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Analysis of Climate Change Impacts on the Food System Security of Saudi Arabia

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Abstract: Climate change poses a challenge to the security and long-term viability of the global food supply chain. Climate unpredictability and extreme weather events have significant impacts on Saudi Arabia's vulnerable food system, which is already under stress. The Kingdom of Saudi Arabia faces distinct challenges in comparison to other dry locations across the world. Here, the per capita water demand is high, the population is growing, the water resources are extremely limited, and there is little information on the existing groundwater supplies. Consequently, it is anticipated that there will be formidable obstacles in the future. In order to make data-driven decisions, policymakers should be aware of causal links. The complex concerns pertaining to the Saudi Arabian food system were analyzed and rationally explained in the current study. A causality analysis examined different driving factors, including temperature, greenhouse gas (GHG) emission, population, and gross domestic product (GDP) that cause vulnerabilities in the country's food system. The results of the long-run causality test show that GDP has a positive causal relationship with the demand for food, which implies that the demand for food will increase in the long run with an increase in GDP. The result also shows that Saudi Arabia's GDP and population growth are contributing to the increase in their total GHG emissions. Although the Kingdom has made some efforts to combat climate change, there are still plenty of opportunities for it to implement some of the greatest strategies to guarantee the nation's food security. This study also highlights the development of appropriate policy approaches to diversify its import sources to ensure future food security.

Keywords: food system vulnerabilities; climate change policy; agriculture; adaptation and mitigation strategies

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1. Introduction

Food security encompasses food, its production, commerce, and nutrition, as well as the processes by which people and nations sustain access to food across time in the face of diverse challenges [1]. When the food system, which includes food supply, access to food, and consumption, is affected by a variety of variables, such as climate change, food security is compromised. Water and food security are critical concerns as a result of climate change, as both are extremely subjective to shifting climatic trends [2]. Global climate change-related issues, such as increasing temperature, the occurrence of droughts, and variability of weather will continue to mount on the existing agricultural ecosystems. Accelerated increases in GHGs in the environment are primary contributors to climate change.

Climate change can have several different effects on food systems, ranging from direct impacts on crop production (e.g., changes in rainfall resulting in drought or flooding, or warmer or cooler temperatures resulting in changes in the length of the growing season) to market, food price, and supply chain infrastructure changes [3]. Direct impacts refer to the effects on specific agricultural production systems produced by changes in physical features, such as temperature levels and rainfall distribution [4]. An increase in temperature may bring about a sudden change in the overall condition of an area [5]. Temperature increases can cause a rapid shift in the overall state of the environment. A temperature rise may result in higher heatwaves and droughts or more heavy rainfall events as well as flush flooding in temperate regions. Similarly, increased carbon dioxide (CO_2) concentrations will benefit a wide variety of crops by increasing biomass buildup and eventual yield. However, not all crops respond favorably to changes in atmospheric CO_2 levels. Certain cereal and forage crops, for example, exhibit decreased protein contents when exposed to high CO_2 [6,7].

Climate change may indirectly impact food production by altering the behavior of some species, such as pollinators, pests, disease vectors, and invading species. Changes in food production settings may result in the emergence of diseases, the introduction of new crop and livestock species, changes in pesticide and veterinary medication usage, as well as changes in the primary transfer routes by which pollutants migrate from the environment to food [8]. Moreover, the rising temperature and warmer oceans may lead to the deterioration of the quality of marine life [8–11]. The effects of climate change on the food system are summarized in Figure 1.

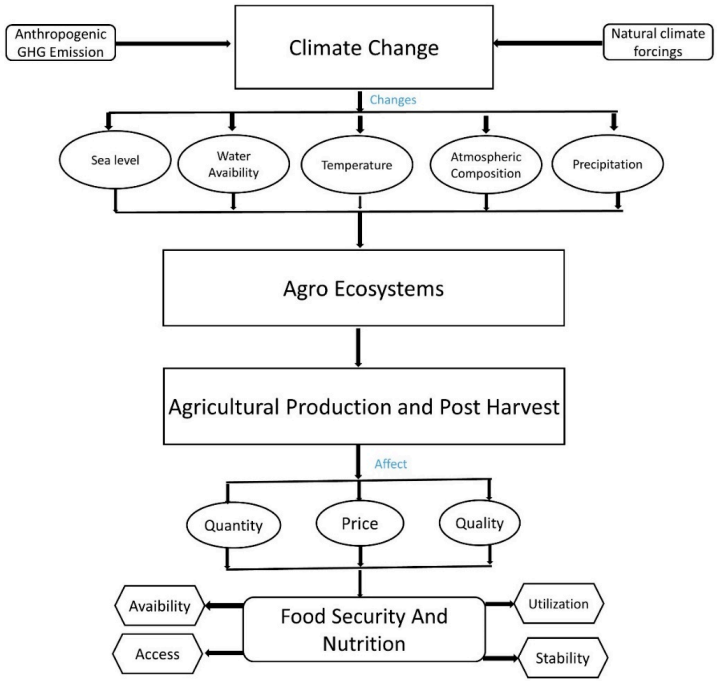


Figure 1. The cascading effects of climate change on food security (adapted from [12]).

The population is another major factor impacting food security. Global human population estimates for 2050 range from 7.96 to 10.46 billion, and the estimated average variant is 9.19 billion [13]. So it will be difficult in the future to feed that much of the population as, in future decades, agricultural and food systems around the world will confront significant problems. As a result of a variety of factors, global food demand continues to rise significantly [14]. Climate change indirectly affects food prices, thus restricting food access to people. Increased food prices have been shown to reduce the nutritional quality of dietary intake, worsen obesity, and amplify health disparities. Developed nations have sophisticated systems in place that may be utilized to adjust to the food safety repercussions of climate change; however, their efficacies vary by country, and their capacities to respond to nutritional difficulties are less clear [8]. Climate change's proportional influence on food security varies by area, although it is most noticeable in developing nations, as well as Africa and the Middle East [15].

