among the variables, confirming the stability and consistency of our data and strengthening the overall integrity of the analysis.

Method of moments quantile regression. Based on the findings of the normality check in Figure 3, the current research observes that the variables are non-normally distributed. Therefore, this study employs the MMQR approach, which extends traditional quantile regression by using moment conditions to estimate parameters across different quantiles (Machado and Santos-Silva 2019). Unlike ordinary least squares, which focuses only on mean effects, MMQR provides a comprehensive analysis of variations across the entire distribution (Machado and Santos-Silva 2019; Bah et al. 2025), making it particularly useful for studying economic and agricultural relationships where key determinants may have different impacts at various performance. Additionally, MMQR effectively handles skewed or heavy-tailed data, common in economic and agricultural research, ensuring robust estimates even amid external shocks, policy shifts, or structural changes (Bah et al. 2025). Its ability to capture nonlinear interactions further enhances its capacity to model complex relationships, accounting for heterogeneity by showing how explanatory variables influence different quantiles (Machado and Santos-Silva 2019). This deeper insight makes MMQR an essential tool for evaluating policy interventions and investment strategies in economic and agricultural sector. The mathematical form of the MMQR test is presented in Equation (11):

$$Q_{y_i}(\tau / X_{it}) = \alpha_i + \delta_i \rho(\tau) + X'_{it} \beta + Z'_{it} \gamma q(\tau) \quad (11)$$

where : $Q_{y_i}(\tau / X_{it})$ – the τ^{th} conditional quantile of the dependent variable y_{it} (food production); i – the 46 SSA countries; t – the time period (2001–2023), given the set of explanatory variables X_{it} ; τ ($0 < \tau < 1$) – the quantile of the conditional distribution being estimated; α_i – the country-specific fixed effects, accounting for unobserved time-invariant heterogeneity across countries; δ_i – the individual-specific coefficient associated with the quantile function $\rho(\tau)$, which is used to estimate the τ^{th} quantile effect; X_{it} – the selected regressors, while X'_{it} is its transpose; β – the corresponding vector of slope coefficients; Z_{it} – an additional vector of explanatory variables, Z'_{it} is its transpose; γ – the associated parameter vector; $q(\tau)$ – function that allows the coefficients related to Z_{it} to vary across different quantiles.

$$\min_q \sum_i \sum_t \rho \tau(A_{it} - (\delta_i + Z_{it} \gamma) q) \quad (12)$$

where: Σ_i and Σ_t – summation over cross-sectional units (countries) and time periods, respectively; $\rho \tau(\cdot)$ – the quantile loss (check) function used in quantile regression estimation; A_{it} – the residual component of the regression.

The quantile loss function is defined in Equation (13):

$$K \rho(A) = (T - 1) AI \{A \leq 0\} + T AI \{A > 0\} \quad (13)$$

To ensure the robustness of the MMQR findings, we also employ the GMM estimation and the panel-corrected standard errors (PCSE) method. GMM is particularly useful for addressing potential endogeneity issues by utilising instrumental variables, thereby providing more consistent and efficient parameter estimates (Arellano and Bond 1991). This is crucial in economic and agricultural studies, where omitted variable bias and simultaneity can affect results. Meanwhile, PCSE accounts for heteroskedasticity and cross-sectional dependence, both common in panel data analysis (Bah et al. 2025). By incorporating these additional methods, we enhance the reliability of our results, ensuring that the observed relationships are not driven by estimation biases or data-specific anomalies.

Dumitrescu–Hurlin panel causality method. Given that causality cannot be inferred from co-integration analysis, this research applied the Dumitrescu–Hurlin panel causality test to determine relationships between the variables (Dumitrescu and Hurlin 2012). This method offers a clearer understanding of how the variables interact, enhancing our ability to forecast trends and identify correlation patterns. By focusing on these causal directions, we aim to provide insights into the dynamics within the data. Equation (14) represents the D–H causality test:

$$\gamma_{it} = \delta_i + \sum_{k=1}^K Y^k Y_{i,t-k} + \sum_{k=1}^K \emptyset^k X_{i,t-k} + \varepsilon_{i,t} \quad (14)$$

where: Y^k and \emptyset^k – the lag and slope parameters that can differ across groups; K – the lag orders, which are assumed to be uniform for all cross-sectional units; δ_i – individual effects that do not change over time.

Furthermore, the null hypothesis of the test asserts that there is no consistent causality throughout the cross-section, whereas the alternative hypothesis suggests that at least one causal relationship exists among

