Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Enhancing food security in sub-Saharan Africa: Investigating the role of environmental degradation, food prices, and institutional quality

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ARTICLE INFO

Keywords:
Food production
Food security
Environmental degradation
Institutional quality
Food inflation

ABSTRACT

In an era of global environmental challenges, understanding the dynamics of food production is crucial, particularly in regions prone to food insecurity and susceptible to climatic variations. Despite extensive research on agriculture in sub-Saharan Africa (SSA), a thorough examination of the combined effects of various determinants, including food prices and institutional quality, on food security remains limited. Using panel data from 2002 to 2020, this study explores the effects of agricultural land, population growth, environmental degradation, income per capita, food prices, capital formation, and institutional quality on food security in 32 SSA countries. Based on the Pedroni and Kao cointegration test outcomes, a long-run correlation between food security and its influencing factors is evident. The findings from the pooled mean group (PMG) models reveal that extended agricultural land leads to enhanced food security both in the short- and long-run. Likewise, population expansion, rising per capita income, and capital formation drive higher food demand, contributing positively to food security outcomes. Conversely, environmental degradation poses a significant threat, impairing food security in the SSA. Mixed results are observed with food prices, where higher prices can both enhance and reduce food security. The poor institutional quality in SSA correlates with food insecurity. Importantly, the Dumitrescu–Hurlin causality test results reveal bidirectional causality between food security and most variables, except for food inflation and institutional quality. The method of moments quantile regression (MMQR) strengthens the robustness of the study findings. Building on these insights, the study recommends focusing on sustainable land use practices, effective environmental management strategies, increased agricultural investment, governance reforms, and implementing balanced pricing mechanisms.

1. Introduction

Food security remains a prominent global concern, as asserted in Sustainable Development Goal 2 of the 2030 Agenda. The goal of ending hunger, food insecurity, and undernutrition has been the focus of recent studies [1,2]. Ensuring access to food and its availability is vital for enhancing human development and potential, as it plays a critical role in strengthening human capabilities [3]. Numerous interrelated variables, including population expansion, climatic issues, conflicts, and land degradation, have threatened global food security [4,5]. Since the beginning of the industrial age, greenhouse gas (GHG) emissions have increased, resulting in greater radiative force that affects the atmosphere, leading to the warming of the earth's surface and climatic changes [6]. Consequently, elevated air temperatures, heavy rainfall, and prolonged droughts affected water availability and agricultural yield, ultimately leading to a reduction in food availability and compromising food security [7]. Environmental shifts greatly affect the lives of rural residents, particularly in sub-Saharan Africa (SSA), who rely predominantly on agriculture for sustenance [8]. Hence, recognizing and adopting sustainable development strategies is essential to ensuring food security and self-reliance within the agricultural sector while also meeting the growing need for food in the face of land degradation [9].

Evaluating food security is crucial for aid, famine risk monitoring, nutrition assessment, and policy shaping, requiring global attention from professionals, policymakers, and researchers [10]. As FAO et al. [11] highlight, food security is a binary state—a person can be either food-secure or insecure. Food security has continuously acquired prominence and economic relevance since the 1974 World Food Conference, which focused heavily on issues related to hunger, famine, and the food crisis [12,13]. Although the description of food security has developed over time, it continues to denote a condition where all

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https://doi.org/10.1016/j.jafr.2024.101241
Received 6 February 2024; Received in revised form 24 May 2024; Accepted 1 June 2024

individuals consistently possess physical, social, and economic access to sufficient, nutritionally adequate food that meets their dietary preferences and requirements, enabling them to maintain active and healthy lifestyles. The four main pillars of this comprehensive definition are utilization, affordability, stability, and availability [14,15]. The declining production of major food crops due to environmental degradation has food security implications in low-income countries [2]. Besides, Pérez-Escamilla [16] points out that inadequate food has harmful consequences for physical, emotional, and cognitive well-being, disrupting social and environmental balance with far-reaching implications. Additionally, Burchi and De Muro [17] suggested that inadequate education, health, and essential life skills can contribute to food insecurity.

Over the past decade, conflicts, climate change, and economic downturns have worsened global food security and nutritional well-being in low- and middle-income nations [5,18]. According to the Global Report on Food Crises (GRFC) [19], the world's hunger rate in 2021 broke all previous records and remains frighteningly high. Approximately 193 million individuals across 53 countries and territories are grappling with severe food insecurity, necessitating urgent interventions. This represents a stark increase of about 40 million people compared to peak levels in 2020 (GRFC and WFP, 2022). In SSA, where high malnutrition rates and low incomes prevail, an estimated 123 million people, constituting 12 % of the total population, were projected to experience severe food insecurity in 2022 [20]. In violent regions of SSA, conflict and institutional fragility significantly threaten food security, with long-term disruptions in food prices lasting years compared to short-term weather-induced price variations [21,22]. According to FAO (2023), approximately 22.5 percent of SSA's population experienced hunger in 2022, reflecting a notable increase compared to other regions. Latin America and the Caribbean had a hunger rate of 6.5 percent, while Asia recorded a rate of 8.5 percent during the same period, which highlights the disparities in the prevalence of undernourishment across regions.

The recent surges in global commodity prices of energy and food items have affected food prices in SSA, especially during the latter half of 2021 and into 2022. Due to Russia's military invasion of Ukraine, significant agricultural commodities like wheat and maize were no longer readily available on a worldwide scale, which increased global food prices [23–25]. In addition, Zhou and Wan [26] and Chavas [27] have demonstrated that rising food prices reduce families' purchasing power, ultimately resulting in a decline in household food security status. Between 2019 and 2021, SSA's undernourishment rate increased by 46 million people, driven by domestic and global shocks [28]. While climate change generally affects global food production, its impacts are unevenly distributed across regions. This impact is expected to worsen food insecurity in developing countries, where a considerable segment of the populace already struggles with ongoing hunger and malnutrition [29]. Additionally, climatic modifications have influenced the production patterns of agricultural goods, becoming a significant factor in the escalating food insecurity in SSA nations. In 2014–2015, approximately one out of every nine individuals globally, and around a quarter of the population in SSA, faced challenges in fulfilling their dietary needs [30]. Being vital for sustaining and enhancing human well-being through food production, the agriculture sector has garnered considerable focus in discussions related to climate change [31].

The scientific explorations observed that the ramifications of climate change on the yield of diverse food crops are deeply consequential [32–35]. Numerous studies have elucidated the detrimental correlation between climate change and food security [34,36–39]. According to Karimi et al. [40] and Costa [41], alterations in temperature and precipitation patterns directly affect crop output and food security. The studies in this area encompass the effects of climate change on rice [42], maize and wheat [43], and potatoes and barley [44]. These authors propose that climate change may harm agricultural growth and production across different regions. Concerning the effects of climate change on food security within specific countries, various researchers have focused their studies on different regions, including Edoja et al. [45] in Nigeria, Warsame et al. [35] in Somalia, Aggarwal et al. [46] in India, Murray-Tortarolo et al. [47] in Mexico, Moonen et al. [48] in Italy, and Chmielewski et al. [49] in Germany. According to this research, climate change appears to influence agricultural productivity substantially. Besides, Gunasekera et al. [50] revealed that an increase in land productivity could elevate Africa's share of global agricultural production and exports, particularly in commodities like cotton, sugar, and oilseeds.