Food security will be a problem in the future for policymakers in the overall Middle East, particularly in the Kingdom of Saudi Arabia (KSA). Saudi Arabia occupies an area of roughly 2,149,690 square kilometers and is home to 30.77 million people [16]. Saudi Arabia occupies the greater share of the Arabian Peninsula and is one of the world's driest countries, devoid of permanent rivers and lakes. It is located in the Middle East's tropical and subtropical desert region between the Arabian Gulf and the Red Sea; temperatures in some regions can exceed 50 °C (122 °F), resulting in oppressively hot and dry conditions. Due to the severe and high temperatures, the environmental conditions are unfavorable for farming [17]. Because of its continental climate, cold winters, hot summers, and unpredictable rainfall, the KSA is one of the most sensitive countries to climate change. In desert countries, such as Saudi Arabia, where indigenous production cannot match demand, food is imported from other countries. Food items are mostly imported into desert nations since the native output is insufficient to fulfill domestic demands, and Saudi Arabia is no different. Numerous agricultural projects have been initiated at various points in time to provide food security and rural development; however, several ended with little or no success [18].

Saudi Arabia's current and future demands for domestic output expansion without resorting to desert agriculture are constrained by land and water shortages. Water resources are critical components of agricultural productivity in every country. Saudi Arabia is one of the nations that could suffer severe water scarcity by 2050. Saudi Arabia's existing water resources indicate that it will be unable to fulfill local food demands, forcing it to import food.

Agriculture consumes over 70% of total water withdrawals globally on average, making it by far the greatest water consumer of all sectors. This results in an inherent link between a country's renewable water resources and its ability to produce food. Saudi Arabia's overall water requirement for the agricultural sector is not always much greater than those of other countries. The fundamental distinction between food production in KSA and other parts of the world is the extent to which Saudi Arabia is water-scarce in comparison to the other nations. However, Saudi Arabia's declarations and certain actions that continue to promote local food production to meet the local demand may only seem feasible for the present condition. Growing consciousness of the importance of increasing water yield has also prompted the Saudi government to reduce support for crops, which needs a lot of water, such as wheat and alfalfa (for livestock production) in favor of organic farming (which requires less water and energy due to the absence of fertilizers and pesticides) for human intake [19,20].

The Kingdom of Saudi Arabia relies mostly on imports as a result of the recent attempt to end crop production. This could have minimal or no effect at this time. In the long run, however, it is likely that any worldwide disruptions in agribusiness caused by climate change or regional instability will exacerbate the problem. It will undermine the nutritional and food security of Saudi Arabia. In order to develop a clear direction for sustainable food security and nutrition, it is vital to examine these factors in the present situation.

Moreover, climate change poses a significant threat to the security and long-term stability of Saudi Arabia's food supply network and has a substantial influence on Saudi Arabia's already-fragile agricultural system. Therefore, the study aims to examine the effects of climate change on the security and long-term sustainability of the food system in Saudi Arabia, taking into account the current situation while also making recommendations for the future.

The next section describes the challenges of food security in Saudi Arabia, followed by the methodological foundation and the data used in this research. Section 3 presents the results of the causality analysis, supplemented by the discussion in Section 4. Finally, Section 5 highlights the conclusions and proposed policy implications.

1.1. Challenges to Food Security in Saudi Arabia

Having a reliable supply of food on hand at all times is crucial for maintaining social order. It is possible to say that people have food access if they have the resources to obtain the foods that are essential for nutritious diets [21]. However, regarding the KSA, due to the lack of agricultural natural resources, increased dependency on food imports, incentives, import tariffs, water limitations, high rates of food loss, and growing pressures from climate change, there will likely be intensified issues related to global food security [15]. Although Saudi Arabia has increased its domestic production of various crops in a short period, Saudi Arabia quickly recognized that wheat growing was water-demanding, putting a strain on the country's groundwater sources. The groundwater table in the Kingdom frequently dries up as a result of poor rainfall and high demand. There is a lack of community and public knowledge and understanding of the water situation despite severe water constraints. Among the most serious vulnerabilities is the growing shortage of natural resources, particularly water and land, which are threatened by degradation, overconsumption, biodiversity loss, pollution, and extreme climatic extremes. Water resources are becoming scarce and stressed as a result of the rising population and wealth, as well as the effects of climate change. The challenge of feeding the Kingdom's population, which is expected to exceed 38 million by 2030, in the face of shifting food preferences, increasing non-food demand for agricultural products, declining agricultural growth and production, and uncertainty caused by changing weather patterns has garnered considerable attention recently. To comprehend the Kingdom's concern about food security, one must first have a thorough understanding of the challenges it faces, which render the Saudi food supply very vulnerable and largely dependent on the global food market.

