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Agriculture, food security, and climate change in South Asia: a new perspective on sustainable development

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Abstract

The South Asian region has faced multiple challenges in the last few decades. This region is susceptible to climate change due to the presence of both drought-prone and coastal areas. It also faces the problem of increasing food-insecurity due to the recent events of crop failure consequent to natural calamities. This study examines the nexus between agricultural production and food security amidst climate change for the South Asian nations from 2000 to 2019. From the empirical investigation, using Driscoll-Kraay and Panel-Corrected Standard Error estimators, we get robust results in the presence of cross-sectional dependence and heteroskedasticity. The simultaneous equation model using 3SLS is also used for the robustness check, considering the probable endogeneity issue in the model. The findings of the study reveal that agricultural production, fertilizer consumption, and land under cereal production play a substantial and positive role in determining food security in the South Asian nations. Furthermore, the varying rainfall patterns coupled with rising temperature, as well as the increasing level of CO_2 emissions are found to impede food security in these nations. Additionally, non-climatic factors related to agriculture and land-use are also found to induce CO_2 emissions, which is a major cause of climate change. Therefore, from a policy perspective, this study suggests that to ensure long-term food security in the South Asian nations, the government should implement effective policy measures, which include the decarbonization of the agricultural sector by encouraging the use of renewable energy sources and promoting climate-resilient agricultural practices.

Keywords Agricultural production · Food security · Climate change · South Asia

Abbreviations

SDG	Sustainable development goals
CO_2	Carbon dioxide emissions

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GFSI	Global food security index
FSI	Food security index
FAVI	Food availability index
FACI	Food accessibility index
FSTI	Food stability index
FUTI	Food utilisation index
AAR	Average annual rainfall
AAT	Average annual temperature
LUCP	Land under cereal production
AGP	Agricultural production
FC	Fertilizer consumption
CPI	Consumer price index
PCA	Principal component analysis
CSD	Cross sectional dependency
CIPS	Cross-sectionally augmented im-pesaran
CADF	Covariate augmented dickey fuller
PCSE	Panel corrected standard error estimator
DSK	Driscoll-Kraay estimator
VIF	Variance-Inflation factor
ARDL	Autoregressive distributed lag
FGLS	Feasible generalised least square
FMOLS	Fully modified ordinary least square
DOLS	Dynamic ordinary least square
IPCC	Intergovernmental panel on climate change
SOFI	State of food security and nutrition in the world

1 Introduction

Eradicating global hunger has become a pressing challenge amidst growing population and increasing environmental pollution. Therefore, more efforts are required to enhance agricultural yield to ensure universal access to nutritious food, always available, for living a healthy and active life. Out of the United Nations' "17 Sustainable Development Goals (SDGs)", *SDG 2* and *SDG 13*, dealing with the issues of "zero hunger" and "climate action," respectively, are particularly relevant for achieving sustainability in food security by the year 2030. Specifically, the framework of *SDG 2* addresses the realm of achieving the zero-hunger target through food security, while *SDG 13* addresses the issue of abating climate change and its effects by promoting sustainable agricultural practices (United Nations, 2015). However, the startling facts presented by various national and international reports have raised concerns regarding these two SDGs, questioning whether the world is on the right path to achieve zero hunger by lessening the effects of climate change. For example, the "State of Food Security and Nutrition in the World" report (SOFI, 2022) reveals that an estimated 2.3 billion people around the world have been moderately food insecure and 923.7 million people have encountered severe food insecurity in 2021.

Climate change affects different aspects of food security, like food access, food quality, and quantity available, as well as food preferences. Climate change also affects all the determinants of malnutrition, including land and crop degradation, which are the greatest contributors to the increasing morbidity and mortality rates globally (Fanzo et al., 2018;

Grace et al., 2012; Pickson & Boateng, 2022). With increasing climate change vulnerabilities and growing demand for food grains, the prevalence of food insecurity has become a major concern in recent times (Garnett et al., 2013; Kan et al., 2022). Despite being vulnerable to climate change, the South Asian economies play an indispensable role in the global food supply and value chains (Rasul, 2021a). As per the Intergovernmental Panel on Climate Change (IPCC), climate-related factors will aggravate the risk of crop failures, resulting in lower agricultural production by 2050 if the current trend continues in the South Asian region (IPCC, 2021).