Considering that agriculture in SSA appears to be rain-fed, any fluctuations in the region's climate might make food production unpredictable [47,51]. Given its extensive arable land and employing over half its population, agriculture is pivotal for SSA's growth and food security [7]. Nonetheless, productivity has stagnated since the 1980s, resulting in insufficient food output and low-value products [52]. The incremental growth in food production within SSA, with an annual increase of less than 1 %, raises concerns regarding its capacity to safeguard against food insecurity, suggesting a potential necessity for both importation and production enhancement [53]. Several studies across SSA, such as Ngoma et al. [54] in Zambia, Abdi et al. [2] in Somalia, and Edoja et al. [45] in Nigeria, indicate that climate change causes crop loss, livelihood disruption, an increase in food insecurity, and a decrease in agriculture's contribution to the nations' output level. Moreover, environmental degradation can directly and indirectly impact food security by altering crop productivity, farmland utilization, and the susceptibility of the food system [55,56]. Despite the recognized importance of sustainable food production and innovative farming techniques in enhancing food security, there remain notable gaps in the body of current literature within the framework of SSA. To address this literature gap, the main aim of this study is to investigate the factors influencing food security in SSA, utilizing panel data spanning from 2002 to 2020.

This study significantly enhances the existing body of knowledge on food security in sub-Saharan Africa by addressing critical gaps in cross-country research and introducing comprehensive methodologies. Firstly, existing research on food security in SSA typically examines isolated factors such as climate change and economic crises [7,54]. However, it often lacks a holistic analysis that explores the interconnections of these factors across different countries within the region. By incorporating diverse variables, including food prices, gross capital formation, and institutional quality, this undertaking offers pioneering empirical insights into the determinants of food security in the SSA region. This approach highlights the complexities of food security and addresses the region-specific challenges that affect productivity and economic access to food resources. Secondly, temperature and carbon emissions have been widely employed as climate change proxies in most research, given the lesser significance of CO_2 emissions in SSA countries (Abdi et al., 2021). The diverse climatic zones within SSA – from the arid deserts of the Sahel to the tropical forests of the Congo Basin – present unique challenges to maintaining and enhancing food security. Since understanding the varied impacts of climate change on food security has become essential, this study uses GHG emissions, which offer a broader perspective on global warming contributors, including methane and nitrous oxide.

In addition, previous studies frequently suffered from methodological limitations, such as ignoring heterogeneity and cross-sectional dependencies among countries. These oversights can skew results and lead to ineffective policy prescriptions [57]. By adopting advanced heterogeneous panel methodologies, including pooled mean group (PMG), mean group (MG), method of moments quantile regression (MMQR), and the Dumitrescu and Hurlin [58] panel causality test, this study ensures the robustness of the findings to enhance their reliability for policy formulation. Finally, this study equips policymakers with empirical insights to enhance agricultural productivity and tackle food security challenges in the SSA. This understanding can inform policies for improved irrigation, subsidized farm inputs, and climate-smart agriculture tailored to regional conditions. Additionally, it informs strategies to optimize resource management, enhance food distribution networks, and develop resilient food systems capable of withstanding shocks, ensuring sustainable farming and reliable food access across the SSA.

2. Materials and methods

2.1. Sampling, variables, and data sources

This undertaking uses annual panel data to examine the factors influencing food security in 32 sub-Saharan African (SSA) countries from 2002 to 2020. The SSA nations in the analysis were selected due to the profound implications of environmental degradation on their food output in recent years. According to Abdi et al. [21] and Adhikari et al. [59], these countries have been subject to altered crop yields because of shifting weather patterns, rising temperatures, and increased disease incidence. Furthermore, water scarcity and food insecurity have been exacerbated by environmental deterioration. In this study, food security serves as the dependent variable. The independent variables include agricultural land, population growth, GHG emissions, GDP per capita, food prices, gross capital formation, and institutional quality. Data for these variables were sourced from the World Development Indicators (WDI), the Food and Agriculture Organization (FAO), and the Worldwide Governance Indicators (WGI). The sample period was chosen based on data availability, noting that some countries lacked data before 2002.

2.2. Variables description

In this study, food security (FS) is the outcome variable. It is derived from the food production index, which measures aggregate food output relative to the baseline period of 2014–2016. The index provides a comprehensive assessment of food security in the selected SSA countries, reflecting the heavy reliance of the population on agriculture for sustenance and livelihood. In addition, the sampling frame for agricultural land (AL) includes the total land area dedicated to cereal production in hectares. This variable captures the scale of arable land used for cereal cultivation. Previous studies have consistently highlighted the pivotal role of land in food production and its potential to enhance Africa's food security [50,60]. Moreover, population growth (PG) is represented by the annual percentage change in population size within the investigated countries. This variable reflects the demographic dynamics and potential increases in food demand over time, contributing to food security [61,62]. The sampling frame for environmental degradation (ED) comprises total GHG emissions measured in kilotons of CO_2 equivalent. This variable serves as a proxy for environmental degradation, reflecting the pollution level and its impact on food production [32,45].

Economic growth (EG) is measured by GDP per capita in constant 2015 US dollars. This variable indicates the average individual's purchasing power within the selected countries, which is essential for assessing their ability to afford food. Notably, GDP per capita contributes positively to food security by improving people's ability to afford food [61]. Besides, food prices (FP) are represented by the percentage of yearly food inflation. This variable reflects economic pressures on food production and access, as rising prices significantly diminish household purchasing power [22,26]. Additionally, the sampling frame for gross capital formation (GCF) includes investment levels in each country measured in constant 2015 US dollars. This variable indicates the extent of agricultural infrastructure and technology investment within the selected SSA countries, thereby playing a crucial role in influencing agricultural productivity and food security. Notably, institutional quality (IQ) is measured as an estimate of regulatory quality, reflecting the effectiveness of government policies facilitating agribusiness within the selected SSA countries. The estimates range from approximately −2.5 (weak) to 2.5 (strong) governance performance. Effective governance can lead to increased agricultural productivity and improve the availability of nutritious food [63,64].

2.3. Econometric model

The current research follows the modeling framework adopted by Fagbemi et al. [65], Segbefia et al. [66], and Abdi et al. [21]. Consequently, this study employs the following panel data models to investigate the influence of agricultural land, population growth, environmental degradation, economic development, food prices, capital formation, and the quality of institutions on food security in SSA countries.

$$FS_{it} = \alpha_0 + \psi_1 AL_{it} + \psi_2 PG_{it} + \psi_3 ED_{it} + \psi_4 EG_{it} + \psi_5 FP_{it} + \mu_{it} \quad (1)$$

$$FS_{it} = \alpha_0 + \psi_1 AL_{it} + \psi_2 PG_{it} + \psi_3 ED_{it} + \psi_4 EG_{it} + \psi_5 FP_{it} + \psi_6 GCF_{it} + \mu_{it} \quad (2)$$

$$FS_{it} = \alpha_0 + \psi_1 AL_{it} + \psi_2 PG_{it} + \psi_3 ED_{it} + \psi_4 EG_{it} + \psi_5 FP_{it} + \psi_6 GCF_{it} + \psi_7 IQ_{it} + \mu_{it} \quad (3)$$

where FS represents food security, AL denotes agricultural land, PG for population growth, ED symbolizes environmental degradation, EG embodies economic growth, FP signifies food price inflation, GCF stands for gross capital formation, and IQ reflects institutional quality. To reduce heterogeneity issues common in diverse panel data and interpret series as percentages, a logarithmic transformation was applied to all variables, except food prices and institutional quality, yielding the modified equation:

$$\ln FS_{it} = \alpha_0 + \psi_1 \ln AL_{it} + \psi_2 \ln PG_{it} + \psi_3 \ln ED_{it} + \psi_4 \ln EG_{it} + \psi_5 FP_{it} + \mu_{it} \quad (4)$$

$$\ln FS_{it} = \alpha_0 + \psi_1 \ln AL_{it} + \psi_2 \ln PG_{it} + \psi_3 \ln ED_{it} + \psi_4 \ln EG_{it} + \psi_5 FP_{it} + \psi_6 \ln GCF_{it} + \mu_{it} \quad (5)$$

$$\ln FS_{it} = \alpha_0 + \psi_1 \ln AL_{it} + \psi_2 \ln PG_{it} + \psi_3 \ln ED_{it} + \psi_4 \ln EG_{it} + \psi_5 FP_{it} + \psi_6 \ln GCF_{it} + \psi_7 IQ_{it} + \mu_{it} \quad (6)$$

