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Climate Change and Food Security in Selected SADC Countries: A Feasible Generalized Least Squares Approach

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ABSTRACT

Climate change poses a significant threat to the attainment of the sustainable development goals (SDGs) and directly affects food security in SADC countries, as it negatively impacts agricultural production, which is a primary source of livelihood. The study examined the impact of climate change and climate variability (rainfall amount, temperature, and carbon emissions) on food security in the SADC region based on 14 countries of the 16 SADC members states. Secondary data for the period 1990-2023 was used. Data analysis was conducted using feasible generalized least squares (FGLS). The results revealed that extreme temperatures and excessive or poor rainfall had a significant negative impact on food security (food availability and food accessibility) both in the short run and in the long run. Rainfall had a significant positive effect on food security (food availability, accessibility, and utilization) in the long run. Lastly, CO_2 emissions positively impacted food availability and accessibility but did not affect food utilization. The study recommended increasing climate change education and training programs to nationals regarding climate change and variability to ensure the adoption of innovative, adaptive and sustainable agriculture strategies such as SMART agriculture complemented by paving way for humanitarian interventions and Non-Governmental Organizations targeting humanitarian, climate change adaptation and climate change mitigation strategies for farmers. Nations should also direct a significant proportion of their budgets towards climate action (climate finance) to speed up the adaptation and mitigation strategies.

Keywords: Climate Change, Food Security, Feasible Generalized Least Squares
JEL Classifications: Q01, Q05, Q56, Q23

1. INTRODUCTION AND BACKGROUND

Climate change is defined in Toromade et al. (2024) as long-term alterations in weather patterns, primarily caused by human activities (such as the burning of fossil fuels, deforestation, and industrial processes). Such human activities release greenhouse gases into the atmosphere, that will trap heat and lead to changes in the Earth's climate system (Toromade et al., 2024) where the repercussions can be multifaceted, encompassing rising sea levels, more frequent and severe weather events, shifts in precipitation patterns, and alterations in ecosystems as explained in Turner et al. (2020). Climate change significantly threatens food security in the Southern African Development Community (SADC) countries because a greater proportion of the countries' population depends on rain-fed agriculture. Extreme weather events like droughts, floods, and cyclones, exacerbated by rising temperatures and erratic rainfall, are increasingly impacting agricultural productivity and livelihoods (Saleem et al., 2024; Ibrahim et al., 2025). This leads to reduced crop yields (van Oort and Zwart, 2018; Davenport et al., 2018; Freduah et al., 2019; Murray-Tortarolo et al., 2018; Trnka et al., 2019; El Bilali, 2019), livestock production (Mare et al., 2018; Naah and Braun, 2019; El Bilali et al., 2020) and overall food insecurity (El Bilali, 2019) affecting millions across the region. In fact, agriculture total factor productivity (TFP) from a national and regional and global perspective. A decline in agriculture total factor productivity in many developing countries is often associated with a hotch-potch of other macroeconomic challenges including but not limited to conflicts (Southern African Development Community, 2020), forced displacements, and migration (OECD, 2022c; OECD, 2023; UNHCR, 2023). A disturbance in total agriculture TFP ultimately affects the economy because the agriculture sector is the main source of raw materials for the manufacturing sector.

Climate change causes droughts, tropical cyclones and conflicts in driving displacement and accentuating food insecurity (Synthesis Report on the State of Food and Nutrition Security and Vulnerability in Southern Africa, 2022). The effects of climate change on food and nutrition security negatively impact 70% of the African population, population living under poverty (food insecurity) rising by 122 million people by 2030 because the agricultural sector is experiencing heavy reverses (Southern African Development Community, 2020). Climate change is characterized by shifts in temperature patterns, precipitation levels, and extreme weather events such as droughts and at times floods, has emerged as one of the most pressing challenges of our time and there to stay hence the need to consider as a serious blockage to the attainment of the sustainable development goals, at national level from short to long term goals, regional goals like Agenda to 2063, Vision 2050 and more. Its far-reaching impacts extend beyond environmental concerns to pose significant threats to global food security (Toromade et al., 2024).

Climate change poses a particular risk to the predominately rain-fed agricultural sector (Ibrahim et al., 2025), which is critical to SADC's regional development, as about 70% of the population of southern Africa depends on it as the main livelihood source (both employment and income) (Global Network against Food Crises: Global Report on Food Crises, 2022). Climate variability (downward and highly variable rainfall and temperature trends) significantly affected agricultural production in the region. In the past two decades, an increasing number of SADC member states have reported declining crop yields due to the impacts of climate change where it was reported that over 43 million people in 11 SADC states (Angola, the DRC, Eswatini, Lesotho, Madagascar, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe) are reported to be experiencing acute food insecurity (Global Report on Food Crises, 2022). This was however exacerbated by the war in Ukraine has which disrupted the global food supplies resulting in acute food shortages that further resulted in rising food prices (Mugoni et al., 2025). This is triggered by the inflated prices of imported commodities (wheat, rice, refined vegetable oils and petroleum products), that are further significantly impacting livelihoods and food security in the SADC region and beyond.

There is growing need to address climate change as a cross-cutting issue has significantly affected the attainment of sustainable development goals (SDGs), peace and security, and regional integration in the Southern African Development Community (SADC), (2020) and Southern African Development Community (SADC), 2020). Apart from derailing the achievement of the SDGs, peace and security and regional integration, the El Niño induced droughts affect the resilience of marginalized households by causing shortages of goods in agro-based economies. Drought induced commodity shortages because of climate change may contribute to rising food prices (inflation), water shortages, public health crises, and disruptions to health and education services. Extreme weather conditions such as the extended dry conditions led to crop failure and reduced yields across the region where for instance, Malawi, Namibia, Zambia and Zimbabwe all declared states of national disaster due to the drought (Southern African Development Community (SADC), (2024). Rising food prices result in food inflation which can further destabilize emerging economies like many SADC states which may further result in macroeconomic instability, conflicts and international migration.