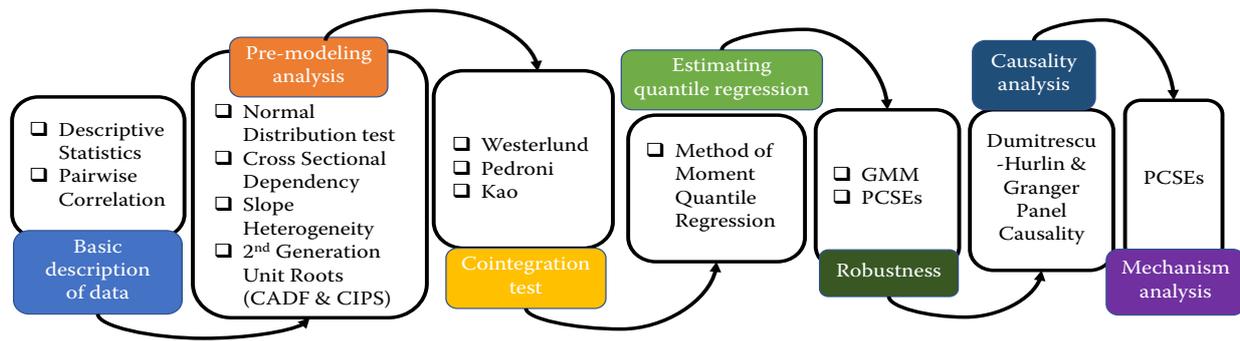


Figure 4. Research estimation flow chart

CADF – Cross-sectionally Augmented Dickey–Fuller (test); CIPS – Cross-sectionally Augmented Im, Pesaran and Shin (panel unit root test); GMM – Generalized Method of Moments; PCSEs – Panel-Corrected Standard Errors

Source: Authors' own construction

the variables. Figure 4 visually presents the estimation procedure utilised in this study.

Principal components analysis

In this research, Principal Component Analysis (PCA) was employed to simplify a complex dataset while retaining essential information. PCA reduces dimensionality by transforming correlated variables into a set of uncorrelated principal components. Using this approach, the researchers constructed a digital technology index, as defined in Equation (15). The results, presented in Table 2, indicate adequate eigenvalues, confirming the index's robustness. Furthermore, the index's validity is supported by a Kaiser–Meyer–Olkin (KMO) value of 0.6005, which

exceeds the recommended threshold. Figure 5 provides a scree plot illustrating the distribution of eigenvalues for the index.

$$Digital\ Technology\ Index_{i,t} = \beta_1 MOB_{i,t} + \beta_2 MPS_{i,t} + \beta_3 SIS_{i,t} + \beta_4 IA_{i,t} + \beta_5 \ln III_{i,t} \tag{15}$$

where: *MOB* – mobile cellular subscriptions (per 100 people); *MPS* – mobile phone subscriptions; *SIS* – secure internet servers (per 1 million people); *IA* – internet accessibility; *III* – the percentage of individuals using the internet (% of the population). β_1 – β_5 – the weights of the components determined by the corresponding eigenvectors of the derived principal components.

Table 2. Principal component analysis results

Variables	Digital technology index				KMO-MSA
	component	eigenvalue	proportion	cumulative	
Mobile cellular subscriptions (per 100 people)	PC1	2.211 31	0.442 3	0.442 3	0.569 6
Mobile phone subscriptions	PC2	1.065 4	0.213 1	0.655 3	0.656 3
Secure Internet servers (per 1 million people)	PC3	0.873 669	0.174 7	0.830 1	0.791 0
Internet accessibility	PC4	0.636 956	0.127 4	0.957 5	0.677 5
Individuals using the Internet (% of population)	PC5	0.212 664	0.042 5	1.000 0	0.574 3
Overall KMO value					0.600 5

PC – principal component; KMO-MSA – Kaiser–Meyer–Olkin measure of sampling adequacy