1.1.1. Adverse Weather Conditions

Saudi Arabia has repeatedly suffered record-breaking temperature extremes over the previous decade, wreaking havoc on the country's socio-economic condition [22]. These unfavorable circumstances have a huge impact on the country's food system. Temperature is directly linked to food production. Saudi Arabia's climate is characterized by high temperatures during the day and freezing temperatures at night. The country has a desert climate, except for the southwest, which has a semi-arid climate. There is significant temperature and humidity variance due to the influence of a subtropical high-pressure system. Summer temperatures range from 45 °C to 54 °C. The heat rises shortly after daybreak and lasts until dusk, with cool nights in between. Winter temperatures rarely drop below 0 °C, but the lack of humidity and the significant wind chill makes for a very chilly climate. Spring and autumn bring milder temperatures, around 29 °C. Evapotranspiration is increased, soil moisture is reduced, and mechanical weathering occurs as a result of high temperatures and low precipitation. In Saudi Arabia, the maximum annual temperature for the coastal plain region is around 39 °C, 29 °C for the foothills, and 28 °C for the mountain region [23,24]. A study was conducted in Saudi Arabia to find out the changes in precipitation and temperature from 1967 to 2016 (50 years) and estimated the major effects of temperature fluctuations on food production. The analysis finds that the average temperature has increased by 1.9 °C over the last five decades, with the highest increase

occurring during the summertime [15]. Additionally, the results indicate that an increase in temperature by one degree Celsius affects agricultural yields by 7–25%. Alam et al. [25] projected that wheat, barley, date, and vegetable yields could decline by more than 30% as a result of temperature and rainfall changes predicted in SRES scenarios. In Saudi Arabia, December and January are ideal corn-planting months [26]. Winter wheat, dates, vegetables, and citrus fruits are the most important crops in Saudi Arabia. Irrigation is required for all of these crops, which could be damaged by climate change. The center and northern regions of the country are home to the bulk of the country's manufacturing operations [27]. Dates are grown in enormous quantities in Saudi Arabia. Total dates output in 1996 amounted to 620,695 tons, mainly originating from the central and eastern regions of the country [28]. According to a regional study, a 1% rise in winter temperatures was shown to reduce agricultural output by 1.12% [28].

1.1.2. Changing Rainfall Pattern

The amount of rainfall in any area affects the amount of water available for agriculture, industry, and other human activities. There is little and irregular rainfall in Saudi Arabia, but it is sporadic at best and extremely heavy during local storms. A combination of Saudi Arabia's western location in the subtropical zone and its natural topography ensures that the western part of the country experiences long periods of dry weather [29–31]. According to research, the annual precipitation is estimated to be around 52.5 mm/year, with a peak of 284 mm in 1996 [29]. The greatest annual rainfall in the coastal plain region is around 100 mm, 230 mm in the foothills, and 650 mm in the mountains. The foothills receive 230 mm of yearly rainfall, whereas the mountains receive 650 mm. More than a few studies have established that elevation has a significant impact on precipitation intensity and dispersion, especially in mountainous areas [23,32]. Due to its moderate elevation and location within the subtropical zone, Jeddah receives a moderate amount of rainfall in comparison to the rest of the country [33]. Between November and May, KSA receives over 80% of its annual precipitation. The southwest, middle, and eastern regions receive the most rain in the spring whilst the second highest rainfall occurs in winter in the eastern and northeastern parts of KSA. Summer is the driest season in KSA, with the exception of the mountainous southwest region. The horizontal distribution of rainfall in autumn is comparable to that in spring, although the volume of rainfall in autumn is less than that in spring [34]. The frequency of floods and droughts will increase as erratic rainfall and a lengthened dry season lead to lower quality grain and weaken grain storing and preserving systems [35]. Rainfall has a good influence on all crops, according to a recent study in Saudi Arabia. Rainfall, on the other hand, was unable to mitigate many of the negative effects of excessive heat [15]. Therefore, in Saudi Arabia, temperature, rather than rainfall is a more crucial factor in food security.

1.1.3. Limited Water Supply

The KSA is one of the world's driest places, with very limited water supplies. Long-term climatic changes have a significant and irreversible effect on water supplies, affecting agriculture production as well as public health. Because depletion occurs far more rapidly than renewal, long-term groundwater withdrawal is not feasible [36]. Therefore, the KSA is supplementing its supply of water with desalination plants' water and treated sewage rather than relying solely on rainwater. The needs of the KSA's people are met by a combination of renewable and nonrenewable sources of water. The Kingdom's deep groundwater reserves are estimated at 1919 bcm (billion cubic meters) and the recharge rate of all deep aquifers is estimated at 2.7 bcm per year [37]. To counteract desertification, the Kingdom has to use marginal land and seawater for forage and crop cultivation, coastal landscaping, and dune stabilization.

Water shortage is also a constraint on agriculture in the nation. Despite the widespread use of sophisticated irrigation methods, poor water consumption persists and is frequently observed on farms. At the moment, irrigation efficiency is 50% in the country which is

a major concern [38]. Additionally, poor water management resulted in massive water loss. According to Global Water Intelligence [39], 30% of desalinated water never reaches end-users and is lost to the environment during distribution. Due to a lack of established processes and a lack of quantitative knowledge, it is impossible to produce accurate estimations of the total amount of this "nonrevenue" water [39]. However, The Arabian Peninsula's irrigated agriculture has grown rapidly in the last four decades due to government policies promoting food security. Since 1980, the area planted for horticultural crops has increased by 12 to 15% per year, while date palms have increased by 4% [37,40]. The areas of salt-sensitive vegetables, melons, and fruit trees have also increased significantly [40]. Increased irrigation and productivity have resulted in a rise in the area of crops farmed. Up until 1990, the area irrigated expanded by 5% per year, then by 1.2% per year following that [40].

1.1.4. Insects, Pests, and Diseases

Pests and disease outbreaks, among other biological hazards, constitute a major threat to the health and well-being of humans, animals, and plants. As a result, they frequently occur concurrently with other disasters, threats, and protracted crises, causing cascade effects, heightening risks, and entrenching vulnerabilities. As the climate changes, so will the patterns of insect and disease infestation. The prevalence of many insects and diseases in the ecological systems has gone up significantly in recent times as a result of the changing precipitation and temperature [41]. Reduced income from meat production, lower crop harvests, decreased forest ecosystems, shifts in aqueous species, and higher control costs all result from insects and illnesses that affect plants and animals, as well as alien invasive aquatic species [42–44]. A summary of the loss of yield for major crops is shown in Table 1.