In this equation, α_0 is the intercept, ψ_1 through ψ_7 are the coefficients of the respective variables, with agricultural land, population growth, economic prosperity, capital formation, and institutional quality expected to positively enhance food security, while environmental degradation and food prices are anticipated to reduce them. The term μ denotes the white noise error component. Utilizing a panel dataset from 32 nations with individual units $i = 1, 2, 3 \ldots, N$ over time periods $t = 1, 2, 3 \ldots, T$.

2.4. Empirical strategy

2.4.1. Cross-sectional dependence and heterogeneity tests

Analyzing cross-sectional dependencies (CD) is a critical step before selecting an appropriate method for econometric modeling, mainly due to the potential correlations in panel data from interconnected countries with regional ties [67]. Typically, methodologies for testing series models fail to address CD, resulting in misleading interpretations and biased results [66]. The emergence of the CD issue is attributed to unobservable factors common across cross-sectional units, causing interlinkages among them. To address the possibility of CD in our panel data study, we first conducted the Pesaran CD test to assess the interdependencies among the cross-sections involved. Pesaran [68] is widely used for its flexibility and applicability across various panel dimensions. It evaluates the null hypothesis, which posits the absence of cross-sectional dependence, against the alternative hypothesis, which suggests the presence of such dependence. Within the framework of balanced panel data, the cross-sectional dependence (CD) statistic proposed by Pesaran can be calculated in equation (7) as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\varphi_{ij}\right)\xrightarrow{d}N(0,1) \tag{7}$$

where N represents the number of observations and T denotes the time period, while φ_{ij} refers to the estimated pairwise correlation coefficients between countries i and j.

In the analysis of panel data, it is also essential to verify the homogeneity of slope coefficients following the CD test. Failure to do so may overlook important country-specific characteristics [69]. The Pesaran and Yamagata [70] test is extensively adopted to investigate whether slope coefficients exhibit heterogeneity. The null hypothesis of this test assumes that slope coefficients are consistent across all units, emphasizing the importance of evaluating the uniformity within the dataset to prevent the exclusion of unique national attributes. The test for homogeneity employs a standardized dispersion statistic, denoted as:

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S}-k}{\sqrt{2K}}\right) \tag{8}$$

where k represents the number of regressors and $\widetilde{S}$ is the adjusted Swamy test statistic. The $\widetilde{\Delta}$ test adheres to an asymptotic standard normal distribution, predicated on the null hypothesis that the error terms conform to a normal distribution, with the presupposition of infinitely large sample sizes (N, T → ∞). For smaller samples, the test is modified to:

$$\widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S}-E(\widetilde{Z}_{iT})}{\sqrt{Var\ (\widetilde{Z}_{iT})}}\right) \tag{9}$$

where $E(\widetilde{Z}_{iT}) = k$, and $Var\ (\widetilde{Z}_{iT}) = 2k(T-k-1)/(T+1)$, to accommodate the finite sample size.

2.4.2. Second-generation unit root test

The presence of cross-sectional dependence significantly impacts the reliability of first-generation panel unit root tests, which assume cross-sectional independence, potentially leading to inaccurate estimates [21]. This necessitates the use of second-generation panel unit root tests, such as the Cross-sectional Augmented Dickey-Fuller (CADF) and the Augmented Cross-sectional Im, Pesaran, Shin (CIPS) tests, as recommended by Pesaran [71]. These tests are designed to accommodate the interdependencies among panel units and the influence of unobserved common factors, ensuring precise and reliable evaluation of variables' stationarity and integration order when cross-sectional dependence is detected. By focusing on the relevant parameters, both tests compare the data to the alternative hypothesis, which states that the data are stationary, with the null hypothesis stating that all variables have a unit root. Initial estimations for the CIPS test are based on the CADF model, with the CIPS statistic calculated from the CADF statistic values for each cross-sectional unit:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N}CADF \tag{10}$$

Therefore, the null hypothesis is rejected when probability values fall below the significant thresholds of 1 %, 5 %, and 10 %. This feature distinguishes the panel autoregressive distributed lag (ARDL) model from conventional panel cointegration approaches, as it possesses the flexibility to accommodate variables with differing levels of integration.

2.4.3. Panel cointegration test

Before assessing long-run relationships between variables, it is crucial to investigate their cointegration potential. The Pedroni [72,73] test is adopted for this undertaking to explore the long-run linkage between the scrutinized variables and food security. The Pedroni test uniquely accommodates heterogeneity by incorporating panel-specific fixed effects and time trends in the cointegration regression, allowing for the autoregressive (AR) coefficient to differ across panels. The Pedroni panel cointegration approach can be presented as follows:

$$Y_{it} = \varphi_i + \gamma_{1i}X_{it} + \gamma_{2i}X_{2it} + \ldots\ldots\gamma_{pi}X_{pit} + \mu_{it} \tag{11}$$

where φ_i and γ_i represent the intercepts and slope coefficients, which are allowed to differ among cross-sections. It is posited that Y, X, and p have identical integration order of I (1). According to the null hypothesis asserting the absence of cointegration, the residuals μ_i would be integrated at I (1). To complement the Pedroni test, the study also employs the Kao [74] cointegration test, which considers both heterogeneity and cross-sectional dependence in assessing cointegration among variables under investigation. Both methods evaluate the null hypothesis of no cointegration against an alternative hypothesis indicating the presence of cointegration, with the hypothesis being rejected at significant probability levels of 1 % and 5 %, thereby indicating a cointegration relationship among the variables.