Source: Authors' own estimation

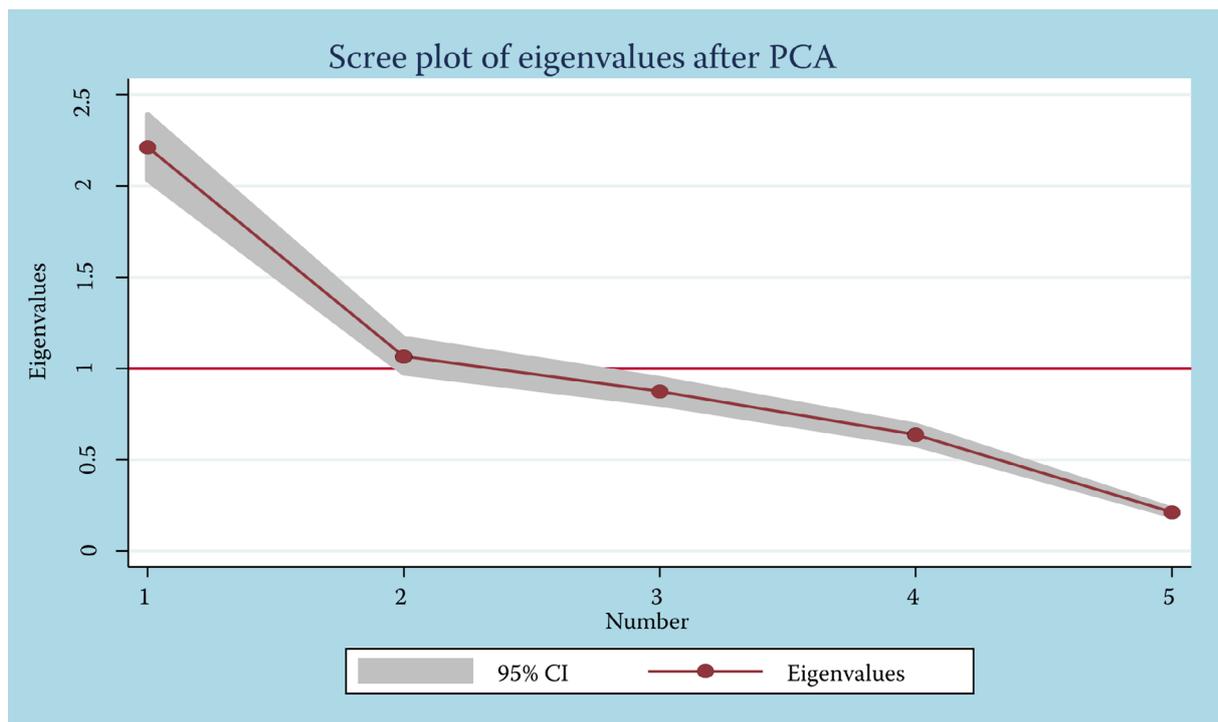


Figure 5. Scree plot depicting the eigenvalue distribution for the digital technology index

CI – confidence interval

Source: Authors' own construction

RESULTS AND DISCUSSION

Direct effect results

The MMQR results presented in Table 3 show that green finance exerts a positive influence on food production across all quantiles, with stronger effects at lower levels of productivity. A 1% increase in green finance raises output by 0.110% at the 10th quantile, 0.056% at the 40th, and 0.023% at the 80th. This pattern indicates that green finance interventions are particularly effective in low performing agricultural regions where financial constraints are more binding. As production increases, the marginal gains tend to diminish, possibly due to improved efficiency or capital saturation. This finding supports the case for prioritising financial support in less productive areas, which aligns with evidence from regions such as SSA and South Asia where green finance has been shown to enhance agricultural performance under credit constraints (Getnet et al. 2025; Massaquoi et al. 2025; Wei et al. 2025).

Agricultural innovation demonstrates a similar but slightly weaker trend. A 1% improvement increases food production by 0.068% at the 10th quantile, 0.049% at the 40th, and 0.037% at the 80th. This result suggests

that innovation is particularly beneficial in regions with low productivity and limited technological diffusion. In contrast, the impact becomes smaller in more developed agricultural sectors where the adoption of existing technologies is already high. These findings are consistent with studies from East Asia and Latin America, which have shown that agricultural innovation yields the largest returns in developing contexts where basic technologies and institutional capacity are still emerging (Marín-García et al. 2025). Therefore, targeted innovation strategies focusing on the development and diffusion of appropriate technologies are crucial to improving productivity in underdeveloped regions.

The results also show that digital technology adoption exerts a significant positive effect across all quantiles, with slightly stronger impacts at higher levels. A 1% increase in digital technology adoption raises production by 0.116% at the 10th quantile, 0.124% at the 40th, and 0.129% at the 80th. This implies that digital tools such as precision agriculture, mobile advisory services, and online market platforms generate greater benefits as agricultural systems become more advanced (Bah et al. 2025). Similar patterns have been observed in Europe and North America, where digitalisation has

Table 3. Method of moment quantile regression result (dependent variable: food production)

Variables	Location	Scale	Lower food production quantiles			Middle food production quantile:		Upper food production quantiles		
			0.10 th	0.20 th	0.30 th	0.40 th	0.50 th	0.60 th	0.70 th	0.80 th
<i>Green finance</i>	0.053*** (0.016)	-0.031*** (0.011)	0.110*** (0.029)	0.083*** (0.022)	0.067*** (0.018)	0.056*** (0.016)	0.045*** (0.015)	0.037*** (0.015)	0.030** (0.014)	0.023* (0.015)
<i>Agricultural innovation</i>	0.048*** (0.011)	-0.011 (0.007)	0.068*** (0.020)	0.059*** (0.015)	0.053*** (0.012)	0.049*** (0.011)	0.045*** (0.010)	0.042*** (0.009)	0.039*** (0.009)	0.037*** (0.011)
<i>Digital technology</i>	0.125*** (0.009)	0.005 (0.006)	0.116*** (0.016)	0.120*** (0.012)	0.123*** (0.010)	0.124*** (0.009)	0.126*** (0.008)	0.127*** (0.008)	0.128*** (0.008)	0.129*** (0.008)
<i>Trade openness</i>	0.087*** (0.017)	-0.035*** (0.012)	0.151*** (0.032)	0.121*** (0.023)	0.103*** (0.019)	0.091*** (0.017)	0.078*** (0.016)	0.069*** (0.015)	0.062*** (0.016)	0.053*** (0.016)
<i>Climate change</i>	-0.017*** (0.006)	0.008* (0.004)	-0.031*** (0.011)	-0.024*** (0.008)	-0.020*** (0.007)	-0.018*** (0.006)	-0.015*** (0.006)	-0.013** (0.005)	-0.011** (0.006)	-0.009 (0.006)
<i>Rural population</i>	0.025** (0.011)	0.022*** (0.008)	-0.014 (0.020)	0.003 (0.015)	0.015 (0.012)	0.022** (0.011)	0.030*** (0.010)	0.036*** (0.009)	0.040*** (0.009)	0.046*** (0.010)
<i>Urban population</i>	-0.029*** (0.012)	-0.021*** (0.008)	0.010 (0.022)	-0.008 (0.016)	-0.019 (0.013)	-0.026** (0.012)	-0.034*** (0.011)	-0.039*** (0.010)	-0.044*** (0.011)	-0.049*** (0.011)
Constants	3.865*** (0.133)	0.439*** (0.092)	3.065*** (0.253)	3.437*** (0.187)	3.660*** (0.155)	3.819*** (0.138)	3.974*** (0.127)	4.084*** (0.123)	4.178*** (0.124)	4.287*** (0.128)
Observations	1 057	1 057	1 057	1 057	1 057	1 057	1 057	1 057	1 057	1 057

***, ** and *significance at 1%, 5% and 10% levels, respectively

Source: Authors' own estimation

enhanced efficiency, improved decision making, and facilitated access to agricultural markets (Shamshiri et al. 2024). The findings highlight the importance of promoting digital technology in regions with the potential to scale and of strengthening institutional support for digital infrastructure and skills development.