Food insecurity has become a cause for concern. Climate change poses a significant threat to global food security, with rising temperatures, rising sea levels, shifting precipitation patterns, and increased frequency of extreme weather events impacting negatively on economic productivity and hence food availability, accessibility, stability and utilization (Jiri, 2020). Understanding the nexus between climate change and food security is paramount in addressing the complex challenges ahead (Toromade et al., 2024). This study drew immense interest from the current world's climatic conditions and variabilities threatening the socio-economic development of the nation's, especially as far as food security and nutrition are concerned. Food insecurity is exacerbated by climate change and its variability, (Molotoks and Smith, 2021). Considering the above food security concern, this study investigates the effects of climate change on food security (food access, availability and utilization) from 1990 to 2023 for selected SADC countries based on data availability.

The study was largely prompted by the fact that climatic conditions have continuously evolved over a very short period, yielding possible food insecurity. Despite the climate change mitigation and adaptation strategies being promoted from national, regional and global policy frameworks, food insecurity remained one of the most threatening problems to many developing economies. Various climate finance initiatives have been rolled out nationally, regionally and globally in attempts to promote the attainment of the sustainable development goals (SDGs) and specifically promote food security, the SADC region remains one of the most food insecurity affected regions. Food availability, accessibility, utilization, and stability continue to be threatened in the region, despite the enormous efforts being made to reduce the negative effects of climate change. This study was also motivated by the fact that most studies on the impact of climate change on food security have been using global price movements and unemployment as some other measures disregarding the real issues related to the shop floor production of food from agricultural, aqua cultural, and apicultural perspectives.

The study used the secondary data and the POLS, FEM, REM, and FGLS on a simple panel data model to assess the impacts of changes in climate to food security in the SADC region. The study looked at a longer period with more climatic and economic cycles. Most of the studies (Raïfatou et al., 2021; Thapa-Parajuli and Devkota, 2016; Aliyu et al, 2020; and Ebi and Ziska, 2018), concentrated on climate change has been an issue affecting agricultural production and food security in general, whereas this research work has taken to extend to the individual forms of food security such as food availability against carbon dioxide emissions, food accessibility against variant precipitation patterns and food utilization against temperatures changes. Most studies Thapa-Parajuli and Devkota, 2016; Nasrullah et al., 2021; Bankole et al., 2020; Mamudu et al., 2017; Li et al., 2022), looked at other areas and countries in Europe, Asia, West Africa, and Central Africa where as this study concentrated on the SADC region only since the areas comprise of shore and offshore land, arid and semi-arid regions, and mountainous and low lying areas prone to all kinds of climatic and weather conditions. Apart from, that most of the studies, (Gooding et al., 2023; Zaied et al, 2015 and Teressa, 2021) were carried out using proxies such as wheat production, livestock production, cereals production and other specific agriculture produce whereas this study looked at the GDP component of agriculture production in the National production statistics to include aquacultural and apicultural production.

A study by Peichl et al. (2019) assessed the impact of rainfall variability on food security and concluded that extreme rainfall conditions, either too much or too little, have significant impact on all the food security elements (Raïfatou et al., 2021). However, he went on to clarify that extreme high rainfall conditions (flooding) have more significant impact compared to little rainfall on the food utilization element (Raïfatou et al., 2021). Furthermore, the impact of climate change on food accessibility was thoroughly discussed by Thapa-Parajuli and Devkota (2016) and echoed the same sentiments that the extremely high temperatures may result in the deterioration of crops, food stuffs and high rise in numerous diseases giving a significant impact on the food utilization element.

A study by Aliyu et al (2020) emphasized the relationship between crop nutritional value and climate change. However, these studies mainly focused on a single climate variable (Carbon emissions) and one indicator of food security (the prevalence of stunting in children under 5 years old). The uniqueness of this study lies in its attempt to go beyond previous empirical investigations by incorporating the three main food security indicators (food availability, accessibility, and utilization) into a single study. The study investigated the impact of climate change on food security in the SADC region over the period 1990-2023, by using simple data panel analysis. However, to explain food security, the study used food availability, food accessibility, and food utilization. Climate change poses a formidable threat to global food security, compromising agricultural productivity, food availability the general human wellbeing. Rising temperatures, changing precipitation patterns, rising sea levels, and increased frequency of extreme weather events are altering the productivity and distribution of food crops, leading to food insecurity and malnutrition. Despite the growing research, empirical evidence on the specific impacts of climate change on food security remains fragmented, particularly in the SADC region. Existing empirical literature has employed univariate analysis neglecting the complex interrelationships between climate variables and food security indicators. Other existing studies have employed limited geographical scope like countries and districts, overlooking the regional specific climate food security dynamics. There is a lack of a comprehensive multivariate model of climate change impacts on food security and quantified relationships between climate variables and food security indicators to give evidence-based policy recommendations for enhancing climate resilience and food security.

The main objective of the study is to assess the impact of climate change on food security. It aimed at establishing the impact of climate change to sustainable development through food security indicators (food availability, food accessibility and food utilization) for the period 1990-2023. Specifically, the study seeks to empirically assess the economic impact of climate change on food security in the SADC region. This study aimed at assessing how the frequent, persistent and inconsistent change in climatic conditions does affects the various forms of food security such as food availability, accessibility, and food utilization in the SADC region. The study investigated the impact of climate change on food security in the SADC region using quantitative techniques for the period stretching from 1990 to 2023. The analysis employed the Pooled Ordinary Least Squares and FGLS models.