2.4.4. Long-run estimation approach

This investigation adopts the heterogeneous panel analysis methodologies proposed by Pesaran et al. [75] and Pesaran [68], including the mean group (MG) and pooled mean group (PMG) approaches, to examine the dynamic interrelations among variables across different countries. The PMG approach assumes uniformity in long-run parameters across different country groups while permitting variations in short-run slope coefficients among countries. This makes PMG a robust and efficient method for estimation in scenarios where long-run homogeneity exists. On the other hand, the MG method proves more suitable for situations where slope coefficients and constants exhibit differences across various country groups. To verify the reliability of PMG and MG estimations, the Hausman [76] test is employed. It is worth mentioning that PMG can handle variables that are either integrated at first difference I (1) or stationary at level I (0), or both. Based on the empirical framework by Fagbemi et al. [65] and Abdi et al. [21], this research employs the following panel autoregressive distributed lag (ARDL) models:

$$\begin{aligned}\Delta lnFS_{it} &= \alpha_0 + \psi_1 lnFS_{it-1} + \psi_2 lnAL_{it-1} + \psi_3 lnPG_{it-1} + \psi_4 lnED_{it-1}\\ &+ \psi_5 lnEG_{it-1} + \psi_6 FP_{it-1} + \sum_{i=1}^{p}\Omega_1\Delta lnFS_{it-k} + \sum_{i=1}^{q}\Omega_2\Delta lnAL_{it-k}\\ &+ \sum_{i=1}^{q}\Omega_3\Delta lnPG_{it-k} + \sum_{i=1}^{q}\Omega_4\Delta lnED_{it-k} + \sum_{i=1}^{q}\Omega_5\Delta lnEG_{it-k}\\ &+ \sum_{i=1}^{q}\Omega_6\Delta FP_{it-k} + \mu_i + \varepsilon_t\end{aligned} \tag{12}$$

$$\begin{aligned}\Delta lnFS_{it} &= \alpha_0 + \psi_1 lnFS_{it-1} + \psi_2 lnAL_{it-1} + \psi_3 lnPG_{it-1} + \psi_4 lnED_{it-1}\\ &+ \psi_5 lnEG_{it-1} + \psi_6 FP_{it-1} + \psi_7 lnGCF_{it-1} + \sum_{i=1}^{p}\Omega_1\Delta lnFS_{it-k}\\ &+ \sum_{i=1}^{q}\Omega_2\Delta lnAL_{it-k} + \sum_{i=1}^{q}\Omega_3\Delta lnPG_{it-k} + \sum_{i=1}^{q}\Omega_4\Delta lnED_{it-k}\\ &+ \sum_{i=1}^{q}\Omega_5\Delta lnEG_{it-k} + \sum_{i=1}^{q}\Omega_6\Delta FP_{it-k} + \sum_{i=1}^{q}\Omega_7\Delta lnGCF_{it-k} + \mu_i + \varepsilon_t\end{aligned} \tag{13}$$

$$\Delta lnFS_{it} = \alpha_0 + \psi_1 lnFS_{it-1} + \psi_2 lnAL_{it-1} + \psi_3 lnPG_{it-1} + \psi_4 lnED_{it-1} + \psi_5 lnEG_{it-1} + \psi_6 FP_{it-1} + \psi_7 lnGCF_{it-1} + \psi_8 IQ_{it-1} + \sum_{i=1}^{p} \Omega_1 \Delta lnFS_{it-k} + \sum_{i=1}^{q} \Omega_2 \Delta lnAL_{it-k} + \sum_{i=1}^{q} \Omega_3 \Delta lnPG_{it-k} + \sum_{i=1}^{q} \Omega_4 \Delta ln\, ED_{it-k} + \sum_{i=1}^{q} \Omega_5 \Delta lnEG_{it-k} + \sum_{i=1}^{q} \Omega_6 \Delta FP_{it-k} + \sum_{i=1}^{q} \Omega_7 \Delta lnGCF_{it-k} + \sum_{i=1}^{q} \Omega_8 \Delta lnGCF_{it-k} + \quad (14)$$

where α_0 denotes the intercept, ψ encapsulates the long-run coefficient, Ω signifies the coefficient for short-run variables, p and q are the lag orders, Δ represents the first difference operator, ε_t is the error component, and μ_i reflects the country-specific influences.

2.4.5. Panel causality technique

The Dumitrescu and Hurlin [58] causality test evaluates non-causality within heterogeneous panel data models with constant coefficients. This focuses on the causal interactions among variables such as agricultural land, population growth, environmental degradation, economic growth, food prices, capital formation, institutional quality, and food security in SSA countries. The objective is to delineate the causal relationships within the specified variables, underscoring the test's effectiveness in diverse panel configurations. Recognized for its adaptability, the test is applicable across heterogeneous panels, irrespective of the N being greater or smaller than the T. This method acknowledges the potential for causation in specific panel segments (Lopez & Weber, 2017). The operational framework and mathematical expression of the Dumitrescu–Hurlin causality test are elucidated in the following equation (15):

$$y_{it} = \alpha_i + \sum_{n=1}^{M} \delta_i^{(n)} y_{i,t-n} + \sum_{n=1}^{M} \varphi_i^{(n)} x_{i,t-n} + \varepsilon_{i,t} \quad (15)$$

where $\delta_i^{(n)}$ and $\varphi_i^{(n)}$ represent the lag and slope parameters that differ among groups, M denotes the lag orders assumed to be uniform across all cross-sectional units, and α_i signifies individual effects that are constant over time. Additionally, the null hypothesis of the test posits the absence of uniform causality across the entire cross-section, whereas the alternative hypothesis indicates the presence of at least one causal relationship between the variables.

3. Analysis and discussion

3.1. Descriptive statistics and correlation analysis

The statistical properties of the dataset, along with the correlation analysis, are detailed in Table 1. In panel A, the descriptive summary sheds light on each variable's central tendencies, variability, and distributional properties. The mean values vary across variables, revealing that lnGCF has the highest mean (21.473) while IQ has the lowest (−0.671), indicating weak institutional structures. Moreover, the average values of lnFS, lnAL, and lnED are 4.488, 13.572, and 9.793, respectively. The standard deviation reveals a substantial deviation from the mean for FP (10.684). However, lnFS presents a value of about 0.235, suggesting relatively limited variability. In terms of extremes, variables like FP exhibit substantial differences between their maximum and minimum values, with the maximum value of FP reaching a striking 119.262. Additionally, the skewness and kurtosis values offer insights into the distributional properties of the data. For instance, the skewness values of the dataset indicate a negatively skewed distribution, except for lnEG, FP, and lnGCF. Furthermore, the kurtosis values, especially for lnPG (9.543) and FP (39.244), highlight the presence of outliers or extreme values in the datasets. Further, the Jarque-Bera tests for normality consistently yielded significant deviations from the normal distribution for most variables. Moving to Panel B, the pair-wise correlations elucidate the relationships between variables. Notably, lnFS demonstrates negative correlations with lnAL, lnPG, lnED, and FP, suggesting that they tend to decrease food security as these variables increase. However, lnFS is favorably correlated with lnEG, lnGCF, and IQ, which indicates that income, domestic investment, and institutional quality enhance food security. Interestingly, lnED has a relatively strong positive correlation with lnEG at 0.220, hinting at the environmental impact of economic prosperity.

3.2. Cross-sectional dependence (CD) and heterogeneity tests

Before analyzing the data, testing the CD and homogeneity of the slope coefficients is required, as demonstrated in Table 2. In Panel A, the CD test results of Pesaran [77] indicate a rejection of the null hypothesis of cross-sectional independence at the 1 % significance level. This suggests that all variables exhibit a significant CD, meaning shared or common factors influence these variables across different regions. In Panel B, the homogeneity of slope coefficients across various cross-sections was assessed using Pesaran and Yamagata [70]. The null

Table 1
Descriptive summary and correlation analysis.