Trade openness also contributes positively to food production, although its effect decreases at higher quantiles. A 1% increase in trade openness results in a 0.151% rise at the 10th quantile, 0.091% at the 40th, and 0.053% at the 80th. The relatively stronger effect at lower quantiles reflects the importance of market access, resource allocation, and technology exchange in less integrated regions. In more developed economies, where trade networks are already well established, the marginal benefits are smaller. This result supports findings from other developing regions, including Latin America and SSA, where trade openness has improved agricultural performance by connecting producers to broader value chains and promoting competitive efficiency (Dithmer and Abdulai 2017).

In contrast, climate change negatively affects food production, especially in lower producing regions. A 1% increase in climate variability reduces production by 0.031% at the 10th quantile, and the effect becomes statistically insignificant at higher levels. This indicates that less productive agricultural systems are more vulnerable to climatic shocks due to their limited adaptive capacity. Comparable evidence from West Africa and South Asia suggests that climate change impacts are more severe in regions that rely heavily on rainfed agriculture and lack adequate adaptation mechanisms (Abdullahi et al. 2024; Sinore and Wang 2025). The result reinforces the importance of climate adaptation strategies, including resilient crop varieties, improved irrigation systems, and sustainable land management practices.

The rural population has a mixed but generally positive influence on food production. At the lower quantiles, the effect is insignificant, suggesting that in low productivity regions, population growth does not immediately translate into higher agricultural output. However, from the 40th quantile onwards, the effect becomes positive and

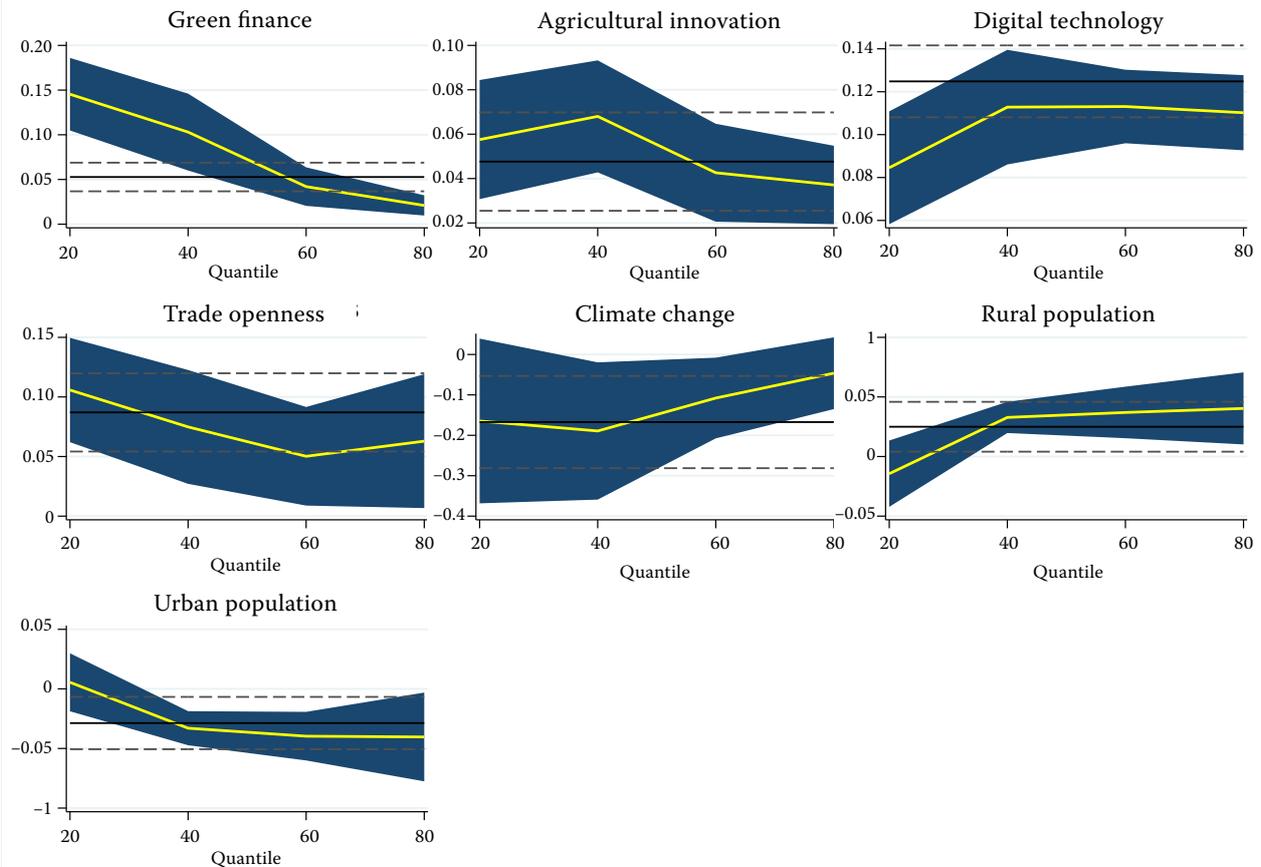


Figure 6. Plot of method of moments quantile regression (MMQR) results highlighting the main findings