Recent studies have documented that the major driver of unprecedented climate change is the increasing carbon dioxide (CO_2) level in the atmosphere, which not only affects food security but also human health (Chandio et al., 2022; Dang et al., 2021). The rising level of CO_2 emissions has led to an increase in global temperature, irregular rainfall patterns, and global warming, which has further aggravated global food insecurity by deteriorating agricultural productivity (Abbas, 2020; IPCC, 2014). Nonetheless, in South Asian countries like India, the agricultural sector remains the major source of income and employment (Chandio et al., 2022; Nookathoti & Behera, 2022). However, this region is also labelled as the most catastrophe-prone area in the world, and in the past two decades, around 750 million people have been impacted by one or more climate-related hazards in the region (Raiser, 2022). In South Asia, the rising global temperature, along with the varying rainfall patterns due to climate change, is deteriorating crop yields (IPCC, 2021; Sivakumar & Stefanski, 2010). Earlier studies have also documented that the South Asian region has experienced varied and heterogeneous impacts of climate variation; while some areas are more prone to flood risks due to intense rainfall, others may suffer from protracted drought situations due to low precipitation (Kelkar & Bhadwal, 2007; Narisma et al., 2007; Sivakumar & Stefanski, 2010).

Apart from directly affecting agricultural production, climate change also adversely affects the natural resources, such as soil, water, and terrestrial resources, which are crucial for agricultural production (Hanjra & Qureshi, 2010). With the increasing climate change variabilities, there are greater variations in agricultural production, food supply, and food prices, which consequently aggravate the state of food insecurity while adversely affecting millions of lives in the South Asian region (Aryal et al., 2019a; Vinke et al., 2017). In a recent report, it has been revealed that about 40.6% of the South Asian population is "moderately or severely food insecure", which shows an increase of 13% in the last five years (SOFI, 2022). Moreover, the increasing urbanization and industrialization in this region have led farm-based households to diversify their sources of income from agriculture towards the service sector, while the growing demand for food still remains a serious concern due to the soaring food price levels (Aryal et al., 2019b; Wang et al., 2017). However, in South Asia, agriculture still plays a pivotal role in maintaining the food security level, as it is the prime source of livelihood for "more than 60% of people and shares 22% of the Gross Domestic product (GDP)" (SOFI, 2022). Therefore, greater knowledge of the consequences of climate change and the adaptive measures to curb these effects is needed to improve agricultural sustainability and to design the policy framework to improve the food security level in this region.

In this study, we examine the effects of agricultural production on food security amidst climate change by considering six South Asian countries, such as Afghanistan, Pakistan, India, Nepal, Bangladesh, and Sri Lanka, spanning from 2000 to 2019. The study area map depicting the level of food security for the year 2022 is given in the Appendix (Fig. 5). It shows that the South Asian countries have an average *FSI* score of 50, which is less than the world average of 62.2 (GFSI, 2022). This implies that, with the increasing vulnerability of climate change, the prevalence of food insecurity in South Asia is a major source of concern. It is observed that, to measure the effect of climate change on food security, earlier studies have either used agricultural production or one of these four indicators, viz., "food availability, food accessibility, food stability, and food utilization," as a proxy for food security. However, measuring food security using such a proxy indicator limits the scope for policy formulation, as food security is not limited to only agricultural production or any particular dimension of food security. Therefore, for the current analysis, we have prepared a "Food Security Index (FSI)" that incorporates all four dimensions of food security to assess the effects of climatic and non-climatic factors on the food security level of the South Asian region. Such an analysis is novel and has not been investigated previously for the South Asian economies.