Table 1. Approximate loss in Saudi Arabia's key crops due to insects, pests, and disease.

Crop	Insect/Pest	Approximate Yield Loss (%)	Season of Occurrence	Reference
Dates	Red palm weevil	12.6–20%	Year-round, but most prevalent between March and May and October and November	[45]
	Termites		Year-round	
	Green and white pit scale insect		Year-round	
	Inflorescence weevil and beetle		June–July	
	Fruit rots		June–July	
	Birds		July–October	
Sorghum	Charcoal rot		winter	[46]
	Gray leaf spot		Winter	
	Smut (Covered kernel) *Sporisorium sorghi*		Winter season	
Millet	Cercospora leaf spot (Cercospora penniseti)		Summer	[46]
	Ergot (Claviceps fusiformis)		Summer	
Cotton	*Micvocevotermes divevsus* Silv.		Spring	[47]
	Eavias insulana Bois.		Spring	
	Oxycavenus hyalinipennis Costa.		Summer	
Sesame	*Antigastra catalaunalis* Dup.		Summer	[47]
	Aphis gossypii Glover.		Spring and summer	

Table 1. *Cont.*

Crop	Insect/Pest	Approximate Yield Loss (%)	Season of Occurrence	Reference
Wheat and barley	*T oxopetera grarnirmn* Rondani	12–26%	Winter and Spring	[47]
	grotis ypsilon R.		Autumn and winter	
	Phytophaga destructor Say.		Summer	
	Scbistocerca gregaria Forsli.		Autumn	
Apple	*Eriosoma lanigera Hausum.*		All year	[47]
	Lepidosaphes ulmi L.		All year	
	Venturia inequalis		All year	

1.1.5. Increasing Population and Urbanization

The Kingdom of Saudi Arabia has seen a surge in population and widespread migration to metropolitan regions in quest of better prospects. Saudi Arabia's population is predicted to increase, mostly as a result of increased life expectancy and a decreasing newborn mortality rate. Saudi Arabia's population expanded from around 4 million in 1960 to approximately 32.5 million in 2018. With its current population, the KSA is the world's 41st most populated country. By 2020, the population is estimated to reach 34.4 million, then grow by 77% to more than 56 million by 2050. These expansions have exacerbated the country's already-scarce water resources' strain and demand [48–50]. Growing urbanization increases food consumption. Urbanization facilitates the establishment of huge supermarkets (retail formats) and increases access to foreign suppliers (imports), hence expanding the available variety of choices in response to the rapid growth in per capita food consumption. As production has been reduced in comparison to prior years, the Kingdom is now more reliant on imported food than ever.

1.2. Climate Change Impact on the Food Supply Chain

Supply chain management has played a vital role in the food retail industry in industrialized countries by efficiently delivering quality products to varied client groups. Saudi Arabia is rapidly catching up with the developed world in terms of super and hypermarket growth [49]. The stability of the food system could be jeopardized by an increase in the severity and intensity of droughts and floods [51]. Climate extremes and climate change increase the risk of food insecurity in this region. Unfortunately, however, population expansion, urbanization, and economic shifts will remain the leading causes of food insecurity through 2030. The economic change will influence employment, income, and people's ability to buy food [28].

Temperature changes, ozone, and water and fertilizer shortages may offset these potential production gains. For example, if temperatures are too high, or if water and nutrients are insufficient, yield increases may be curtailed or reversed. In alfalfa and soybean plants, high CO_2 has been linked to lower protein, nitrogen, and quality. Reduced grain and forage quality can reduce pasture and rangeland productivity [51]. It is also found that extreme weather can impede agricultural growth and warmer and wetter conditions, as well as higher CO_2 levels, favor the growth of weeds, pests, and fungi. Due to insect pest infestation, Saudi Arabia faces around 12.6–20% yield losses annually [45]. Floods and droughts can destroy crops and diminish production. High evening temperatures harmed maize output in the US Corn Belt in 2010 and 2012, and an unusually hot winter claimed USD 220 million in Michigan cherry losses in 2012. Saudi Arabia has the same scenario as well [49,51].

2. Materials and Methods

An overview of the procedures used in this investigation is shown in Figure 2. As can be seen from the figure that firstly data related to food (imported and produced) and

climatic as well as socio-economic parameters were collected from the open literature. The same data were used for causality analysis. Based on the results of the causality analysis, long-term and short-term demands are predicted. Finally, different mitigation measures to combat the effect of climate change on food security are critically discussed.