2. LITERATURE REVIEW

2.1. Theoretical Literature Review

Theoretically, the study is premised on various theories such as the Malthusian Population growth theory (Malthus, 1798), Food Systems Theory (Gillespie and van den Bold , 2016), Food availability and Entitlement Theory (Sen, 1981), and the Ricardian Theory (Ricardo, 1817). The Malthusian theory of population growth highlighted that food production grows linearly, while population grows exponentially leading to food scarcity. In exploring theories concerning food security, Neo-Malthusian theory argues that food security and sustainable development are intrinsically linked (Affoh et al., 2022). The food systems theory analyses food security within broader food systems, considering production, processing, distribution, and consumption. It stressed that food security is a complex issue that requires a systems approach and outlined the four pillars of food security, the food system functions and the food systems actors (farmers, processors, traders and consumers). The model is biased towards agricultural food production as the main influencer of food security. The food systems theory, however, overlooked the role of external factors such as climate change and economic shocks.

Food availability and entitlement theory focused on entitlements rather than food availability. And argued that what causes food insecurity is related to what people own or possess. The model attributed food availability declines to the entitlements, endowments and exchange policies of the land. The theory shifted focus from food availability to entitlements an important concept that can affect the food security element of food stability. More so the theory integrated into development economics and policy and therefore included vulnerable groups: Women, children, and marginalized communities. The Ricardian theory explained how land rent and environmental factors affects agricultural production, focusing on the concept of diminishing returns it measures the sensitivity of agricultural production to climate change indicating that agricultural production practices are directly and correlated with climatic variables together with other factors. The theory estimates how much observed cross-sectional variations of land values or revenues can be explained by climatic or other confounding factors as in Tun et al. (2020). Ricardian theory can measure long-run effects of climate change considering the ability to adapt (Bozzola et al., 2018). According to the model, climate change results in long-term resource shortages such as worsening soil conditions, water, disease and pest outbreaks which adversely impact on crop and livestock productivity. The approach has been widely used in existing literature to evaluate the effects of climate change on agriculture for instance it has been applied in previous studies by Tun et al. (2020) and Van-Passel et al. (2018). These theories were reviewed to scrutinize how climatic variabilities affect human food security in the SADC region as well as to see how it influences state international food security.

2.2. Empirical Literature Review

Affoh et al. (2022) carried out a study on the Impact of climate variability and change on food security in Sub-Saharan Africa. The results show that rainfall and CO_2 emissions have a positive and significant effect on food availability in the long run while temperature change exhibited a negative and significant impact on food availability. A slight temperature rise in temperate regions was found to be beneficial for crop yields. In Gambia, Belford etal (2024), investigated the link between climate change, food security and economic growth and found that agriculture has positive correlation with food security, average annual rainfall change has significant and negative impact on food security while food security and GDP per capita have unidirectional relationship.

Musebe (2018), examined the implications of climate change and variability on food security in Kenya using a multiple linear regression model on food security (FS). The results revealed that increase in temperature and reduction in rainfall had significant effect on food security in Kenya. Chiara and Giacomo (2023) examined the relationship between food security and global warming in Uganda and found that smallholder farms in the Northern and Eastern regions have a lower probability of being food secure than those in the Western areas.

Affoh (2022) examined the impact of climate variability and the food accessibility estimating using the Pooled mean group estimation technique and results revealed a significant positive effect of rainfall on food accessibility. Iizumi et al. (2021) analyzed the impact of rising temperatures on Sudan's domestic wheat output and consumption and results revealed that temperature variations showed negative impact on food utilization in Sudan. Teressa (2021) examined the impact of climate change on Food security and Nutritional (food utilization) in Western and Central Africa and found that temperature increases negatively affect food utilization. Increased carbon emissions reduce dietary iron, zinc, protein, and other macro- and micronutrients in some crops, (Wiebe et al., 2015). With little studies concentrating in SADC, literature on food utilization and accessibility is still scant as components of food security hence this study is going to contribute in that regard and add to the literature on food availability.

2.3. Conceptual Framework

The following diagram shows the conceptual framework which is an attempt to establish the theoretical and empirical relationship between the dependent variables, independent variables, mediating variables and moderating variables as presented in Figure 1.

The diagram shows the relationships among the categorical elements of food and nutrition security and gives a pictorial explanation of the methodology showing the various models to be regressed. It shows how climate change measured by rainfall (climate change) affects food security indicators (food availability, accessibility and utilization), how carbon emissions (climate change) affect food security indicators (food availability, accessibility and utilization) and how temperature changes (climate change) affect the three food security indicators (food availability, accessibility and utilization) used in this analysis.

3. RESEARCH METHODOLOGY

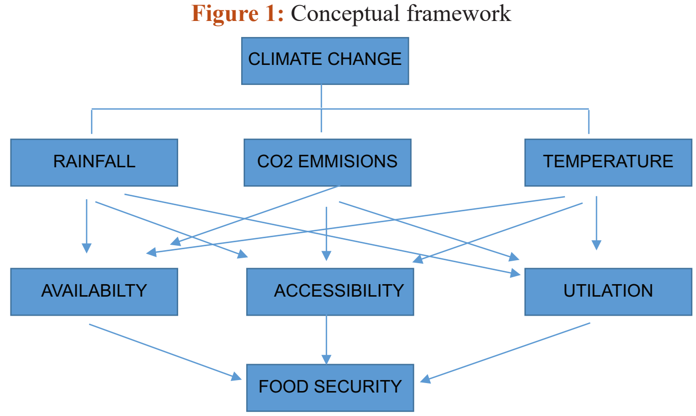
This section covers the research methodology used in this study (data collection, data sources and time domain, definition and justification of variables, model specification, econometric estimation techniques (pre-estimation to post-estimation tests).