In light of this, we make a novel contribution to the corpus of literature by answering the following questions: (1) Do agricultural factors (agricultural production, land under cereal production, and fertiliser consumption) lead to climate change through increasing CO_2 emissions? (2) Do climatic factors (CO_2 emissions, annual average temperature, and rainfall) affect agricultural production in the South Asian region? And finally, (3) Do agricultural and climatic factors affect the food security level in the South Asian region? The study has primarily two objectives: First, to analyse the nexus between agricultural and climate-related factors. And second, to assess the role of agricultural factors in maintaining food security amidst changes in climatic factors in the South Asian economies. Thus, to assess the effect of agricultural factors on food security amidst climate change, we use the simultaneous equation modelling technique to get robust outcomes. Furthermore, this study empirically contributes to the corpus of literature by employing the Panel Corrected Standard Error (PCSE) and Driscoll-Kraay Standard Errors (DSK) estimators to get robust results in the presence of heteroscedasticity, cross-sectional dependency, and autocorrelation problems in the model. However, these estimators do not account for the potential endogeneity and simultaneous bias in the model. Therefore, to check the robustness of the findings, we use the three-stage least square (3SLS) method, which endeavours to remedy the problem of endogeneity and simultaneous bias among the variables. By estimating a simultaneous equation model to analyse the nexus between agriculture, food security, and climate change, this study reports new solutions and implications to increase food security and attain sustainable development goals for South Asian economies.

Following the introduction section, the literature review is presented in Sect. 2, and the theoretical background and hypotheses of the study are presented in Sect. 3. Furthermore, the data and methodology of the study are discussed in Sect. 4, and the empirical findings and discussion of the study are discussed in Sect. 5. And finally, the conclusion and policy implications of the study are discussed in Sect. 6.

2 Literature review

With the increasing threat of climate change, the agricultural sector is struggling to meet the growing demand for food grains, which has ultimately given rise to global food insecurity. Moreover, the prevalence of climate change has numerous detrimental effects on food prices, food quality, and food security. In this context, we have explored some of the earlier studies that have investigated the nexus between climate change, agriculture, and food security. This helps us to find out the research gap, thereby providing the basis for further investigation.

2.1 Climate change and food security

Food security is extremely vulnerable to climate change because any variations in climatic factors directly affect crop yield, which dampens the availability of food in a country (Ahmad et al., 2011). More specifically, studies have demonstrated that the increasing concentration of carbon dioxide is the leading cause of the unprecedented level of climate change that has detrimental impacts on food security (Kogo et al., 2020). A study by Chandio et al. (2020b) assessed the impact of technical progress, climate change, and financial development on the cereal production of Pakistan over the period from 1977 to 2014. Using the ARDL bounds testing approach, they state that CO_2 emissions negatively affect cereal production. This is mainly because the increasing concentration of carbon dioxide reduces the nutrient content of crops and reduces the water holding capability of soil, which affects not only crop yield but also food quality and human health (Vermeulen et al., 2012; Mukhopadhyay et al., 2021; Firdaus et al., 2020). Likewise, Vysochyna et al. (2020) assessed the environmental determinants of food security for 28 post-socialistic countries from 2000 to 2016. They found that food security is adversely influenced by CO_2 emissions while being positively influenced by renewable electricity production. They have also suggested that the government should promote the use of renewable energy, electrification of rural areas, and the use of clean fuels to control carbon emissions and ensure food security in the long-run. Another study by Sibanda and Ndlela (2019) assessed the nexus between agriculture, industrial output, and CO_2 emissions in South Africa for the period from 1960 to 2017. They illustrated that climate change due to increased CO_2 emissions deteriorates food security by altering global temperature and rainfall patterns.