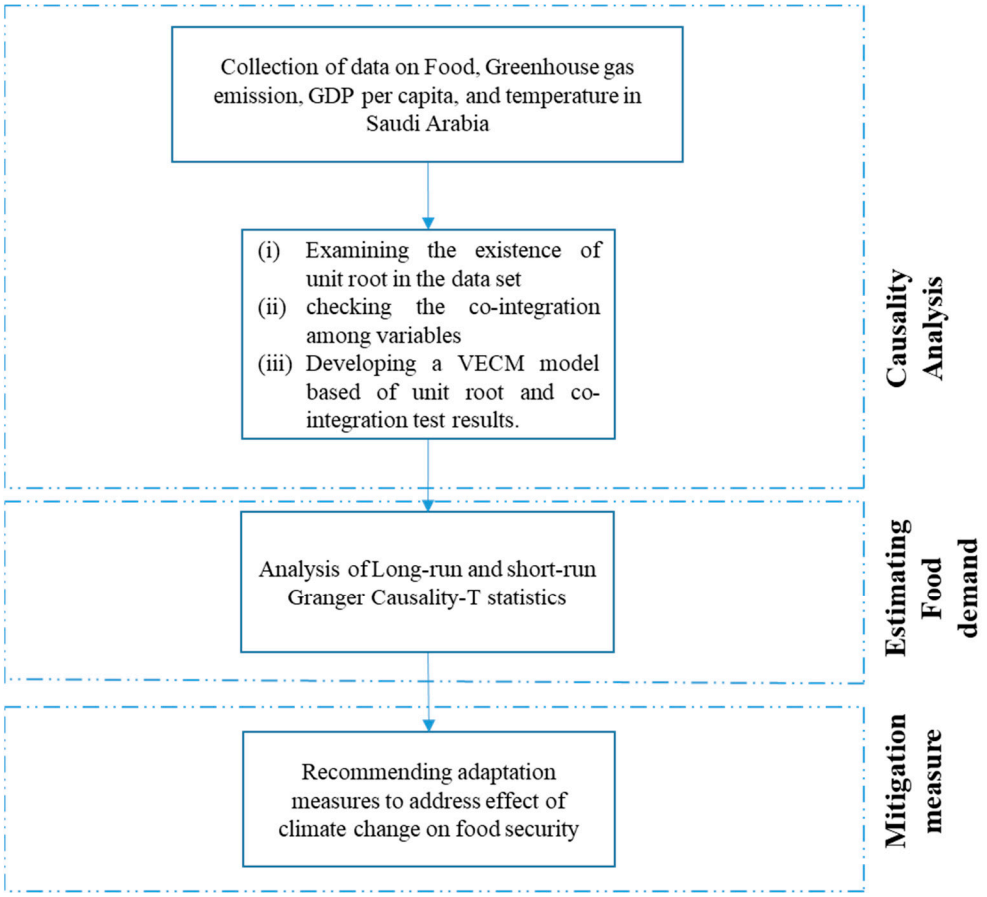


Figure 2. Methodology of the current study.

2.1. Causality Analysis

This study used the EViews statistical software tool to conduct a causality analysis in order to identify imported and produced food in Saudi Arabia. Several determinants, such as GHG (greenhouse gas emissions), Pop (total population of Saudi Arabia), GDP (the sum of all domestic goods produced in Saudi Arabia in a single year divided by the population of that country), and Temperature (average temperature of Saudi Arabia), were analyzed.

Through the development of the vector error correction model (VECM), both short-run and long-run evaluations of the causality were conducted. A VECM is used in this study because it is a widely used method and it explores all interactions among explanatory variables for both short- and long-run and estimates the influence of each explanatory variable on the dependent variable [52,53]. Another reason for using the VECM is that variables used in this econometric analysis are co-integrated among themselves [54]. For instance, greenhouse gas emissions, population number, average temperature, and GDP combined contribute to the demand for food, while GDP often contributes to greenhouse gas emissions. These associations among explanatory variables themselves make the models interdependent. According to Pasinetti [55], the majority of current econometric analysis is done using fully interdependent models, and the Neoclassical theoretical framework of economics supports the interdependence of these variables. For variables that are not interdependent but have a causal relationship, Pasinetti [55] considers that the Classical and the Keynesian theories of economics better represent those variables.

Table 2 lists the specifics of the data used by these models, and then Tables 3 and 4 outline the necessary components and crucial steps in creating VECMs.

Table 2. Data used in causality analysis.

Variables	Descriptions	Year	Unit	Data Source
Food	Food = food imported + food produced (including grains, fruits, and vegetables)	1990–2019	tons	Saudi Arabian Monetary Agency: Annual Statistics [56]
GHG	Greenhouse gas emissions	1990–2019	Million tons of CO_2-Eq.	World Resource Institute [57]
Pop	Total population of Saudi Arabia	1990–2019	Million	World Development Indicators: Databank [58]
GDP	The sum of all domestic goods produced in Saudi Arabia in a single year divided by the population of that country.	1990–2019	Billion USD	World Development Indicators: Databank [58]
Temp	Average temperature of Saudi Arabia	1990–2019	Degree Celsius	Earth Policy Institute Data Bank [59]

Table 3. Unit root test results of dependent as well as independent variables.

At level	Test Statistics: ADF		Test Statistics: PP	
	Intercept	Intercept & Trend (I&T)	Intercept	(I&T)
Food	−2.12 (2)	−4.41 *** (0)	−2.04 (2)	−4.41 *** (0)
GHG	−2.30 (2)	−3.00 (2)	0.08 (2)	−1.59 (1)
Pop	−3.13 ** (7)	−4.49 *** (6)	2.95 (2)	−1.30 (2)
GDP	0.18 (0)	−2.03 (2)	0.19 (1)	−2.06 (1)
Temp	−2.57 (2)	−4.81 *** (2)	−2.36 (1)	−4.81 *** (1)
	At first difference			
Food	−5.99 *** (0)	−6.05 *** (0)	−8.95 *** (2)	−9.45 *** (5)
GHG	−3.24 ** (2)	−3.30 ** (2)	−3.24 ** (2)	−3.25 ** (2)
Pop	−4.39 *** (6)	0.47 (6)	−3.26 ** (2)	−3.45 ** (2)
GDP	−4.55 *** (2)	−4.58 *** (2)	−4.49 *** (2)	−4.52 *** (2)
Temp	−8.31 *** (2)	−8.14 *** (2)	−21.45 *** (2)	−24.99 *** (2)

Significance levels at 0.05 and 0.001 are indicated by **, and ***, respectively. Schwarz Info Criterion (SIC) is used for selecting Lag Lengths and these are presented within parenthesis.