3.1. Model Specification

The model was built using empirical evidence showing the impact of climate change on food security from the secondary data collected on food security and the factors that affect food security. Adopting a multiple linear regression model from Musebe et al. (2018) who argued that besides the effects of climate change on food security, theories state that there are other socio-economic factors that may contribute may influence food security indicators differently hence the need to make the three used indicators in different models as dependent variables in a multivariate panel data analysis. The multivariate linear regression model specification's functional form will be as follows:

$$FSAvl_{it} = \beta_0 + \beta_1 rgdp_{it} + \beta_2 rf_{it} + \beta_3 temp_{it} + \beta_4 agland_{it} + \beta_5 ce_{it} + \beta_6 popg_{it} + \varepsilon_{it}$$

Figure 1: Conceptual framework



Conceptual framework (Adopted from Affoh et al., 2022)

$$FSAcc_{it} = \beta_0 + \beta_1 rgdp_{it} + \beta_2 rf_{it} + \beta_3 temp_{it} + \beta_4 agland_{it} + \beta_5 ce_{it} + \beta_6 popg_{it} + \varepsilon_{it}$$

$$FSUtz_{it} = \beta_0 + \beta_1 rgdp_{it} + \beta_2 rf_{it} + \beta_3 temp_{it} + \beta_4 agland_{it} + \beta_5 ce_{it} + \beta_6 popg_{it} + \varepsilon_{it}$$

The models have then been converted into natural logarithms to capture the significant variations in some of the variables and country specific data patterns which resemble acute changes from period to period. The natural logarithm transformation was done because of inherently positive and exhibit exponential relationships and for easy interpretation of the coefficients as elasticities. This has been presented as follows.

$$\text{In}(FSAvl_{it}) = \beta_0 + \beta_1 \text{In}(rgdp_{it}) + \beta_2 \text{In}(rf_{it}) + \beta_3 \text{In}(temp_{it}) + \beta_4 \text{In}(agland_{it}) + \beta_5 \text{In}(ce_{it}) + \beta_6 \text{In}(popg_{it}) + \varepsilon_{it}$$

$$\text{In}(FSAcc_{it}) = \beta_0 + \beta_1 \text{In}(rgdp_{it}) + \beta_2 \text{In}(rf_{it}) + \beta_3 \text{In}(temp_{it}) + \beta_4 \text{In}(agland_{it}) + \beta_5 \text{In}(ce_{it}) + \beta_6 \text{In}(popg_{it}) + \varepsilon_{it}$$

$$\text{In}(FSUtz_{it}) = \beta_0 + \beta_1 \text{In}(rgdp_{it}) + \beta_2 \text{In}(rf_{it}) + \beta_3 \text{In}(temp_{it}) + \beta_4 \text{In}(agland_{it}) + \beta_5 \text{In}(ce_{it}) + \beta_6 \text{In}(popg_{it}) + \varepsilon_{it}$$

The food security indicators have been used as variables in the food security models to determine the contribution of each variable to the individual nation's food security measured using the three food security indicators.

3.2. Summary of Variables

The summary of variables and expected signs are presented in Table 1.

3.3. Definition and Justification of Variables

Food security in this study is defined and measured through three elements are; the prevalence of severe food insecurity in the total population (accessibility), the average of the share of dietary energy supply derived from cereal as used in Mohamadinezhad and Shekarchizadeh (2025), roots, and tubers as a percent (utilization) and lastly per capita food supply variability (availability) according to Worth (2020), Farooq et al. (2022), Sigma et al. (2024) and Rehman et al. (2024). Climate change is measured through three proxies that is carbon emissions as in Farooq et al. (2022), average annual temperature as in Simane et al. (2025), Ekhalfi et al. (2025), and average annual rainfall as in Ekhalfi et al. (2025) and Simane et al. (2025). Other control variables used in this study include economic growth as in Fernandes and Samputra (2022), utilized agricultural land as in Ekhalfi et al. (2025) and population growth rate as in Fernandes and Samputra, (2022), utilized agricultural land as in Oussama, et al, (2025) and population growth rate as in Rehman et al, (2024), Henderson, et al, (2025), Rehman et al, (2024) and Ghosh et al, (2024).

Table 1: Summary of variables and expected signs

Variables explanations	Variables symbols	Expected sign
Food security		
Availability	$FSAvl_t$	Dependent variables
Accessibility	$FSAcc_t$	
Utilization	$FSUtz_t$	
Economic growth (USD)	$rgdp_{it}$	+ (positive)
Agricultural land (Hectares)	$agland_{it}$	+ (positive)
Carbon dioxide emissions (metric tons per capita)	ce_{it}	+ (positive)
Population growth (%)	$popg_{it}$	−(negative)
Average annual temperature (°C)	$temp_{it}$	± (positive/negative)
Average annual rainfall (MM)	rf_{it}	± (positive/negative)

3.4. Summary of Variables and Data Sources

This study used secondary data sourced from international institutional data bodies like the international monetary fund (IMF), food agricultural organization (FAO) and the World Bank. Table 2 shows the variable name, variable code, variable description and data sources.

3.5. Econometric Estimation Technique

In the first step of estimation, the study employed categorical elements of food security growth using the ordinary least squares approach for the period with fixed effects models (FEM) and the period with random effects models (REM). The models' temporal components were tested overtime for redundant fixed effects with the Hausman test and evaluate the consistency of random effects using the Breusch–Pagan Lagrange (LM) multiplier, which allows to choose between a regression of random effects and a straightforward OLS regression. Correlation between independent variables (multicollinearity) was tested using the correlation matrix and variance inflationary factor (VIF). The existence of residual autocorrelation will be examined using Durbin–Watson statistics. The model's goodness of fit was assessed using modified R-squared. To obtain results that are not spurious, variables were tested for stationarity through conducting unit root tests using the Im-Pesaran-Shin (IPS) unit root tests. The Wooldridge test for autocorrelation was performed to check for autocorrelation. To avoid biased estimates, the researchers performed cross-sectional dependence tests to check if the residuals are not correlated across entities using the Pesaran Cross-Sectional Dependence Test. To ensure efficient