Source: Authors' own construction

significant, with a 1% increase in rural population leading to gains of 0.022% and 0.046% at the 40th and 80th quantiles, respectively. This finding implies that rural labour contributes more effectively in regions where agricultural systems are better developed and supported by adequate infrastructure and technology (Huttunen 2019).

By contrast, urban population growth exhibits a more complex and predominantly negative relationship with food production. It is insignificantly positive at the 10th quantile, becomes insignificantly negative at the 20th and 30th, and then significantly negative from the 40th to the 80th quantile. A 1% increase in urban population reduces food production by 0.026% at the 40th quantile and 0.049% at the 80th quantile. This outcome likely reflects the conversion of agricultural land for urban use, shifts in labour away from farming, and changing consumption patterns. Similar dynamics have been reported in rapidly urbanising regions of East Africa and Southeast Asia (Gutu-Sakketa 2023).

The examination of the coefficients related to location effects confirms that most independent variables

display positive and statistically significant relationships with food production, although the strength of these effects varies across quantiles. The positive and statistically significant influence of green finance, agricultural innovation, digital technology, trade openness, and rural population collectively enhances the conditional distribution of food production from the 10th to the 80th quantiles. As illustrated in Figure 6, these results indicate that financial, technological, and institutional factors are fundamental drivers of agricultural performance. However, their effectiveness is not uniform and depends on the existing level of productivity.

Robustness check and endogeneity analysis

To strengthen the robustness of our findings, we introduce three additional dependent variables that reflect the multidimensional nature of food security, using the PCSE model. Relying solely on food production may not fully capture the broader context of food security. Table 4 includes *per capita* food supply as a proxy for food availability, average dietary energy supply adequacy for

Table 4. Robustness check results

Variables	Food production	Food availability	Food accessibility	Food stability
<i>Green finance</i>	0.053*** (0.012)	0.014*** (0.001)	0.008*** (0.000)	0.018 (0.011)
<i>Agricultural innovation</i>	0.048*** (0.008)	0.014*** (0.006)	0.028*** (0.007)	0.059*** (0.015)
<i>Digital technology</i>	0.125*** (0.015)	0.010*** (0.001)	0.021*** (0.003)	0.112*** (0.018)
<i>Trade openness</i>	0.087*** (0.015)	0.017*** (0.001)	0.015*** (0.001)	0.073*** (0.035)
<i>Climate change</i>	−0.017*** (0.008)	−0.002*** (0.000)	−0.004*** (0.001)	−0.019* (0.011)
Control variables	yes	yes	yes	yes
Constants	3.865*** (0.141)	7.505*** (0.006)	15.265*** (0.012)	7.430*** (0.142)
R^2	0.277 6	0.710 8	0.707 0	0.124 1
Observations	1 057	1 057	1 057	1 057
Number of countries	46	46	46	46

***, ** and *significance at 1%, 5%, and 10% levels, respectively

Source: Authors' own estimation

food accessibility, and cereal yields as a measure of food system stability. The results consistently show that green finance, agricultural innovation, digital technology, and trade openness have a positive and significant impact on food production, availability, accessibility, and stability in SSA. In contrast, climate change has a negative effect, reducing all four dimensions across SSA.

Moreover, the MMQR methodology outperforms traditional panel regression models by effectively capturing the heterogeneous relationships between the dependent variable and explanatory factors across different quantiles of food production. This highlights the varying impact of key determinants at different production levels and underscores the importance of adopting a nuanced analytical approach over conventional methods. Table 5 presents the endogeneity test results, examining how the variables of interest affect food production. The Arellano-Bond test for first-order autocorrelation [AR (1)] is highly significant, while the second-order test [AR (2)] and the Hansen test yield P -values above 0.1. These findings confirm that the assumptions of the system GMM model are satisfied, supporting the reliability of the regression estimates.

Dumitrescu–Hurlin panel causality results

Table 6 presents the estimated individual variable causality on food production at the 1% to 5% significance

levels, providing important insights for policymakers in the design of effective strategies to enhance food security in SSA. The Dumitrescu–Hurlin Granger causality analysis reveals bidirectional causal relationships between green finance and food production, agricultural innovation and food production, digital technology and food production, as well as between rural and urban populations and food production. These results suggest that investments and policies targeting these factors not only stimulate agricultural output but also benefit from its expansion, thereby creating a reinforcing cycle of sustainable agricultural development. The bidirectional nature of these relationships highlights the importance of an integrated policy framework that promotes coordination among financial mechanisms, technological advancement, and demographic transformation. Green finance initiatives such as sustainable agricultural credit and climate-smart investments can enhance food production by improving resource efficiency and resilience (Getnet et al. 2025). Likewise, progress in agricultural innovation and digital technology, including precision farming and AI-based analytics, can optimise productivity (Bah et al. 2025), while effective management of rural and urban population dynamics ensures adequate labour supply, improved market access, and equitable resource distribution (Gutu-Sakketa 2023).