Furthermore, studies have also documented that variations in climatic factors, viz., temperature and rainfall, due to climate change are the primary reasons behind substantial reductions in the land productivity of several crops, which affect the fundamental basis of agriculture and lead to poor accessibility of food (Rasul, 2021a). A study by Belloumi (2014) explored the nexus between climate change and food security in ten Eastern and Southern African (ESA) countries for the period from 1961 to 2011, using a fixed-effect model. The study found that variability in rainfall with increasing temperature, adversely affects agricultural production in the ESA countries. In addition, extreme temperature reduce agricultural productivity via increased evapotranspiration and decreased soil moisture, which significantly reduces food security by altering the food availability dimension (Rasul, 2021a). This is also evident from the IPCC's, 2019 report that a one-degree increase in temperature will result in land degradation, water scarcity, and a 3.2% reduction in rice yield globally. Along with the detrimental effects of rising global temperature, varying rainfall patterns also affect food security via deteriorating agricultural productivity. Low rainfall in winter, when water is decisive for agricultural production, and frequent rainfall in rainy and summer seasons with higher intensity led to the occurrence of extreme weather events, which impede food security (Rasul, 2021b). Moreover, numerous studies have documented that, as an effect of climate change, unusual hikes in temperature and irregular rainfall have adverse effects on global food security by disrupting agricultural production, reducing soil fertility, and shifting crop seasons (Agovino et al., 2018; Arora, 2019; Randell et al., 2022; Shahzad et al., 2021). Hence, the far-reaching consequence of climate change on the agro-ecosystem is clearly visible, which has severe effects on the environment, food security, human health, and overall wellbeing of the global population.

2.2 Agriculture-food security nexus

On the one hand, agriculture is considered as a part of the climate change issue, but on the other hand, it also provides a solution to mitigate climate change. Although the agricultural sector contributes to almost one-third of global greenhouse gas emissions, it also provides an opportunity to mitigate carbon emissions through carbon sequestration and subsequently reduce the environmental risks to food security (Edame et al., 2011). Numerous studies have found that the agricultural sector plays a prominent role in ensuring food security via employment generation and eradicating poverty and hunger in various countries (Braun et al., 2004; Gregory et al., 2012; Kumar & Sharma, 2013). A study by Yu and You (2013) examined the typology of food security in developing countries using factor and sequential typology analysis methods. They documented that global food security can only be attained by boosting food production, especially in developing countries that require to utilize their capabilities in order to enhance agricultural production for achieving and sustaining food security. They also highlighted that factors related to agricultural production, such as fertilizer consumption, use of agricultural machinery, land under cereal production, and energy consumption, also play an essential role in enriching the level of food security.

To this end, Zhai et al. (2017) investigated the impact of climate change and technical advancement on wheat production in inland China over the period from 1970 to 2014. Using the ARDL approach, they found that agricultural machinery and fertilizer consumption significantly and positively affect the per-hectare wheat yield in China. This is primarily because the deployment of agricultural machinery and fertiliser usage helps to improve soil fertility and plays an indispensable role in enhancing agricultural productivity (Chandio et al., 2021). Another study by Kumar et al. (2021) assessed the effects of climate change on cereal production for the lower-middle-income nations over the period from 1971 to 2016, using FGLS, FMOLS, and DOLS model estimators. They concluded that rainfall and land under cereal production have a significantly positive effect on crop production, while temperature adversely affects crop production. More specifically, land under cereal production shows the harvested area of a country and plays a crucial role in ensuring food security by enhancing agricultural output (Kumar et al., 2021). Similar studies have also reported that agricultural intrusion programmes play a substantial role in enriching agricultural production, which helps to alleviate hunger and ensure food security, especially in lower- and middle-income countries (Chandio et al., 2020b; Ahsan et al., 2020; Sibhatu et al., 2022).