Table 2: Summary of variables measures and data sources

Variables	Indicators	Source
Food utilization ($FSUtz_{it}$)	Share of dietary energy supply derived from cereals, roots and tubers (percent) (3-year average).	FAO
Food accessibility ($FSAcc_{it}$)	Prevalence of severe food insecurity in the total population (percent) (3-year average).	FAO
Food availability ($FSAvl_{it}$)	Per capita food supply variability (kcal/cap/day).	FAO
Economic growth ($rgdp_{it}$)	Gross Domestic Product-Annual Growth US$ per capita, 2015 prices.	World bank
Agricultural land ($agland_{it}$)	Agriculture land (hectares).	FAO
Carbon emissions (ce_{it})	Emissions (CO_2) On-farm energy use.	World Bank
Population growth ($popg_{it}$)	Population-Estimations and Projections from the annual census.	World Bank
Temperature ($temp_{it}$)	Average annual temperature (°C).	FAO
Rainfall (rf_{it})	Average annual rainfall (millimeter).	FAO

estimates, the Wald Test was executed to detect heteroscedasticity while the Jarque- Bera (JB) test was used to test Normality.

To remedy the observed econometric problems of panel autocorrelation, cross-sectional dependency, heteroscedasticity and autocorrelation if found, the researcher will rely on two estimation techniques (Feasible Generalized Least Squares –FGLS and Panel Corrected Standard Errors PSCE) as suggested by Reed and Ye (2011) and Beck and Katz (1995). The rule of thumb in selecting which model to apply is to use FGLS if time dimension is greater than or equal to cross sections (T>N) where T is the number of periods and N represents the number of cross sections and PCSE when the number of cross sections is greater than time period (N>T) according to Greene (2018), Adeleye et al. (2021) and Adeleye et al. (2022). For this study, time period was greater than cross sections ([T>N] where T is the number of periods and N represents the number of cross sections), the FGLS procedure was found to be more efficient than the panel corrected standard errors (PSCE) which works well when the number of cross sections is greater than time period (N>T) according to Qian (2016), Greene (2018), Adeleye et al. (2021) and Adeleye et al. (2022) in the case of autocorrelation, heteroscedasticity, cross-sectional dependence and multicollinearity.

4. RESULTS PRESENTATION, INTERPRETATION AND DISCUSSION OF RESULTS

4.1. Descriptive Statistics

The following Table 3 shows the variables and the summary of descriptive statistics. The dependent variables (food availability, food accessibility, and food utilization) have mean values of 62.361, 26.098 and 36.372 respectively for all the 14 countries over the 33 years. Their standard deviations are estimated at 12.22, 12.596 and 30.295 over the same period. The minimum in the dataset in absolute terms is 0.0083 for carbon emissions in the Democratic republic of Congo in the year 2000 and the maximum is 95894.12 for the population same country in the year 2021. Table 3 shows the descriptive statistics.

Summary statistics Table 3 indicates that there are more variations in the panel dataset, from between countries than within variation for all food security indicators elements (FSAV, FSACC and FSUTZ) indicated by the values of 12.244, 12.816 and 18.414 against 3.133, 2.415 and 24.542 respectively. The average CO_2 is 1052.899, varying from between 0.0083 mt/capita and 1697.22 mt/per capita. There is more between variation (2796.189) than within variation (912.916) indicating great variations between one country and the next. This is in line with theoretical literature as countries more industrialized (such as South Africa) tend to have more emissions per capita than those less industrialized (such as Lesotho) according to Kopra et al. (2020), Yang et al. (2022) and Ritchie (2023). The country with the highest percentage of agricultural land under production had 28.24% of the agricultural land while 2.5% was recorded for the country with the least agricultural land. On average high economic production has been observed where there is more arable land put under agriculture.

Table 3: Summary statistics

Variable	Obs	Mean	Standard deviation	Min	Max
FSAV					
Overall	N=476	62.36134	12.21973	38	82
Between	n=14		12.24414	42.26471	80.85294
Within	T=34		3.133421	53.80252	75.09664
FSACC					
Overall	N=476	26.09895	12.59609	3.2	55
Between	n=14		12.81561	3.226471	49.7
Within	T=34		2.414971	17.66366	32.09307
FSUTZ					
Overall	N=476	36.37185	30.29529	2	207
Between	n=14		18.41356	14.08824	66.08824
Within	T=34		24.54183	−19.03992	182.9601
RGDP					
Overall	N=476	1.28761	5.469843	−26.34912	57.90365
Between	n=14		1.235427	−1.315384	3.174777
Within	T=34		5.33844	−25.29832	57.58873
POPG					
Overall	N=476	15964.41	19394.15	71.057	95894.12
Between	n=14		19096.7	88.28441	62544.6
Within	T=34		6065.074	−10592.65	49313.93
TEMP					
Overall	N=476	0.6828676	0.4456057	−0.698	2.267
Between	n=14		0.1313224	0.4185882	0.8522647
Within	T=34		0.4272201	−0.7306618	2.268956
RF					
Overall	N=476	996.3172	511.897	285	2330
Between	n=14		530.3916	285	2319.412
Within	T=34		16.34994	646.9055	1030.288
CO_2					
Overall	N=476		2847.613	0.0083	16971.22
Between	n=14		2796.189	0.0522794	10456.42
Within	T=34	1052.899	912.916	−4012.703	7567.695
AGLAND					
Overall	N=476	3447.238	3994.54	1.463	16967.03
Between	n=14		3991.042	2.920971	13160.82
Within	T=34		1065.145	437.9431	9954.972

Source: Author's computation from STATA17

Table 4: Im-Pesaran-Shin (IPS) panel unit root tests results

Variable	Test statistic	P-value	Order of integration
FSAV	−3.2079	0.0007	I (0)
FSACC	−8.3119	0.0000	I (0)
FSUTZ	−3.5564	0.0002	I (0)
RGDP	−6.4559	0.0000	I (0)
POPG	2.4867	0.0068	I (1)
TEMP	−10.9671	0.0000	I (0)
RF	2.05193	0.0043	I (2)
CO_2	1.9817	0.0091	I (2)
AGLAND	−1.6723	0.0472	I (1)

Source: Author's computation from STATA 17

Of the eight variables under study food utilization is the only one that had more within variation (24.542) than between variation (18.414) signifying great variation within an individual country.