Panel A: descriptive statistics								
	lnFS	lnAL	lnPG	lnED	lnEG	FP	lnGCF	IQ
Mean	4.488	13.572	0.932	9.793	6.987	7.180	21.473	−0.671
Std. Dev.	0.235	1.711	0.365	1.448	0.864	10.684	1.608	0.567
Maximum	5.200	16.781	1.734	13.227	8.903	119.262	25.128	0.900
Minimum	3.621	9.689	−0.949	5.781	5.562	−11.154	17.358	−2.548
Skewness	−0.841	−0.520	−2.258	−0.197	0.628	4.588	0.062	−0.072
Kurtosis	3.677	2.519	9.543	3.426	2.443	39.244	2.976	4.090
Jarque-Bera	83.211	33.242	1600.878	8.510	47.862	35411.860	0.410	30.635
Probability	0.000	0.000	0.000	0.014	0.000	0.000	0.815	0.000
Observations	608	608	608	608	608	608	608	608
Panel B: pairwise correlations								
lnFS	1							
lnAL	−0.113	1						
lnPG	−0.130	0.299	1					
lnED	−0.084	0.722	0.125	1				
lnEG	0.130	−0.313	−0.511	0.220	1			
FP	−0.203	0.115	−0.003	0.118	0.005	1		
lnGCF	0.082	0.554	0.042	0.873	0.442	0.146	1	
IQ	0.112	0.061	−0.393	0.151	0.509	−0.060	0.288	1

Table 2
Cross sectional dependence and heterogeneity test.

Panel A: Cross sectional dependence test				
H_0: cross-sectional independence				
Variable	CD-test	p-value	corr	abs (corr)
lnFS	61.05	0.000	0.629	0.709
lnAL	32.12	0.000	0.331	0.460
lnPG	3.78	0.000	0.039	0.428
lnED	59.83	0.000	0.616	0.686
lnEG	48.01	0.000	0.495	0.678
FP	18.13	0.000	0.187	0.259
lnGCF	67.16	0.000	0.692	0.700
IQ	2.75	0.006	0.028	0.396

Panel B: Homogeneity test		
H_0: slope coefficients		
	statistic	p-value
$\widetilde{\Delta}$	10.785	0.000
$\widetilde{\Delta}$ Adjusted	14.866	0.000

hypothesis assumes these slope coefficients are the same across the cross-sections. The results indicate that both the $\widetilde{\Delta}$ and $\widetilde{\Delta}$ adjusted statistics are significant at the 1 % level, leading to the rejection of the null hypothesis. This suggests that the slopes of the explanatory and the dependent variables differ across the various cross-sections.

3.3. Panel stationarity analysis

Panel unit root tests are instrumental in heterogenous panel data analysis to determine the stationarity properties of the series. As demonstrated in Table 3, the outcomes from the second-generation unit root tests, such as CIPS and CADF, indicate distinct integration orders. The CIPS test results of lnFS, lnAL, lnPG, lnED, and FP suggest evidence against the null hypothesis of a unit root, indicating that the series is stationary at levels, i.e., I (0). However, lnEG and lnGCF were stationary after first differencing, i.e., I (1). In addition, the CADF test findings indicate that lnAL and FP were the only variables stationary at I (0), while all other variables became stationary at I (1). Therefore, the results from the various stationarity tests recommend that the variables are stationary at mixed integration orders. This reinforces to further the panel cointegration analysis proposed by Pesaran et al. [75] to examine the long-run and short-run linkage among food security and explanatory variables.

3.4. Pedroni and Kao cointegration test results

The examination of potential cointegration relationships among the variables was carried out using Pedroni [72,73] and Kao [74] cointegration tests, as presented in Table 4. Beginning with the Pedroni cointegration test results, the Modified Phillips-Perron (PP), PP, and

Table 3
Second-generation unit root tests.

	CIPS		CADF	
	Level	Δ	Level	Δ
lnFS	−2.325***	−4.643***	−1.906	−3.182***
lnAL	−2.913***	−4.822***	−2.138**	−3.253***
lnPG	−2.117**	−2.191**	−1.864	−2.457***
lnED	−2.449***	−4.646***	−1.952	−3.347***
lnEG	−1.513	−3.193***	−1.581	−2.691***
FP	−4.627***	−5.343***	−3.129***	−3.983***
lnGCF	−1.852	−3.872***	−1.951	−3.040***
IQ	−2.235**	−4.479***	−1.707	−3.347***

Notes: ***, **, * denote significance levels at 1 %, 5 % and 10 %, respectively. Δ stands for stationarity at the 1st difference.

Table 4
Cointegration test results.

	Statistic	p-value
Pedroni cointegration test		
Modified Phillips–Perron t	7.349	0.000
Phillips–Perron t	−3.009	0.001
Augmented Dickey–Fuller t	−3.774	0.000
Kao cointegration test		
Modified Dickey–Fuller t	0.684	0.247
Dickey–Fuller t	−0.325	0.372
Augmented Dickey–Fuller t	2.472	0.007
Unadjusted modified Dickey–Fuller t	−4.489	0.000
Unadjusted Dickey–Fuller t	−3.765	0.000

Augmented Dickey-Fuller (ADF) statistics are all statistically significant, providing compelling evidence against the null hypothesis of no cointegration. On the other hand, the Kao cointegration test results reinforce the evidence of cointegration among the series. While the modified Dickey-Fuller (DF) and DF statistics exhibit insignificant p-values, the ADF, the unadjusted modified DF, and the unadjusted DF statistics stand out with significance less than 0.05 percent thresholds, emphasizing the presence of cointegration in the model. Consequently, the combined evidence from the Pedroni and Kao cointegration tests leans strongly towards the presence of long-run equilibrium relationships among the examined variables.

3.5. Long-run and short-run results

The study estimates the long- and short-run effects of agricultural land, population growth, environmental degradation, per capita income, food prices, domestic investment, and institutional quality on food security in SSA countries. For the preference of the most appropriate estimator, the Hausman test was used to compare the PMG and MG estimators. As presented in Table 5, the Chi-square value of Model I is 1.27, Model II is 2.26, and Model III is 0.72 with a p-value of 0.9381, 0.8942, and 0.9982, respectively, implying acceptance of the null hypothesis of homogeneity across the models. Thus, the Hausman test outcomes suggest that the PMG procedure may be more suitable than the MG estimator for all three models under consideration. Remarkably, the PMG is a robust and consistent estimator, which allows for heterogeneous short-run dynamics with a common long-run equilibrium impact. Thus, the panel ARDL model (1, 1, 1, 1, 1, 1, 1, 1) is estimated based on the Akaike Information Criterion (AIC) to interpret the dynamics of food security in SSA countries.

In all PMG models, the long-run increase in agricultural land is positively associated with enhanced food security in SSA. The magnitude of the coefficients differs, indicating potential differences in the strength of association across models. Moreover, the SSA nations' population growth has a favorable relationship with food security in Model I and Model II of the PMG estimator. In the long-run, the analysis indicates that environmental degradation adversely impacts food security in SSA across all PMG models. Additionally, the analysis reveals an affirmative association between per capita income and food security in the long-run, which was statistically significant only in Model I. While Models I and II's findings indicate that increasing food prices enhances food security in the long run, the outcomes of Model III reveal that increased food prices might reduce food security. In the long-run, gross capital formation has a favorable linkage with food security in SSA nations, which is statistically significant in Model II. On the other hand, the long-run results indicate that institutional quality has a negative and statistically significant relationship with food security in the SSA nations.

Transitioning to the short-run results of the PMG approach, the estimates indicate that only agricultural land was statistically significant across all three models. The outcome that increased agricultural land

Table 5
Long-run and short-run results of the PMG approach.