3 Research gap

In the earlier studies, while some researchers have considered agricultural production as a measure of food security (Agovino et al., 2018; Ahsan et al., 2020; Aryal et al., 2019a, 2019b; Shahzad et al., 2021), a few others have taken one of the different pillars of food security, viz., "food availability, food accessibility, food stability, and food utilisation," as a proxy variable (Kumar & Sharma, 2013; Kumar et al., 2017; Vysochyna et al., 2020). However, in this study, we have taken all four pillars of food security to prepare a "Food Security Index (FSI)" and then examined the impact of agricultural production on food security amidst climate change. In the current analysis, by preparing a food security index to circumvent the wide concept of food security and then using it to examine the food security-agriculture-climate change nexus in a simultaneous equation framework, we make a novel contribution to the existing trend of studies. It is observed that there is no empirical study in this domain for a particular geographical region, like South Asia. Considering a specific geographical region helps to capture its region-specific vulnerabilities to climate change. This is specifically relevant for South Asia, which is considered one of the most catastrophe-prone areas in the world. To bridge these research gaps, the current study investigates the effect of agricultural production on food security in the presence of several climatic factors using the 3SLS estimator in a simultaneous equation model. The theoretical framework for the study is provided in the next section.

4 Theoretical background and hypotheses

The concept of food security is multi-dimensional, with more than 200 definitions available in earlier studies (Hoddinott, 2009). This was first introduced in 1974 at the "World Food Conference of FAO[1]", where "availability of food is considered as the sole component of measuring food security." Subsequently, after many amendments, in the year 2002, FAO described food security as follows: "when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2002). Since then, the description of food security has encompassed all the four aspects, i.e., "food availability, food stability, food accessibility, and food utilization" (Kumar & Sharma, 2013). *Food availability* focuses on the "production of food grains through agriculture", which captures the availability of food grains at all times. *Food accessibility*, on the other hand, refers to the "economic capability of a person to afford and obtain adequate amounts of food either through production, purchase, or transfers for survival." The *food stability* dimension deals with the "continuous and periodical availability of food grains in the market to maintain the continuity in demand and supply of food grains." Finally, *food utilization* is primarily associated with the "quality, safety, and nutrient contents of the food and the ability of the body to absorb it effectively." The theoretical framework is presented in Fig. 1, indicating the effect of climate change and agricultural factors on food security.

However, before measuring the impact of climate change on food security, it is crucial to know the definition of climate change. According to Church and White (2006), climate change is described as "the changing weather patterns and life-threatening weather events, such as increasing global temperatures, rainfall, and sea levels." Therefore, to measure the impact of climate change on food security, we have incorporated CO_2 emissions, average annual rainfall, and average annual temperature as climatic factors, which are indicated with the red arrows in Fig. 1. It is argued that the variation in climatic variables, such as increasing CO_2 emissions, increasing temperature, and variation in annual precipitation, are the root causes of frequent extreme event occurrences that hinder the physical and economical accessibility of food (Wibe et al., 2019; Chandio et al., 2020a). Moreover, climate change also negatively affects soil fertility and agricultural production, which have detrimental effects on food security (FAO, 2008a). Since the variations in climatic factors have detrimental effects on food security, the signs of the elasticity parameters of the climatic factors are presumed to be negative, i.e., $\frac{\beta FSI_{it}}{\beta CO_{2it}} < 0$, $\frac{\beta FSI_{it}}{\beta AAR_{it}} < 0$, and $\frac{\beta FSI_{it}}{\beta AAT_{it}} < 0$. Furthermore, the green arrows in Fig. 1 show the impact of non-climatic factors related to agriculture and land use on food security. Nonetheless, studies have highlighted that, although the agricultural sector is susceptible to climate change, with the growing demand for food grains,

[1] Food and Agricultural Organisation of the United Nations.

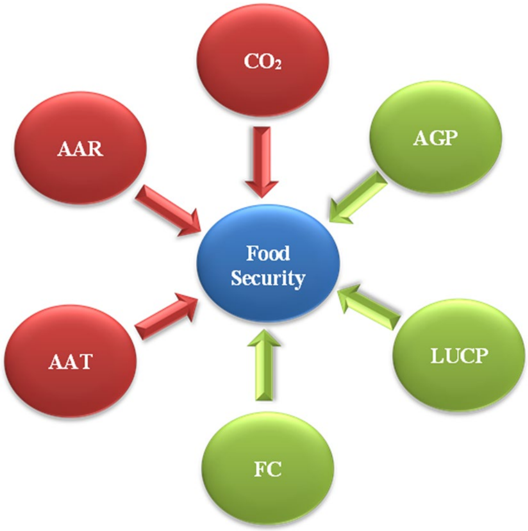

Fig. 1 Theoretical framework. *Note*: AAR: Average Annual Rainfall; AAT: Average Annual Temperature; CO2: Carbon-emission; AGP: Agricultural Production; LUCP: Land Under Cereal Production; FC: Fertiliser Consumption