4.2. Unit Root Tests

As presented in Table 4, the test statistics showed that all the dependent variables, food availability, food accessibility, and food utilization, plus other explanatory variables (RGDP per capita, and annual mean temperature) were stationary in level at 5% significant

Table 5: Correlation matrix

	RGDP	POPG	TEMP	RF	CO_2	AGLAND	FSAV	FSACC	FSUTZ
RGDP	1.000								
POPG	−0.074	1.000							
TEMP	−0.032	0.274	1.000						
RF	−0.011	0.114	−0.020	1.000					
CO_2	−0.004	0.452	0.067	−0.332	1.000				
AGLAND	−0.059	0.949	0.212	−0.006	0.616	1.0000			
FSAV	−0.074	0.373	0.093	0.174	−0.294	0.2641	1.000		
FSACC	−0.0259	0.1037	0.117	−0.204	−0.35	0.0249	0.504	1.0000	
FSUTZ	0.0463	−0.123	0.0374	0.014	−0.12	−0.1254	−0.18	−0.0739	1.0000

Source: Author's computation from STATA 17

level as shown in Table 4. Population growth and agriculture land indicated non-stationarity in level and the variables were stationary after first differencing. Carbon emissions and rainfall indicated non-stationarity in level and after first differencing hence approaches such as Panel ARDL were rendered inappropriate paving way for either Feasible Generalized Least Squares (FGLS) or Panel Corrected Standard Errors (PSCE) regression analysis.

4.3. Correlation Matrix Analysis

Table 5 shows that all regressors are not linearly dependent on one another hence the models will not suffer from multicollinearity problems. The results show that the correlation between FS and CO_2 is positive. The same applies to RGDP per capita and Agricultural land.

4.4. Multicollinearity Test

The multicollinearity test was conducted by estimating the variance inflation factor (VIF). Gujarati (2008) underscores that variables do not suffer multicollinearity if VIF is very low. With the mean variance inflation factor (6.36) value which is <10, the table below excludes the possibility of multicollinearity in the set of variables selected for the estimation which is also confirmed by results from the correlation matrix. Table 6 presents the results from VIF.

4.5. Hausman, Breusch Pagan Lagrange Multiplier (LM) and Normality Tests

The Hausman test was carried out to determine whether to use fixed effects or random effects. Given that the probability of the chi-squared was found to be 0.0002, leading to the rejection of Null hypothesis of the Hausman Specification test thereby paving way for the appropriateness of the fixed effects model. This was proceeded by the breusch pagan lagrange multiplier (LM) test for random effects which also pointed to the relevance of the fixed effects model justified by the Prob > chibar2 = 0.0000 for the models of food (availability, accessibility and utilization) security. The Normality test was also carried out using the Jaque-Berra (JB test) where the results showed that the probability of chi-squared was (0.0018) which is significant even at the least significance level and hence the Null hypothesis of normality was rejected. The residuals of the model are not normally distributed therefore the researchers concluded that there were outliers in the data.

4.6. Cross-Section Dependence Tests

In most cases involving macro panels, cross-sectional dependence is a problem that can lead to biased estimation (Greene, 2018; Adeleye et al., 2021; Adeleye et al., 2022). This is especially true for longer panels like the one for this study of 33 years. (Baltagi and Baltagi, 2008). Table 7 shows the pesaran cross sectional dependence test results where the P values were found to be significant signifying the existence of cross-sectional dependence across panels.

Table 6: Variance inflation factor results

Variable	VIF	1/VIF
AGLAND	20.07	0.0498
POPG	16.76	0.059658
CO_2	2.50	0.400205
TEMP	1.42	0.705595
RF	1.28	0.780698
RGDP	1.02	0.980051
Mean VIF	6.36	

Source: Author's computation from STATA 17

Table 7: Pesaran test results

Variable	CD-test	P-value	Correlation	Abs (correlation)
FSAV	3.88	0.000	0.070	0.315
FSACC	5.15	0.000	0.093	0.273
RGDP	9.92	0.000	0.178	0.242
POPG	54.56	0.000	0.981	0.981
TEMP	33.62	0.000	0.604	0.604
AGLAND	8.69	0.000	0.156	0.536

Source: Author's computation from STATA 17

4.7. Serial Autocorrelation and Heteroscedasticity

To test whether the residuals are not serially correlated the Wooldridge test for autocorrelation was performed and the results were significant at 1%, (0.0000) indicating the presence of serial autocorrelation among residuals meaning that the residuals from the estimated model are correlated over time. The modified wald test for groupwise heteroscedasticity in fixed-effect regression was conducted, and the results were significant, signifying the presence of heteroscedasticity. Table 8 shows an extract of the three dependent variables' constants tested for heteroscedasticity that results from food availability, food accessibility, and food utilization.

With presence of heteroscedasticity, autocorrelation and cross-sectional dependency, OLS estimates are inefficient, meaning the variance of the error term is not constant across all observations. FGLS and PCSE estimation techniques becomes imperative given that they address these by weighting observations based on their estimated error variances, giving more weight to observations with smaller variances (Bai et al., 2021; Miller and Startz, 2019; Sandoval, 2023). OLS also provides inefficient estimates when autocorrelation exists, meaning there's a correlation between error terms at different time points or locations which are best subverted by FGLS and PCSE techniques thereby guaranteeing more accurate estimates (Greene, 2018; Bai et al., 2021; Miller and Startz, 2019; Adeleye et al., 2022; Sandoval, 2023). Given that, for robust, efficient, flexible and consistent estimates, either the PCSE or FGLS techniques become the most appropriate for this study as highlighted in Adeleye et al. (2021) and Sandoval (2023). For this study, time period was greater than cross sections (T>N) where T is the number of periods and N represents the number of cross sections), the FGLS procedure was found to be more efficient than the panel corrected standard errors (PSCE).