Variables	PMG			MG		
	Model I	Model II	Model III	Model I	Model II	Model III
Long-run findings						
lnAL	0.729***	0.154*	−0.028	1.340	0.396**	−0.277
	[0.034]	[0.086]	[0.036]	[0.991]	[0.192]	[0.688]
lnPG	0.431***	0.499***	−0.054*	−0.836	−0.622	0.299
	[0.142]	[0.136]	[0.030]	[0.922]	[0.938]	[0.765]
lnED	−0.762***	−0.190*	0.460***	0.193	−1.360	0.023
	[0.171]	[0.109]	[0.043]	[0.699]	[0.858]	[0.558]
lnEG	0.455***	0.102	0.061	−2.755	2.594	−2.665
	[0.142]	[0.138]	[0.078]	[3.381]	[1.658]	[3.476]
FP	0.007***	0.007***	−0.005***	0.003	−0.002	0.009
	[0.002]	[0.002]	[0.001]	[0.003]	[0.002]	[0.012]
lnGCF		0.172***	−0.002		−0.074	0.362
		[0.036]	[0.019]		[0.149]	[0.570]
IQ			−0.216***			−0.400
			[0.022]			[0.351]
Short-run findings						
ECT_{t-1}	−0.110***	−0.126***	−0.202***	−0.524***	−0.685***	−0.895***
	[0.029]	[0.032]	[0.047]	[0.079]	[0.099]	[0.156]
ΔlnAL	0.147***	0.210***	0.208***	0.155**	0.097	0.112
	[0.056]	[0.056]	[0.060]	[0.063]	[0.073]	[0.108]
ΔlnPG	−0.270	−0.139	−0.068	−0.201	−0.322	−1.136
	[0.221]	[0.140]	[0.137]	[0.378]	[0.511]	[0.813]
ΔlnED	0.059	0.033	−0.086	0.089	0.051	0.101
	[0.122]	[0.112]	[0.128]	[0.129]	[0.167]	[0.246]
ΔlnEG	−0.129	−0.114	−0.050	−0.400	−0.350	−1.325*
	[0.219]	[0.192]	[0.196]	[0.254]	[0.366]	[0.758]
ΔFP	−0.000	0.000	0.000	0.000	−0.001	−0.001
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
ΔlnGCF		0.005	0.024		0.097	0.085
		[0.024]	[0.027]		[0.068]	[0.084]
ΔIQ			0.007			−0.091
			[0.031]			[0.138]
Constant	−0.145***	−0.066**	0.016	0.891	0.500	2.204
	[0.048]	[0.026]	[0.047]	[1.948]	[2.722]	[4.344]
Observations	576	576	576	576	576	576
No. of countries	32	32	32	32	32	32
Hausman test	1.27	2.26	0.72			
P-value	0.9381	0.8942	0.9982			

Note: ***, **, * represents significance levels at 1 %, 5 % and 10 %, respectively. Values in parenthesis […] denote the standard errors.

boosts food security in the short-run aligns with our long-run findings. This consistency across time frames suggests that greater expansion in agricultural land reliably leads to enhanced food security. In the short-run, variables such as population growth, environmental degradation, income per capita, food prices, gross capital formation, and institutional quality had negligible effects on food security in SSA. Moreover, the error correction term (ECT) represents the speed at which short-run shocks in the explanatory variables adjust towards long-run equilibrium. Strikingly, the coefficients of ECT are negative and significant in the three models, indicating that any short-run deviation in food security will be corrected annually by the explanatory variables by approximately 11 %, 12 %, and 20 %, respectively.

Table 6
Simultaneous quantile findings (Dep. Var: lnFS).

Variables	Model I			Model II (lnGCF)			Model III (lnGCF and IQ)		
	Q = 0.25	Q = 0.50	Q = 0.75	Q = 0.25	Q = 0.50	Q = 0.75	Q = 0.25	Q = 0.50	Q = 0.75
lnAL	0.381**	0.333***	0.292***	0.322***	0.285***	0.252***	0.329***	0.293***	0.258***
	(8.120)	(10.170)	(7.030)	(6.420)	(8.290)	(5.750)	(6.630)	(8.350)	(5.690)
lnPG	0.031	−0.020	−0.063	0.009	−0.023	−0.052	−0.001	−0.025	−0.048
	(0.550)	(-0.510)	(-1.250)	(0.170)	(-0.630)	(-1.110)	(-0.010)	(-0.730)	(-1.070)
lnED	0.365***	0.378***	0.389***	0.299***	0.326***	0.350***	0.298***	0.320***	0.341***
	(5.820)	(8.710)	(7.000)	(4.680)	(7.460)	(6.260)	(4.810)	(7.340)	(6.010)
lnEG	0.486***	0.465***	0.448***	0.225**	0.207***	0.190**	0.280**	0.244***	0.210**
	(5.690)	(7.870)	(5.920)	(2.020)	(2.720)	(1.960)	(2.540)	(3.150)	(2.090)
FP	−0.001*	−0.002***	−0.002***	−0.002**	−0.002***	−0.002***	−0.002**	−0.002***	−0.002***
	(-1.610)	(-3.100)	(-2.930)	(-1.930)	(-3.130)	(-2.650)	(-1.990)	(-3.170)	(-2.680)
lnGCF				0.115***	0.108***	0.102***	0.104***	0.102***	0.100***
				(3.950)	(5.430)	(3.990)	(3.600)	(5.010)	(3.770)
IQ							−0.085*	−0.071**	−0.058
							(-1.900)	(-2.260)	(-1.410)
Observations	608	608	608	608	608	608	608	608	608

Note: Values in parenthesis (…) denote the t-statistics.

3.6. Quantile regression results

Furthermore, the findings in Table 6 present the results of simultaneous quantile regression of different quantiles ($Q = 0.25$, $Q = 0.50$, and $Q = 0.75$). Across various quantiles, agricultural land exhibits a constructive connection with the dependent variable for all models; at the lower end of the distribution, the association strengthens. The relationship remains positive but might show a slight decline in magnitude at the median and the 75th quantile. This implies increased agricultural land is associated with enriched food security during the 25th quantile. However, the population growth coefficient is negative but not statistically significant across most quantiles and models. In addition, environmental degradation is strongly positive across all quantiles and models. At the lower end of the dependent variable's distribution, higher GHG emissions are associated with improved food security. In the middle and higher cases of the distribution, environmental degradation's positive relationship remains consistent, which suggests that the impact of GHGs remains influential even as the dependent variable approaches its median and higher quantiles.

Across the different quantiles, per capita income has a favorable linkage with food security, although the strength of this association declines with distribution. At lower quantiles, increased economic growth enhances food security, while at the 50th and the 75th quantiles, the positive association between income per capita and food security declines slightly. This suggests that very high GDP per capita influence on food security is less pronounced at higher distribution levels. Additionally, the coefficient for food prices is consistently negative and statistically significant across all quantiles and models. This indicates that higher food prices are associated with reduced food security. When gross capital formation is introduced in Model II, the outcomes indicate that increased domestic investments play a pivotal role in food security throughout the quantiles. This positive relationship remains evident and consistent with lower values of the dependent variable. Gross capital formation continues to be a driving factor at the median and higher quantiles, but it declines compared to lower quantiles. Conversely, institutional quality is negatively associated with the dependent variable at the 25th quantile, indicating that enhanced institutional quality might be linked to reduced food security. However, the negative relationship persists but may weaken slightly, implying that while institutional quality remains influential throughout the distribution, its impact might diminish at the higher end.