Table 4. Johansen's test of co-integration results.

Co-Integration Equation (CE) Number	Hypothesis	Trace Statistics	Max Eigenvalue Statistics
r = 0	No CE	140.38 ***	74.30 ***
r = 1	At most 1 CE	66.08 ***	38.38 ***
r = 2	At most 2 CE	27.70 *	21.56 **
r = 3	At most 3 CE	6.14	5.99
r = 4	At most 4 CE	0.15	0.15

Note: Significance levels at 0.1, 0.05 and 0.001 are indicated by *, **, and ***, respectively.

2.1.1. Model Specifications

This study constructed a distinct model for food (imported + produced including grains, fruits, and vegetables). A variety of independent or explanatory factors have been discovered for this dependable factor. The model included food as the dependent variable and GHG (greenhouse gas emissions), Pop (total population of Saudi Arabia), GDP (the sum of all domestic goods produced in Saudi Arabia in a single year divided by the population of that country) and temperature (average temperature of Saudi Arabia) are dependent variables.

Considering the aforementioned, the following is defined in this investigation.

$$(\text{Food})t = \alpha + \beta 1\ \text{Tempt} + \beta 2\ \text{GDPt} + \beta 3\ \text{Popt} + \beta 4\ \text{GHGt} + \varepsilon t \quad (1)$$

where α: the intercept; t: the year; $\beta 1$ to $\beta 4$: coefficients for independent or explanatory variables; and ε: constant error terms.

Equation (2) is the logarithmic form of Equation (1).

$$\text{Ln}\ (\text{Food})t = \ln(\alpha) + \beta 1 \ln(\text{Tempt}) + \beta 2 \ln(\text{GDPt}) + \beta 3 \ln(\text{Popt}) + \beta 4 \ln(\text{GHGt}) + \ln \varepsilon t \quad (2)$$

2.1.2. Developing VECM Models

Understanding causal linkages between dependent and independent variables require:

(i) Testing for the presence of unit roots in the set of data;
(ii) Verifying the existence of co-integration within factors;
(iii) Developing a VECM based on the results of these tests

Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests were used to look for evidence of unit roots in a given factor. The existence of unit roots indicates that a data series is quasi [56]. A key requirement for using time series data in a VECM is that the parameter is quasi-just at the threshold and static at the first divergence [57]. The ADF test was used because it is widely considered to be a reliable unit root test [58]. However, the ADF test is sometimes limited in its capacity to discard a unit root [59], thus the PP test is utilized in conjunction with the ADF test. Furthermore, [56] confirmed that combining both procedures is likely to produce trustworthy results. Given the unit root, this study used Johansen's test of co-integration to identify which of the two variables (direct and indirect) were co-integrated. The creation of a VECM model required co-integration between a minimum of 2 factors. In order to test for the presence of co-integration among multiple parameters, we analyzed trace statistics (TS) and maximum eigenvalue statistics (MES). It was expected that using two different types of statistics would yield reliable results. Throughout this research, we built the VECM and then performed the Granger causality analysis using the results of the unit test and the co-integration test to learn more about the connection between food and nutrition security and its underlying causes in both the short- and long-term.

3. Results and Discussion

3.1. Causality Analysis

3.1.1. Unit Root Test

Examining the unit root test outcomes is shown in Table 3. As evident from Table 3, the optimal lag length based on Schwarz info criterion (SIC) for the variables is two.

3.1.2. Johansen's Test of Co-Integration

One of the conditions that must be met in order to begin work on a VECM model is the existence of at least one co-integrating equation. This indicates that at least two of the time-series parameters that were utilized in this investigation required to be incorporated among each other [60]. According to Table 4, the model has at least one co-integrating equation at a significant level of 0.01. For the purpose of this study, the application of a vector error correction model rather than a vector autoregressive model (VAR) is supported by this evidence.

In Table 5, we can see the generated model's co-integrating coefficients for several explanatory or independent variables. How one independent variable affects another is indicated by the sign of the coefficient. Table 5 shows that the coefficient of each independent variable is positive. This means that an increase or decrease in greenhouse emissions, population, GDP, and the average temperature of Saudi Arabia will increase or decrease the demand for food, respectively.

Table 5. Co-integrating equation.

Dependent Variable: Food			
Explanatory Variable	**Coefficient**	**Standard Error**	**T Statistics**
Constants	-4.7×10^8	7.7×10^8	−0.61
GHG	1.3×10^5	2.4×10^4	5.63
Pop	4.02×10^5	7.4×10^5	0.54
GDP	6.3×10^4	8.3×10^3	7.6
Temp	2.06×10^7	1.7×10^6	11.9

3.1.3. Short- and Long-Run Granger Causality (GC) Tests

Granger causality tests were used to examine the long-term and short-term effects of particular independent factors (such as GDP/capita, populations, GHG, and temperature) on food security. Granger causality tests have the advantage of examining the direction of causation between both independent and dependent variables. As indicated in Table 6, F-statistics were used to determine the short-run relevance of factors in causing an event, while t-statistics were employed for long-run causality running [61].

Table 6. Short-run and long-run causality tests.