Table 5. Endogeneity test results

Variables	One-step system GMM	Two-step system GMM
<i>Food production (-1)</i>	0.515*** (0.124)	0.621*** (0.113)
<i>Green finance</i>	0.285*** (0.101)	0.253*** (0.081)
<i>Agricultural innovation</i>	0.039** (0.020)	0.085** (0.047)
<i>Digital technology</i>	0.076* (0.027)	0.117*** (0.095)
<i>Trade openness</i>	0.058** (0.035)	0.054** (0.028)
<i>Climate change</i>	-0.006 (0.017)	-0.009 (0.013)
<i>Rural population</i>	0.125*** (0.062)	0.073** (0.048)
<i>Urban population</i>	-0.116*** (0.074)	0.062*** (0.036)
<i>Time fixed effect</i>	yes	yes
Observations	1 011	1 011
Number of countries	46	46
Instruments	28	28
Tests (<i>P</i> -values)		
AR1 test	0.000***	0.000***
AR2 test	0.159	0.109
Hansen test	0.292	0.191

***, ** and *significance at 1%, 5%, and 10% levels, respectively

AR1 and AR2 – first and second-order autocorrelation; GMM – generalised method of moments

Source: Authors' own estimation

The findings also indicate unidirectional causality whereby policies aimed at expanding food production contribute to greater trade openness and improved climate change adaptation. Increased food production can strengthen trade competitiveness, reduce dependence on imports, and generate export opportunities, thereby supporting economic stability (Brewer et al. 2023). Although climate change remains a critical challenge, its adverse impact on agricultural output can be mitigated through adaptive measures such as the development of climate-resilient crop varieties, sustainable land-use practices, and the adoption of appropriate technological innovations (Getnet et al. 2025; Sinore and Wang 2025). These results underline the need for a comprehensive and interconnected policy approach that simultaneously addresses economic, technological, environmental, and demographic dimensions. By leveraging these interdependencies, policymakers can formulate strategies that

not only strengthen food security but also foster economic growth, trade expansion, and climate resilience within the agricultural sector.

Mediation and interaction variables effects analysis

Mechanisms and interaction effects of green finance on food production. The findings presented in Table 7 indicate that R&D mediates the relationship between green finance and food production. Green finance positively influences R&D, suggesting that sustainable financial investment promotes innovation and technological advancement. Both green finance and R&D directly enhance food output by 0.068% and 0.038%, respectively, supporting the view that investment in sustainable finance stimulates technological progress that contributes to higher agricultural productivity.

Further analysis of the interaction effects shows that the combination of green finance and R&D increases

Table 6. Dumitrescu–Hurlin (D–H) panel causality finding

Null hypothesis	W-stat.	Z-bar stat.	Prob.	Direction
Green finance \Leftrightarrow Food production	2.954***	9.371	0.000	bidirectional
Food production \Leftrightarrow Green finance	3.518***	12.076	0.000	
Agricultural innovation \Leftrightarrow Food production	2.553***	7.448	0.000	bidirectional
Food production \Leftrightarrow Agricultural innovation	2.718***	8.241	0.000	
Digital technology \Leftrightarrow Food production	1.803***	3.851	0.000	bidirectional
Food production \Leftrightarrow Digital technology	3.611***	12.521	0.000	
Trade openness \Leftrightarrow Food production	1.150	0.719	0.472	unidirectional
Food production \Leftrightarrow Trade openness	2.691***	8.112	0.000	
Climate change \Leftrightarrow Food production	1.513**	2.461	0.014	unidirectional
Food production \Leftrightarrow Climate change	1.012	0.057	0.954	
Rural population \Leftrightarrow Food production	5.863***	23.321	0.000	bidirectional
Food production \Leftrightarrow Rural population	5.756***	22.807	0.000	
Urban population \Leftrightarrow Food production	5.122***	19.769	0.000	bidirectional
Food production \Leftrightarrow Urban population	6.489***	26.327	0.000	

*** and **significance at 1% and 5% levels, respectively; \Leftrightarrow – does not Granger-cause; Prob – probability

Source: Authors' own estimation

food production by 0.057%, emphasising the importance of research-driven innovation in improving agricultural outcomes. The interaction between green finance and digital technology raises food output by 0.021%, highlighting the critical role of digital tools in optimising agricultural processes and resource management. Similarly, when green finance is combined with agricultural innovation, food production rises by 0.025%, underscoring the significance of funding modern agricultural practices such as improved crop varieties, soil enhancement, and sustainable pest management.

Aligning green finance with climate adaptation results in a 0.019% increase in food production. This finding demonstrates that investments in climate-smart

farming practices, including drought-resistant crops and adaptive technologies, enhance the resilience of the agricultural sector to climatic shocks. These results suggest that green finance contributes to food production not only through direct investment but also through its role in facilitating innovation, digital transformation, and climate adaptation.