3.7. Dumitrescu–Hurlin panel causality test

The Dumitrescu and Hurlin [58] panel causality test was employed to investigate the causal connections among various variables in the panel dataset. The test results in Table 7 reveal a bidirectional causality between agricultural land and food security in the SSA. This mutual causation displays that expansions or contractions in agricultural land directly affect food security levels, while changes in food security can similarly drive land-use alterations. As a result, any policy or factor impacting one will have ramifications for the other. Similarly, a two-way causal linkage exists between SSA nations' population growth and food security. Interpretively, this relationship implies that an increasing population, with its higher food demand, can influence food production strategies, while variations in food security levels may affect population dynamics, potentially impacting migration patterns, birth rates, and other demographic aspects. The study also identifies a bidirectional causality between environmental degradation and food security. This indicates that intensification or changes in food yield activities have significant implications for GHG emissions, highlighting the environmental impact of agricultural practices. Concurrently, shifts in environmental degradation might alter agricultural production methods. Regarding this, SSA governments could consider adopting a holistic approach to farming policies that prioritize sustainable agricultural practices, conservation efforts, and land-use planning. This approach may involve implementing agroforestry practices, investing in renewable energy sources for agricultural operations and improving agricultural infrastructure can help reduce GHG emissions associated with farming activities.

In the economic domain, the two-way linkage between income per capita and food security indicates that economic growth can stimulate increased food output in the SSA countries, driven by higher demand for diverse food products. Conversely, a robust agricultural sector can contribute to economic prosperity. Contrastingly, the analysis shows no causal relationship between food prices and food security, suggesting that while these factors may correlate, they do not directly influence each other. Regarding capital investment, a bidirectional causality exists between gross capital formation and food security. This implies that investments in infrastructure, technology, or capital assets can significantly impact agricultural productivity in the SSA economies, and the state of agricultural output can guide investment decisions. Finally, there is unidirectional causality from food security to institutional quality. This suggests that changes in food security levels can significantly influence the quality of institutions, possibly affecting policies, governance, and economic conditions.

Table 7
Dumitrescu–Hurlin causality test results.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Causality direction
lnAL ≠ lnFS	2.115***	2.954	Bidirectional
lnFS ≠ lnAL	2.900***	5.366	
lnPG ≠ lnFS	2.416***	3.878	Bidirectional
lnFS ≠ lnPG	9.272***	24.946	
lnED ≠ lnFS	3.928***	8.525	Bidirectional
lnFS ≠ lnED	3.509***	7.238	
lnEG ≠ lnFS	2.422***	3.897	Bidirectional
lnFS ≠ lnEG	3.256***	6.461	
FP ≠ lnFS	1.189	0.109	No causality
lnFS ≠ FP	1.427	0.839	
lnGCF ≠ lnFS	2.858***	5.238	Bidirectional
lnFS ≠ lnGCF	2.536***	4.247	
IQ ≠ lnFS	1.774	1.904	Unidirectional
lnFS ≠ IQ	4.833***	11.305	

Notes: ≠ indicates that variable "X" does not homogenously cause variable "Y". *** signifies a 1 % significance level.

3.8. Discussion of the results

Across the various estimators, our findings indicate that increased agricultural land consistently correlates with improved food security in the SSA. This result is consistent with earlier research by Chandio et al. [8], Abdi et al. [7], Warsame et al. [35], and Chandio et al. [null]. By using crop-level data, Dewati and Waluyati [78] and Koirala et al. [60] discovered a constructive relationship between land area and rice production. This implies that SSA countries with more agricultural land might produce more food in the long-run, as more land typically allows for more agricultural activities and potentially higher food yields. In addition, the study outcomes that population growth has a supportive link with food security align with Devesh and Abdullah [61]. Moreover, Chandio et al. [null] reveal that the rural population contributes to the enhancement of cereal production in Southeast Asia economies. In the meantime, Warsame et al. [35] and Ali Warsame and Hassan Abdi [21] discovered that the rural population has a considerable negative impact on crop production in Somalia. Zarei [79] reveals that, over the past few decades, there has been an increase in water, energy, and food requirements, correlating with the rise in population growth. The positive impacts of population growth on food security propose that, as SSA countries' populations grow, there is also a tendency for their food production to increase. This could be due to increased demand for food necessitating higher production levels. Nonetheless, Fagbemi et al. [65] highlighted that SSA's rising population growth rate diminishes the likelihood of effectively improving food production and security.

The results of the study that food security in the SSA may exhibit heightened sensitivity to environmental degradation parallels with the findings of Chandio et al. [4], Ozdemir [9], and Edoja et al. [45] using a variety of food crops in different countries. The observed adverse impacts are likely attributable to the escalating global CO_2 emissions, which detrimentally affect the agricultural sector's productivity, exacerbating food insecurity challenges within the SSA region. In addition, Abdi et al. [2] investigated the ability of Somalia's primary crops to withstand the effects of climate change, with an emphasis on maintaining food security. They found that climate variability detrimentally affects the long-run yields of sorghum, rice, and beans. Although environmental pollution is associated with economic development, this raises a potential clash between economic advancement and the sustainability of food security. Contrary to our results, studies by Abdi et al. [7], Alexandrov et al. [6], and Ali Warsame and Hassan Abdi [21] have reported that carbon emissions positively and significantly impact the output of cereals. Additionally, we observed from the analysis that per capita income positively relates to food security. This finding aligns with the observations of Fagbemi et al. [65] and Bashir and Yuliana [80], who found that a rise in per capita income leads to higher food consumption, potentially driving an increase in food production. By examining the factors influencing food security in Oman, Devesh and Abdullah [61] presented that income per capita and population growth had a beneficial impact on food security. This implies that SSA countries with a higher income per capita tend to have improved food security. Economic prosperity might support better infrastructure, technologies, and agricultural practices that can enhance food security.

Moreover, the findings of the study suggest that although increasing food prices may enhance food security, they can also potentially reduce it. This implies that in situations where food prices are high, there is an incentive for producers to increase output. In line with our results, Bashir and Yuliana [80] found that rising rice prices positively impact rice production levels in Indonesia. On the other hand, due to various factors, such as reduced demand resulting from higher prices and increased costs of production inputs, increased food prices reduce food security. Although SSA countries exhibit a high vulnerability to global food price fluctuations, Okou et al. [22] reveal that food inflation tends to be lower in nations with higher local food production levels. Besides, Zereyesus et al. [25] observed that food insecurity in low- and middle-income countries continues to be high, attributed to recent incidents, including the COVID-19 pandemic, increased prices of food commodities, and the uncertainties stemming from the Russian invasion of Ukraine. This situation necessitates that SSA enhance food self-sufficiency and develop resilience against external shocks to ensure stable and secure food supplies amidst global uncertainties. Furthermore, our finding that gross capital formation positively contributes to food security in SSA is supported by Chandio et al. [81], who observed that physical capital enhances crop output. The implication is that increased investment in agricultural capital assets or related infrastructure could result in elevated food yields. This enhancement may stem from the infusion of advanced technologies, the implementation of more efficient irrigation systems, or the adoption of superior farming practices.