	Short-Run Granger Causality-F Statistics					**Long-Run Granger Causality-T Statistics**
	Ln (Food)	**Ln (GHG)**	**Ln (Pop)**	**Ln (GDP)**	**Ln (Temp)**	**Error Correction Terms**
Ln (Food)	-	0.43 (0.66)	0.06 (0.96)	2.31 (0.13)	0.57 (0.58)	3.43 *** (0.004)
Ln (GHG)	0.78 (0.48)	-	6.90 *** (0.008)	8.13 *** (0.004)	2.07 (0.16)	0.61 (0.55)
Ln (Pop)	0.13 (0.88)	1.02 (0.39)	-	0.50 (0.62)	1.00 (0.39)	0.30 (0.77)
Ln (GDP)	0.21 (0.81)	2.45 (0.12)	1.83 (0.19)	-	1.53 (0.25)	2.01 * (0.06)
Ln (Temp)	0.94 (0.41)	0.27 (0.77)	1.26 (0.31)	3.10 * (0.07)		1.04 (0.31)

Note: Significance levels at 0.1 and 0.01 are indicated by * and ***, respectively. Values within the parentheses are probability values or *p*-values.

The results of the long-run causality test show that GDP has a positive causal relationship with the demand for food and the relationship is significant at 0.1 level. This implies that the demand for food will increase in the long run with an increase in GDP. Given that the progress of a country depends on GDP and continuous growth in the GDP is desirable for Saudi Arabia, the country needs to focus on its food security in the long run. The GDP does not directly affect food demand in the short run. The findings of the short-run causality test demonstrate the existence of a possible connection between population and GDP to GHG emissions, and the results are substantial at 0.001 level. This means that Saudi Arabia's GDP and population growth are contributing to the increase of their total greenhouse gas emissions in the short run. Similar findings are found by another research that applied a cross-sectional autoregressive distributed lags (CS-ARDL) estimator for analyzing the dynamic relationship among carbon dioxide emissions, energy consumption (disaggregated), natural resources, urbanization, and economic growth for Gulf Cooperation Council countries. Their findings also revealed that urbanization (i.e., urban population), GDP growth, and the consumption of non-renewable energy deteriorate the quality of the environment (i.e., increase CO_2 emissions) [62]. To reduce GDP-induced greenhouse gas emissions, Saudi Arabia needs to ensure a smooth transition towards a low-carbon economy. Technological innovations and increased investment in environmental technologies (such as clean energy) are recommended by Majeed et al. [63] for

lowering ecological footprint including emissions levels [63]. The result also shows that Saudi Arabia's GDP has a causal relationship with average temperature and the causal relationship is running from GDP to average temperature.

According to the results of the analysis, it is apparent that, on the one hand, the demand for food would increase as the GDP rises and, on the other hand, the GDP is vital for the development of the country. Again, the relationship between population growth and GDP expansion, and GHG emissions was discovered. Consequently, adaptation methods (managing the negative consequences of the environmental transition to promote resilience and minimize vulnerability) are necessary for controlling food system security indicators. The following section discusses different adaptation measures, which ultimately address managing the indicators which are vulnerable to overall food security.

3.2. Adaptation Initiatives to Climate Change Impacts on the Food System in Saudi Arabia

Kingdom is especially vulnerable to the negative effects of climate change due to its arid climate. A rise in temperatures of 3 to 5 degrees Celsius would have catastrophic effects on agriculture and other areas of the economy [64,65]. It is a critical component of climate strategy, particularly in nations that are severely vulnerable (e.g., Saudi Arabia). Actions for climate change adaptation connected to the food system in Saudi Arabia may be divided into three categories: supply-side, infrastructure, and demand-side.

3.2.1. Supply-Side Measures

Food production (grain production, livestock, and fisheries), storage, transportation, processing, and commerce all include supply-side adaptation. Agricultural production is anticipated to experience a loss in output as a result of climate change. Stopping or drastically reducing winter wheat and some other crop yields in the Kingdom owing to a lack of water is not a viable long-term solution. Possible solutions to the problem include expanding the use of conservation agriculture, establishing a stricter water consumption policy, improving research and development, and boosting the application of efficient irrigation systems, such as drip and sprinkler irrigation [15]. Many existing and emerging agricultural management strategies may be implemented in the Kingdom to counter climate change's impact on food security. Increasing soil organic matter, improving agricultural management, increasing food yield, and preventing and reversing soil erosion are all potential adaptation approaches. Soil maintenance including adjusting planting time, cultivation conditions, or variety has all been shown to increase agricultural output in past research [66–73]. Agriculture production could be enhanced by biophysical adaptation options including pest and disease management [74] along with water management [75]. To mitigate the effect of drought, the Kingdom may implement restricted measures on farms, such as seeding drought-resistant types and conserving water via the building of mini-dams [76,77].

Integrated nutrient management could be practiced in the Kingdom to enhance food security. This method integrates nitrogen management strategies, such as crop rotations, mixed cropping, nitrogen fixation, decreased plowing, covering crop use, compost and bio-fertilizer use, soil analysis, and more. This practice also includes optimizing fertilizer application distribution, rates, and timing, using various fertilizer types, and employing delayed-release fertilizers [78–80]. So, a potential outcome of this initiative could be improved nutrient uptake, optimized fertilizer use, and reduced emissions [81–85]. These methods could help even more by reducing the need for making synthetic fertilizer and the emissions that come with it in the Kingdom.

Agroforestry (a collection of various land management strategies that combine trees/plants with crops and/or animals throughout time and place) has the potential to be implemented in the food system to counter climate change [86–93]. Agroforestry should be integrated into support networks that give growers access to resources and education to increase economic independence in order to reduce vulnerability and maximize the benefits. This might include altering legislation, boosting extension systems, and offering business possibilities to facilitate

adoption [80,94]. Livestock farming in KSA has the potential to diversify incomes, switch to farming, integrate crops, switch grazing animals to browsing species, create multi-species herds, allow movement, and better manage soil and nutrients to adjust to climate change. As a bonus, grassland maintenance, rounding up, food and grain preservation, produced from a variety, and cooling systems might be implemented [95].