Mechanisms and interaction effects of digital technology on food production. Table 8 highlights the mediating roles of agricultural credit and farmers' education in the relationship between digital technology and food production. The findings indicate that digital tools significantly enhance access to finance and knowledge, enabling farmers to invest in modern inputs and

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Table 7. The mechanisms of green finance influence research and development, ultimately impacting food production

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	R&D	Food production				
<i>Green finance</i>	1.092*** (0.102)	0.068*** (0.013)	0.062*** (0.012)	0.014*** (0.006)	0.095*** (0.015)	0.092*** (0.016)
<i>R&D</i>	–	0.038*** (0.012)	–	–	–	–
<i>Green finance</i> × <i>R&D</i>	–	–	0.057*** (0.021)	–	–	–
<i>Green finance</i> × <i>digital technology</i>	–	–	–	0.021*** (0.005)	–	–
<i>Green finance</i> × <i>agricultural innovation</i>	–	–	–	–	0.025** (0.002)	–
<i>Green finance</i> × <i>climate change</i>	–	–	–	–	–	0.019* (0.006)
Control variables	yes	yes	yes	yes	yes	yes
Constants	–12.200*** (0.509)	4.453*** (0.111)	4.763*** (0.143)	4.442*** (0.057)	4.418*** (0.125)	4.404*** (0.125)
R^2	0.267 1	0.109 8	0.077 7	0.076 8	0.110 2	0.113 9
Wald χ^2 (3)	4 219.24***	37.79***	32.84***	42.59***	45.74***	41.32***
Observations	1 058	1 058	1 058	1 058	1 058	1 058
Countries	46	46	46	46	46	46

***, ** and *significance at 1%, 5% and 10% levels, respectively

Source: Authors' own estimation

adopt advanced farming techniques. Digital technology directly increases food production by 0.122%, while agricultural credit contributes an additional 0.058%. This outcome demonstrates that technological innovation not only improves production efficiency but also expands financial access, allowing farmers to obtain better inputs and strengthen risk management.

Two key mechanisms are evident in this relationship. The first operates through agricultural credit, where digital platforms facilitate financial inclusion by improving access to loans and payment systems, thereby enabling timely investments in productivity-enhancing resources. The second operates through farmers' education, as digital learning platforms provide real-time agricultural information, technical training, and advisory services that improve knowledge and decision-making (Bah et al. 2025).

The interaction effects provide further insight into the combined influence of digital technology with complementary factors. When digital tools

are integrated with financial services, food production increases by 0.254%, indicating that enhanced financial connectivity supports smallholder farmers in managing risks and stabilising yields. When linked with education, digital technology has the strongest impact, increasing production by 0.733% by improving decision-making on best practices and climate-smart farming techniques (Bah et al. 2025). Furthermore, the combination of digital technology with climate change adaptation raises food production by 0.041%, as tools such as remote sensing, mobile-based weather forecasts, and data-driven advisory systems enable farmers to anticipate and respond effectively to climatic variability.

These findings suggest that digital transformation enhances food production both directly and indirectly through its effects on financial inclusion, knowledge dissemination, and adaptive capacity. Strengthening digital infrastructure, promoting agricultural e-learning, and integrating financial technologies into rural

Table 8. The mechanisms of digital technologies influence agricultural credit and education, impacting food production

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Agricultural credit	Food production	Farmer's education	Food production	Food production	Food production	Food production
<i>Digital technology</i>	0.354*** (0.042)	0.122*** (0.014)	0.028*** (0.002)	0.125*** (0.010)	0.115*** (0.013)	0.105*** (0.010)	0.091*** (0.014)
<i>Agricultural credit</i>	–	0.058*** (0.015)	–	–	0.056*** (0.014)	–	–
<i>Education</i>	–	–	–	0.034*** (0.011)	–	0.037*** (0.018)	–
<i>Digital technology × Agricultural credit</i>	–	–	–	–	0.254** (0.099)	–	–
<i>Digital technology × Education</i>	–	–	–	–	–	0.733*** (0.511)	–
<i>Digital technology × Climate change</i>	–	–	–	–	–	–	0.041*** (0.011)
Control variables	yes	yes	yes	yes	yes	yes	yes
Constants	–6.467*** (0.208)	4.644*** (0.159)	1.495*** (0.039)	4.655*** (0.404)	4.682*** (0.142)	4.742*** (0.046)	4.616*** (0.150)
R ²	0.217 9	0.223 3	0.936 0	0.220 5	0.232 0	0.237 9	0.244 7
Wald chi ² (3)	8 773.55***	81.89***	8 966.37***	472.81***	87.82***	456.47***	90.20***
Observations	1 057	1 057	985	985	1 057	985	1 057
Countries	46	46	46	46	46	46	46

***, ** and *significance at 1%, 5% and 10% levels, respectively

Source: Authors' own estimation

systems can therefore play a pivotal role in achieving sustainable productivity growth.

Mechanisms and interaction effects of trade openness on food production. Table 9 presents evidence of the mediating role of foreign direct investment (FDI) in the relationship between trade openness and food production. The results indicate that trade openness significantly attracts FDI, which facilitates capital inflow, technology transfer, and the exchange of expertise. These processes support modern farming practices, infrastructure development, and improvements in agricultural productivity. The direct effects show that trade openness and FDI increase food production by 0.076% and 0.027%, respectively, demonstrating that international integration and investment play crucial roles in enhancing agricultural output.