Another striking result from the study highlights that institutional quality adversely influences food security in the SSA nations. This suggests that poorer institutional frameworks in SSA are associated with lower levels of food yield. These frameworks encompass the entire government setup, including the effectiveness of specific executing ministries, such as the agriculture ministry, as well as the broader regulatory environment. Several studies, such as Subramaniam et al. [82] and Cassimon et al. [63], have concurred that effective governance contributes to the availability and accessibility of food for everyone. Moreover, Nsiah and Fayissa [15] and Yiadom et al. [64] identified good governance as one of the key drivers of agricultural efficiency and growth in Africa. This suggests that enhancing the quality of institutions can provide smallholder farmers with improved access to markets, financing, and inputs, which leads to increased agricultural productivity and elevated food security. However, Oyelami et al. [83] disclosed that institutional quality plays a minimal role in achieving food security. Poor institutions often entail inadequate governance, a lack of support for agricultural policies, insufficient infrastructure, and ineffective management of resources, all of which can hinder agricultural productivity. Additionally, weak institutions might fail to provide necessary services, such as access to credit and market information, further negatively impacting food production. Zhou and Wan [26] concluded that variations in institutional factors are the primary determinants of differing food security statuses. Moreover, corruption and political instability, common in regions with low institutional quality, can disrupt supply chains and agricultural investment, exacerbating food production challenges.

4. Conclusion

In the context of mounting global environmental trials, it becomes imperative to comprehend the complexities of food security dynamics, especially in areas grappling with food shortages, vulnerable to climatic fluctuations, and undergoing rapid demographic transformations. Although there is a substantial body of research addressing agriculture in sub-Saharan Africa, a comprehensive analysis of the collective impact of diverse factors, such as food pricing dynamics and the quality of institutional frameworks, on food security is still notably scarce. Therefore, this study utilizes panel data from 2002 to 2020 to examine the effects of agricultural land, population growth, environmental degradation, food prices, gross capital formation, and institutional quality on food security in 32 SSA countries. The study identified cross-sectional dependence to apply panel cointegration methods such as PMG and MG and refuted the null hypothesis that the slope coefficients are homogeneous. Regarding this, we employed second-generation unit root tests, specifically CADF and CIPS, to ascertain the integration order of the variables, revealing a mixed stationarity of I (0) and I (1). Furthermore, the long-run cointegration relationship between the scrutinized variables and food security was established through Pedroni and Kao cointegration tests. The MMQR analysis confirmed the robustness of the long-run findings obtained through the PMG method. Additionally, the study utilized the Dumitrescu-Hurlin test to ascertain the causality pathways among these variables.

The outcomes from the PMG models indicate that an increase in agricultural land in SSA facilitates a greater range of agricultural activities, potentially leading to enhanced food security in the short- and long-run. In addition, the results highlight that as the population in SSA countries expands, there is a rising demand for food, necessitating an upsurge in production to meet this demand. Regarding environmental degradation, the long-run analysis across all PMG models exhibits a negative impact on SSA's food security, echoing the detrimental effects of environmental deterioration in exacerbating food insecurity challenges. The analysis also found that increased per capita income might raise demand for diverse food items with greater purchasing power, enhancing food security in the long-run. In terms of food prices, the long-run findings are mixed. While some models indicate that higher food prices incentivize increased production and security in SSA, others suggest that elevated prices might reduce food security due to decreased demand and higher input costs. This creates a trade-off where producers may benefit from higher prices, but consumers, especially low-income households, face greater food insecurity. Additionally, input suppliers might see increased demand, while retailers and processors could experience squeezed profit margins due to higher raw material costs.

In the long-run, gross capital formation in SSA has a positive and significant impact on food security, which indicates that food security can be enhanced through increased investment in related capital and infrastructure. However, SSA's institutional quality demonstrates a negative long-run relationship with food security, suggesting that poor governance and institutional frameworks are linked to lower food yields.

The ECT in all models is negative and significant, suggesting a swift adjustment of short-run deviations towards long-run equilibrium, with annual corrections by the explanatory variables ranging from 11 % to 20 %. Additionally, the Dumitrescu–Hurlin causality test results reveal that food security has bidirectional causality with agricultural land, population growth, environmental degradation, income per capita, and gross capital formation. However, it was observed that food security has no causal relationship with food inflation. The results also highlight a one-way causality from food security to institutional quality.

The SSA nations often grapple with political instability, economic constraints, and pressing environmental issues like climate change, severely impacting food security and overall development. Based on the study's results, we propose targeted policy measures tailored to SSA countries' distinct challenges to enhance food security effectively. First, they should encourage sustainable expansion and efficient use of agricultural land to increase food production capacity. This policy approach promotes the optimal utilization of agricultural resources, contributing to a more sustainable and resilient agricultural sector. Second, policymakers should implement policies to mitigate GHG emissions and counter environmental degradation, recognizing their negative impact on agricultural output and food security. In nations like Somalia, Ethiopia, South Sudan, and Kenya, facing severe climate change impacts, it is essential to implement policies that facilitate the adoption of climate-resilient farming techniques to mitigate environmental impacts and maintain agricultural productivity. Third, they should focus on policies that stimulate gross capital formation in agriculture, thereby enhancing food production. This includes investment in agricultural infrastructure and technology. Fourth, addressing the identified negative correlation between institutional quality and food yields necessitates strengthening institutional frameworks and governance within the agricultural sector to enhance production capabilities. In politically unstable regions such as Sudan and the Central African Republic, implementing policies that enhance regulatory oversight, increase transparency, and encourage participation in agricultural decision-making is crucial. Such reforms are pivotal in stabilizing agricultural sectors and advancing sustainable development initiatives, which are key to ensuring long-term food security. Finally, policymakers should develop a robust approach to managing food prices, recognizing the complex impact of price changes on food production, demand, and security in the region. For economies like Nigeria, where agricultural price volatility is linked to dependency on fluctuating global oil prices, establishing mechanisms to stabilize food prices is vital.

Funding

This research is supported by SIMAD University, Somalia (Grant number: SU-PG-2023-015).

CRediT authorship contribution statement

Abdikafi Hassan Abdi: Visualization, Validation, Supervision, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Abdisalan Aden Mohamed:** Writing – review & editing, Writing – original draft. **Farhia Hassan Mohamed:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Abbreviations

GHG	Greenhouse Gases
FAO	Food and Agriculture Organization
GRFC	Global Report on Food Crises
WFP	World Food Program
SSA	Sub-Saharan Africa
PMG	Pooled Mean Group
MG	Mean Group
MMQR	Method of Moments Quantile Regression
GMM	Generalized Method of Moments
WGI	Worldwide Governance Indicators
WDI	World Development Indicators
CD	cross-sectional dependencies
CADF	Cross-sectional Augmented Dickey-Fuller
CIPS	Cross-sectional Im, Pesaran, Shin

Appendixes

Table A1
List of countries and codes

No.	Country	Code	No.	Country	Code
1.	Angola	AGO	17.	Madagascar	MDG
2.	Benin	BEN	18.	Mali	MLI
3.	Botswana	BWA	19.	Mauritania	MRT
4.	Burkina Faso	BFA	20.	Mozambique	MOZ
5.	Burundi	BDI	21.	Namibia	NAM
6.	Cameroon	CMR	22.	Niger	NER

(*continued on next page*)

Table A1 (*continued*)

No.	Country	Code	No.	Country	Code
7.	Comoros	COM	23.	Nigeria	NGA
8.	Chad	TCD	24.	Republic of the Congo	COG
9.	Côte d'Ivoire	CIV	25.	Rwanda	RWA
10.	D.R. Congo	COD	26.	Senegal	SEN
11.	Eswatini	SWZ	27.	Sierra Leone	SLE
12.	Gabon	GAB	28.	Somalia	SOM
13.	Gambia	GMB	29.	South Africa	ZAF
14.	Guinea	GIN	30.	Tanzania	TZA
15.	Guinea-Bissau	GNB	31.	Togo	TGO
16.	Kenya	KEN	32.	Uganda	UGA

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