Controlled-environment agriculture could be another adaptation technique of the Kingdom to mitigate climate change. This approach relies mostly on soilless hydroponic or aquaponics production technologies. Aeroponics is a further evolution of hydroponics that substitutes water as a growth medium with an aerosol of nutrients [96]. Although aquaponics appears to have the potential to produce proteins on urban farms, the technology has not yet evolved, and its environmental and economic performance is unknown [97,98]. Controlled-environment agriculture is often practiced in urban areas to utilize the benefits of short supply chains [98].

3.2.2. Infrastructure Side Measures

Desert lands and high mountains dominate the majority of the Kingdom's landscape, whereas residential communities are commonly found on the valleys' banks; therefore, building and maintaining dams could be of great assistance in meeting the water needs of the nearby population and mitigating the risks and damage associated with flash food [99]. In addition, the "climate-proof" rural roads and transport networks could be another crucial adaptation measure against flash floods to enhance food security [100].

3.2.3. Demand-Side Measures

Adapting Sustainable Eating Habits

Switching to more plant-based diets (such as pulses, nuts, fruits, and vegetables) and less animal-based diets, particularly from grazing animals, could have a beneficial effect on climate change through a substantial reduction of greenhouse gas emissions [101,102]. This shift could not only improve biodiversity preservation and environmental health through decreasing demand on ecosystems and farmland used for grazing [103] but also boost people's health by lowering obesity and morbidity from diet-related illnesses [104–107]. Since about 71% of the Saudi population is overweight, this adaptation strategy could enhance national health [108]. However, the move to sustainable healthy diets might have a negative influence on the agriculture sector's financial stability [109,110]. Thus, effective food system-oriented reformation strategies are required to progress forward into sustainable and nutritious diets. These strategies should combine agricultural, healthcare, and environmental methods to tackle reciprocal advantages and complaints in several areas (agricultural production, commerce, well-being, environmental conservation, etc.) and eliminate detrimental consequences (global warming, species extinction, and food insecurity) [111,112].

Reducing Food Loss and Waste

The edible components of animals and plants produced for human use that are unutilized are referred to as food loss and waste (FLW) [113]. Due to limitations in farming technology, storage, and packing, food loss happens as a result of spoiling, spillage, or other unforeseen outcomes [114]. Food waste refers to edible food that is discarded or allowed to deteriorate in the distribution (food and retail service) and consumption phases of the food supply chain [115]. Adaptation techniques that reduce food waste could reduce variability in harvest, thus enhancing food security [116]. Annual food waste in Saudi Arabia is estimated to be worth SAR 40 billion. To prevent this loss, the National Foundation for Food Preservation has been established [117]. Optional strategies for reducing food loss and waste (FLW) include going to invest in cultivation and post-harvesting innovations, increasing taxes and other rewards to decrease business and customer-level waste, mandating FLW disclosure and reducing objectives for big food businesses, legislating discriminatory practices, and actively advertising aesthetically imperfect goods [118].

4. Policy Implications

The food system landscape of the Kingdom will face significant challenges due to the multi-faceted detrimental effects of climate change. Domestic agriculture will lose productivity due to climate change while the demand will continue to grow. On the other hand, global climate change will affect the market which will challenge the Kingdom's food security due to unavailability or increased price. The econometric analysis revealed a causal relationship between GDP and population with food demand. For meeting the food demand, the Kingdom is forced to rely on imports because there is insufficient water (both renewable and non-renewable) supply to support domestic agricultural production. The consumption of nonrenewable groundwater by domestic production will eventually lead to its depletion. It is difficult to make decisions about the nation's groundwater supplies that are based on evidence when we do not have a complete assessment of this resource. This study will help take an evidence-based policy decision in this regard.

The Kingdom's policymakers must gain a comprehensive understanding of the available water resources, and the possible opportunities pertinent to demand management and domestic food production for short- and long-term durations. The government has to find out appropriate business models to support the Kingdom's food import. The coupling between GDP and food demand needs to be investigated and the researchers should determine the ways to decouple the GDP from the food demand. Finally, the policymakers should focus on research-based innovation focusing on every element of the food system, considering local challenges and opportunities to ensure food security.

5. Conclusions

As the domestic food production of the Kingdom is constrained by the availability of groundwater and wastewater, the food supply is mainly dependent on imports. The food demand will continue to increase because of population growth. Meeting the demand through domestic production will cause tremendous pressure on the remaining nonrenewable groundwater. The unavailability of current national estimation of groundwater resources makes the situation difficult for data-driven policymaking. There is also significant wastage of food within the supply chain. The opportunities for demand management and the increase of food supply are already identified in the literature. The government took several initiatives to encourage private investment in international agribusiness to support food import in Saudi Arabia.

Based on the currently available literature it is found that climate change has a substantial impact on Saudi Arabia's already fragile food supply system and the challenges will be graver in the future. This study adopted a causality analysis to assess the variables, including temperature, GHG emissions, population, and GDP as potential contributors to the nation's food system's vulnerabilities. The findings of the long-run causality test indicate that the GDP has a positive causal relationship with the demand for food, indicating that the demand for food will increase with an increase in GDP in the long run. Additionally, the result indicates that Saudi Arabia's GDP and population growth contribute to the country's rising GHG emissions. Although the Kingdom has taken some steps, there are still ample opportunities to identify effective food security policies especially considering its unique challenges and opportunities.

This study utilized temperature, population, GDP, and GHG emissions as the key indicators of food security. However, water usage is an additional crucial indicator of food security. In the future, including water usage will allow for more precise modeling. In addition, this study quantified the import based on the number of important crops. Future research can incorporate the other crops to completely comprehend the influence of climate change on the Saudi Arabian food security system.

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