4.8. Simple Pooled OLS Regression Results

Table 9 below shows the results from the Linear regression for the dependent variables of food (availability, accessibility and utilization) security on selected explanatory variables.

From the results of the regression model, a percentage change in the agricultural land leads to a positive 0.0008 and insignificant change in food availability at 10% level of significance. A percentage change in population leads to a 0.0003 unit change in food availability and the coefficient is significant at all confidence levels. The coefficients of carbon emissions in all three linear regression results have indicated an inverse relationship with the food security indicators. The R^2 value of 0.798 implies that approximately 79.8% of the variation in food security as measured by food availability is explained by carbon dioxide emissions, economic growth, agriculture land, annual mean temperature, average precipitation, and population growth. From the results of the food accessibility regression model, a percentage change in carbon dioxide emissions leads to a 0.0034 negative but significant unit change in food accessibility. A percentage change in rainfall leads to a 0.0122 negative change in food accessibility and the coefficient is insignificant at all confidence levels. The coefficients of carbon emissions in all three linear regression results have indicated an inverse relationship with all the food security indicators. The R^2 value of 0.4067implies that approximately 40.67% of the variation in food security measured by food accessibility is explained by carbon dioxide emissions, economic growth, agriculture land, annual mean temperature, average precipitation, and population growth rate. From the results of the regression model, a percentage change in the carbon dioxide emissions leads to a 0.0013 negative but insignificant unit change in food utilization. A percentage change in rainfall leads to a 0.0004 unit change in food utilization and the coefficient is insignificant at all confidence levels. The coefficients of carbon emissions in all three linear regression results have indicated an inverse relationship with the food security indicators.

However, from the Pooled OLS, Random and Fixed Effects (though not presented) regression analysis, there were observed heteroscedasticity, autocorrelation and cross-sectional dependency in the preferred fixed effects model hence the researchers employed Parks' Feasible Generalized Least Squares estimator. The results obtained from an FGLS model are by default free from econometric problems of heteroscedasticity, autocorrelation, and cross-sectional dependency and produce efficient, robust, flexible and consistent estimates (Greene, 2018; Adeleye et al., 2021; Adeleye et al., 2022; Sandoval, 2023). The results of the FGLS estimation are shown in Table 10.

4.9. FGLS Regression Results on Food (Availability, Accessibility and Utilization) Security

The FGLS results show that the independent variable carbon emissions exert a negative and statistically insignificant impact on food availability (food provision.) in the SADC region. The results are consistent with earlier studies of Leichenko and Silva

Table 8: Test for heteroscedasticity (wald test) results

Variable	Coefficient	Standard error	Z	P~|z|	95% confidence interval	Interval	Wld Chi2
FSAV	54.45312	1.051951	51.76	0.000	52.39133	56.5149	562.53
FSACC	38.08001	15239242	72.68	0.000	37.05314	39.10689	1065.74
FSUTZ	29.81332	2.83154	10.53	0.000	24.26361	35.36304	35.88

Source: Author's computation from STATA 17

Table 9: Linear regression model results for food availability, accessibility and utilization

Food security models	Model 1 ($FSAvl_{it}$)	Model 2 ($FSAcc_{it}$)	Model 3 ($FSUtz_{it}$)
Variable	Coefficient	Coefficient	Coefficient
Economic growth ($rgdp_{it}$)	−0.0673 (0.0785)	0.0036 (0.0822)	0.2212 (0.2528)
Agricultural land ($agland_{it}$)	0.0008* (0.0005)	0.0004 (0.0005)	0.0015 (0.0015)
Carbon emissions (ce_{it})	−0.003*** (0.0023)	−0.0034** (0.0003)	−0.0013* (0.0008)
Population growth ($popg_{it}$)	0.0003*** (0.0001)	0.0002** (0.0001)	−0.0004 (0.0003)
Temperature ($temp_{it}$)	−1.2339 (1.0189)	0.804 (1.0674)	5.4684* (3.283)
Rainfall (rf_{it})	−0.0026** (0.001)	−0.0122*** (0.001)	(0.0004) (0.0031)
Constant	61.6425*** (1.2964)	35.9984*** (1.3581)	35.0644*** (4.1773)
Number of observations	476	476	476
R-squared	0.798	0.4067	0.0296
Adjusted R-squared	0.726	0.3991	0.0172
F-test	92.848	6. 469	6. 469
F	−564.937	−53.57	2.39
Prob>F	0.000	0.000	0.000

***P<0.01, **P<0.05, *P<0.1. Source: Author's computation

Table 10: FGLS regression on food (availability, accessibility and utilization) security

Food security models	Model 1 ($FSAvl_{it}$)	Model 2 ($FSAcc_{it}$)	Model 3 ($FSUtz_{it}$)
Variable	**Coefficient**	**Coefficient**	**Coefficient**
Economic growth ($rgdp_{it}$)	0.0096 (0.0619)	−0.0453 (0.0413)	0.117565 (0.1562)
Agricultural land ($agland_{it}$)	0.0016*** (0.0004)	−0.0007 (0.0003)	0.0001 (0.0008)
Carbon emissions (ce_{it})	−0.0026*** (0.001)	−0.0034*** (0.0002)	0.0001 (0.0004)
Population growth ($popg_{it}$)	0.0001 (0.0001)	0.0004*** (0.0001)	−0.0003* (0.0002)
Temperature ($temp_{it}$)	−0.5658 (0.7377)	−0.3140 (0.4479)	3.5119* (2.1133)
Rainfall (rf_{it})	0.0029*** (0.0011)	−0.0132*** (0.00044)	0.0023 (0.0023)
Constant	54.453*** (1.0519)	38.0800*** (0.5239)	29.8133*** (2.8315)
Number of observations	476	476	476
Estimated covariance	14	14	14
Estimated coefficients	7	7	7
Wald chi2 (6)	562.53	1065.74	53.97
Prob>Chi2	0.000	0.000	0.000

***P<0.01, **P<0.05, *P<0.1. Source: Author's computation

(2014) who found that climate change harms food security under direct biophysical mechanisms. However, crops and other plants grow better in the presence of higher carbon dioxide levels thereby leading to increased yields as alluded to by Nasrullah et al. (2021). This conforms with theoretical literature as suggested by the Environmental Kuznets Curve hypothesis in its first stages. The results of this investigation, however, contradict those of Nabi et al. (2020) who found a negative relationship between carbon dioxide emission and food insecurity.