The interaction effects further reveal that the combination of trade openness and FDI raises food production

by 0.037%, amplifying productivity gains through increased financial resources and technological advancement. Trade openness also promotes higher agricultural output when aligned with digital technology, resulting in a 0.019% increase in food production. This finding suggests that digital tools improve supply chain efficiency, expand market access, and enhance precision farming, thereby strengthening the positive effects of trade liberalisation on the agricultural sector.

Conversely, when trade openness interacts with climate change, food production declines by 0.026%. This negative effect reflects the increased vulnerability of open economies to external climatic shocks, particularly in regions where agricultural systems depend heavily on natural conditions and lack adequate adaptation mechanisms. The result highlights the potential trade-off between global market exposure and environmental resilience.

Table 9. The mechanisms of trade openness influence foreign direct investment (FDI), which ultimately impacts food production

Variables	(1)	(2)	(3)	(4)	(5)
	FDI in agriculture	Food production	Food production	Food production	Food production
<i>Trade openness</i>	0.894*** (0.079)	0.076*** (0.017)	0.074*** (0.019)	0.036*** (0.013)	0.108*** (0.019)
<i>FDI in agriculture</i>	–	0.027** (0.010)	–	–	–
<i>Trade openness</i> × <i>FDI in agriculture</i>	–	–	0.037** (0.022)	–	–
<i>Trade openness</i> × <i>digital technology</i>	–	–	–	0.019*** (0.005)	–
<i>Trade openness</i> × <i>climate change</i>	–	–	–	–	–0.026** (0.011)
Control variables	yes	yes	yes	yes	yes
Constants	–2.811*** (0.574)	4.295*** (0.128)	4.298*** (0.127)	4.148*** (0.116)	4.284*** (0.138)
R^2	0.163 4	0.055 7	0.055 8	0.099 6	0.069 6
Wald chi ² (3)	284.66***	32.14***	32.18***	32.62***	36.09***
Observations	1 058	1 058	1 058	1 058	1 058
Countries	46	46	46	46	46

*** and **significance at 1% and 5% levels, respectively

Source: Authors' own estimation

These findings suggest that trade openness contributes to food production through its capacity to attract FDI and foster digital integration; however, it can also heighten sensitivity to climate risks. Consequently, trade policies should aim to promote sustainable investment, strengthen digital infrastructure, and enhance adaptive capacity through the adoption of resilient crop varieties, sustainable land management, and climate-smart agricultural practices.

CONCLUSION

Food insecurity continues to pose a significant challenge in SSA, intensified by the adverse effects of climate change and rapid population growth. This study evaluates the influence of green finance, agricultural innovation, digital technology, trade openness, and climate change on food production across 46 SSA countries over the period 2001 to 2023. Rural and urban population growth are included as control variables, while mediating effects are analysed through R&D, FDI, farmer education, and agricultural credit.

The findings contribute to theoretical understanding through the application of sustainable development

theory, innovation diffusion theory, climate resilience theory, and trade liberalisation theory. First, the results affirm sustainable development theory by demonstrating that green finance significantly enhances food production, particularly in countries with low agricultural productivity. This suggests that financial instruments aimed at environmentally sustainable agriculture can generate broad productivity gains. Crucially, the analysis identifies a mediation pathway in which green finance stimulates R&D activities, which, in turn, improve innovation capacity and agricultural efficiency. This confirms that the effects of green finance are not limited to direct funding of agricultural inputs but extend to enabling systemic innovation. However, the declining marginal effect in higher-performing regions indicates that green finance delivers the most value in addressing structural deficiencies, consistent with the theory's emphasis on equity and strategic resource allocation. Second, the evidence supports innovation diffusion theory by showing that agricultural innovation and digital technology significantly enhance food production, especially in less developed contexts. These technologies are mediated through farmer education and agricultural credit, which facilitate adoption

and scale-up. Digital platforms also serve as enablers of information flow and service delivery, aligning with the theory's emphasis on institutional support in facilitating diffusion processes. Third, the results align with climate resilience theory by showing that climate change exerts a negative impact on food production, especially in vulnerable areas. Nevertheless, the study reveals a reinforcing dynamic: as agricultural output increases, resilience capacity also improves. This reflects a feedback mechanism through which increased productivity supports adaptive strategies such as conservation agriculture, irrigation, and the use of climate-resilient crop varieties. Fourth, trade liberalisation theory is validated by the positive association between trade openness and food production, particularly in countries with lower output. Trade integration fosters technology transfer and market access, while FDI acts as a mediation channel that strengthens agricultural infrastructure and capacity. However, the reduced effect of trade openness at higher production levels implies that institutional and policy conditions moderate its efficacy. Fifth, the study highlights reciprocal relationships whereby improvements in food production also enhance trade integration and support climate adaptation. These bidirectional dynamics suggest that food production is both shaped by and a driver of broader structural transformation in the region.

Policy implications emerge clearly from these findings. First, governments should expand access to green finance in low-performing sectors and strengthen its links with R&D. Second, investing in digital infrastructure and farmer education will accelerate innovation uptake. Third, trade policies must lower barriers and enhance institutions to attract investment. Fourth, agricultural planning must include climate resilience strategies, such as improved irrigation and early warning systems. Finally, balanced rural and urban development policies are essential to preserve farmland, improve labour productivity, and secure long-term food systems in SSA.

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