agriculture plays a substantial role in attaining food security (Smutka et al., 2009; Otsuka, 2013; Pawlak & Kolodziejczak, 2020). Studies have demonstrated that more productive and climate-resilient agricultural practices can enhance food security by affecting the food availability dimension (Pawlak & Kolodziejczak, 2020). Moreover, fertilizer consumption and land under cereal production also induce agricultural productivity, which consequently improves food security in a country. Since non-climatic factors related to agriculture and land use have a favourable impact on food security, the signs of the elasticity parameters of non-climatic factors are presumed to be positive, i.e., $\frac{\beta FSI_{it}}{\beta AGP_{it}} > 0$, $\frac{\beta FSI_{it}}{\beta FC_{it}} > 0$, and $\frac{\beta FSI_{it}}{\beta LUCP_{it}} > 0$. Based on the earlier literature and theoretical framework, the following hypotheses have been developed for the current study.

4.1 Hypotheses

H1 Agricultural sector positively affects food security.

The agricultural sector plays a decisive role in determining the level of food security as well as economic growth because it provides employment to a sizable portion of the total population globally (Kumar et al., 2017). In the context of South Asia, it is home to about one-third of the world's poor, who primarily depend upon agriculture and also feed more than 20% of the global population (Rasul, 2021a). In short, agriculture plays a significant role in providing employment, augmenting economic growth, and determining the level of food security in South Asian countries. Therefore, we investigate the impact of agricultural production on food security in South Asian countries.

H2 CO_2 emission has adverse effects on food security.

South Asian countries are facing key development challenges such as growing urbanization, rapid industrialization, and rapid population growth (Spijkers, 2010; Hasnat et al.,

Table 1 Description of variables and data sources

Variables	Unit of Measurement	Symbol	Source
Food Security Index	Index prepared using food availability, food accessibility, food stabilization and food utilization	FSI	FAO
Carbon emission	In Kiloton	CO_2	WDI
Average Annual Rainfall	Millimetre	AAR	CCKP
Average Annual Temperature	Degree in Celsius	AAT	CCKP
Agriculture Production	Gross Production Index Number, 2014–2016 = 100	AGP	FAO
Fertilizer Consumption	Kg Per Hectare of arable land	FC	WDI
Land Under Cereal Production	Hectare of land	LUCP	WDI
Consumer Price Index	Index value (2010 = 100)	CPI	WDI

FAO: Food and Agriculture Organisation, WDI: World Development Indicator, CCKP: Climate Change and Knowledge Portal

2018), resulting in CO_2 emissions and environmental degradation. The higher concentration of greenhouse gases like CO_2 in the atmosphere leads to deterioration of soil fertility and the nutritional value of crops, which directly affect the food security level of a country in the long-run (Ebi & Ziska, 2018; Myers et al., 2015; Qureshi et al., 2016). In this regard, it can be inferred that CO_2 emissions deteriorate the agricultural sector and consequently give rise to food insecurity. With this backdrop, we examine the direct effect of CO_2 emissions on the level of food security in South Asian countries.

H3 The interaction of AAR and AAT negatively affects food security.

Varying temperature and rainfall have a mixed impact on various crops across different parts of the world, which might lead to higher yields for some crops while reducing the yield of others (Kumar et al., 2021). However, in South Asia, the variation in annual rainfall and temperature due to climate change is seen to intensify the occurrence of extreme events such as floods, forest fires, and heat waves, which affect agricultural production and food supply and subsequently worsen the food security level (Aryal et al., 2019b; Schmidhuber & Tubiello, 2007; Wang et al., 2017). Hence, it can be assumed that increasing temperature and the variation in annual rainfall dampen the agricultural sector and consequently aggravate the level of food insecurity. Therefore, we investigate the interaction effect of *AAR* and *AAT* on the food security level of the South Asian countries.