Results also revealed that an increase in agricultural land under production exerts a negative significant impact on food security. The variable was found to be significant from 1% significant level. Results of this study also revealed a positive and statistically significant relationship between RGDP per capita and food availability from 1% significance level, thus if RGDP per capita increases by 1%, the food provision will rise by approximately 0.01884. The results were consistent with economic theory such as the Poverty, Growth, and Inequality Triangle which sees economic growth within an economy being the best way to eliminate food insecurity and assist those at the bottom through the trickle-down effect. Thus, if the nation experiences economic growth through increases in RGDP, we expect people's lives to improve, as people will have more income, better houses, food, and access to health care leading to an increase in food provision signifying a reduction in food insecurity. Population growth rate was found to have a negative and statistically significant impact on food accessibility and food utilization in the SADC region. If the population grows by 1%, the food provision will decline by -0.0003. The results of the study followed the Gary Becker theory of human capital which emphasizes the need for human capital investment in social expenditures that ultimately reduce food insecurity. These findings are also theoretically supported by Romer (2011) who argued that as population increases output per head also increases until an optimal population is achieved. However, an increase in population above the optimal level will be associated with decreased output per head.

Mean annual temperature despite being positive was found to be an insignificant determinant of food security contradicting Dang and Trinh (2022) who found that increases in temperatures increase food insecurity. This is because global warming increases food insecurity, with more noticeable effects in poorer regions with no mitigation policies against greenhouse emissions. Dang and Trinh (2022). Average precipitation (RF) shows a negative but statistically insignificant impact on food security more specifically food accessibility in the SADC region. This finding aligns with the results of Dang and Trinh (2022) and Burke et al. (2015), who also observed limited or inconsistent effects of rainfall on food access. However, it contrasts with Armand et al. (2019), who found a significant relationship, suggesting that in some contexts, precipitation plays a more decisive role in determining food security outcomes.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Summary of Study

The main objective of the study was to investigate the impact of climate change on food security in 14 selected countries in the SADC region. The selected countries excluded Tanzania due to the unavailability of the data. The findings from the FGLS regression results show that climate change insignificantly impacts food security in the SADC region when measured by either carbon dioxide emission per capita or average precipitation or annual mean temperature. The continuous and steady economic growth experienced explains why more output will be produced and people's lives will improve, even when most of the resources in the region are not yet fully employed. This gives the elements of food security to hinge on the potential maximum utilization of the factors of production in the region. Also, economic growth (RGDP), agricultural land under production, and population growth all have statistically significant impacts on food security in the selected SADC countries (population growth exerts a negative impact while economic growth and agricultural land under production exert a positive impact on food security).

5.2. Policy Recommendations

Based on the findings of this study, there is tremendous need in the region to significantly invest in climate adaptation, mitigation, and resilience building strategies (disaster risk reduction) to reduce its adverse effects of climate change on food security in both the short and long run. Targeting economic growth is essential for the region to escape the cycle of food insecurity. Southern African countries governments and policymakers should also maintain macroeconomic stability and address structural constraints to accelerate growth by reducing the high costs of doing business and excessive regulatory burdens. Policymakers in the SADC region must therefore pursue integrated economic growth which is essential for raising output and income as well as ensuring that the advantages of economic growth are widely distributed. Economic integration will enable the region to complement each other's efforts as the same countries in the same region sometimes experience different climatic conditions in a year. However, economic growth must occur faster than population expansion if it is to have a positive impact on alleviating poverty.

As the region is dominated by countries that significantly rely on the primary production systems like agriculture, the adoption of green and sustainable production means will result in economic growth that may in turn exert a positive and significant impact on food security in the region. Regional efforts to end extreme poverty (food insecurity) must focus on boosting agricultural output and productivity. This can be done by the promotion and adoption of high-yield crop varieties and intensifying the use of land through increased irrigation where rain-fed agriculture is insufficient/ impossible. Moreover, policymakers in SADC countries should make deliberate efforts to strengthen welfare-oriented strategies such as productive safety nets and emergency relief aid programs. Policymakers should also consider land reform as it improves distribution and growth because in most African states, there has been unequal distribution of the land inherited from the colonial regimes leaving some large tracks of land underutilized. However, such programs (land redistribution) should target economically active populations (age), education levels and farming experience and household farming assets as highlighted in Matsvai et al. (2022) because many of the beneficiaries of such programs worsened the underutilization of agricultural land hence food insecurity continues.

5.3. Areas of Further Research

Due to countries within the region being heterogeneous (rainfall patterns, mean temperature and levels of macroeconomic activity) in some of the measurements and scales used, econometric modeling of climate change and food security may bring different and more informative results based on country specific evidence (time series analysis). Future studies should also consider the inclusion of other food security indicators like stability (to broaden the general understanding the effects of climate change on food security). Future studies should use other proxies of food security like multidimensional poverty index, share of dietary energy supply derived from cereals, roots, and tubers (percent) (3-year average), Prevalence of severe food insecurity in the total population (percent), Per capita food supply variability (kcal/cap/day) which would give different results. Despite the current study concentrating on the production side of food security, other control variables like the occurrence of wars, global price increases, and population movements can be infused as control variables and different and equally informative results can be revealed.

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