5 Data and methodology

5.1 Data

This study explores the effect of agricultural production on the food-security level amidst climate change, considering a panel dataset of six South Asian countries, i.e., "Afghanistan, Pakistan, Nepal, India, Bangladesh, and Sri Lanka," over the time period from 2000 to 2019. The data for the same has been compiled from various secondary sources and is mentioned in Table 1. South Asian countries are selected for the analysis because about 412.9 million people in the South Asian countries are severely food insecure (SOFI, 2022).

Moreover, about 60% of the South Asian population depends directly or indirectly on the agriculture sector; thus, the unprecedented level of climate change poses a major risk to livelihood as well as food security in this region (Rasul, 2021b). Therefore, assessing the nexus between "climate change, agriculture production, and food security" is crucial for the South Asian nations to formulate effective policies for ensuring sustainable food security in this region. The main dependent variable in this study is the "Food Security Index (FSI)", which is prepared by using the four pillars of food security, i.e., "food availability, food accessibility, food stability, and food utilization" as specified by the FAO. Moreover, we use CO_2 emissions, average annual rainfall (*AAR*), average annual temperature (*AAT*), agricultural production (*AGP*), fertilizer consumption (*FC*), and land under cereal production (*LUCP*) as the independent variables. While CO_2 emissions, *AAR*, and *AAT* represent the climatic factors, *AGP*, *FC*, and *LUCP* are the non-climatic factors associated with agriculture and land use. Moreover, inflation proxied by the Consumer Price Index (*CPI*) is taken as a control variable in the study because food price level plays a decisive role in maintaining food security by affecting the food accessibility dimension of food security (FAO, 2008b). The selection of dependent, independent, and control variables is based on the literature review and theoretical background of the study. The description of variables and the data sources are mentioned in Table 1.

5.2 Preparation of the food security index

The FAO does not signify any specific format for aggregating the four pillars of food security to prepare a composite food security index. Therefore, to prepare the composite index, the given steps have been followed, which is consistent with some of the prior studies (Krishnamurthy et al., 2014; Vysochyna et al., 2020). At first, each of the 18 indicators classified under the four pillars of food security, as mentioned in Appendix Table 8, is normalised to ensure that they positively relate to the composite index. For the normalisation process, if the indicator with a higher value signifies a positive effect on food security, for instance, "average dietary energy supply or average value of protein supply", it has been normalised using the given formulae as mentioned in Eq. (1).

$$X = (x - \min(x)) / (\mathrm{Max}(x) - \mathrm{Min}(x)) \tag{1}$$

If the indicator with a higher value signifies an unfavourable effect on food security, such as "cereal import dependency ratio or per-capita food production variability", it has been normalised as follows:

$$X = (\mathrm{Max}(x) - x) / (\mathrm{Max}(x) - \mathrm{Min}(x)) \tag{2}$$

In the Eqs. (1–2), Min (x) and Max (x) are the lowest and highest values of any given indicator, respectively. The normalisation procedure allows us to organise the values of the given indicators within a range from 0 to 1. Following the normalised values of the indicators, we use principal component analysis (PCA) to prepare the "Food Availability Index (*FAVI*), Food Accessibility Index (*FACI*), Food Stability Index (*FSTI*), and Food Utilisation Index (*FUTI*)." The PCA is used to prepare the index as it reduces the dimensionality of the dataset while maximising the interpretability and minimising the data loss. PCA does so by converting all the correlated variables into new independent or uncorrelated variables that gradually maximise the variance. Finally, the FSI is prepared by taking the average of *FAVI*, *FACI*, *FASI*, and *FUTI*, as mentioned in Eq. (3).

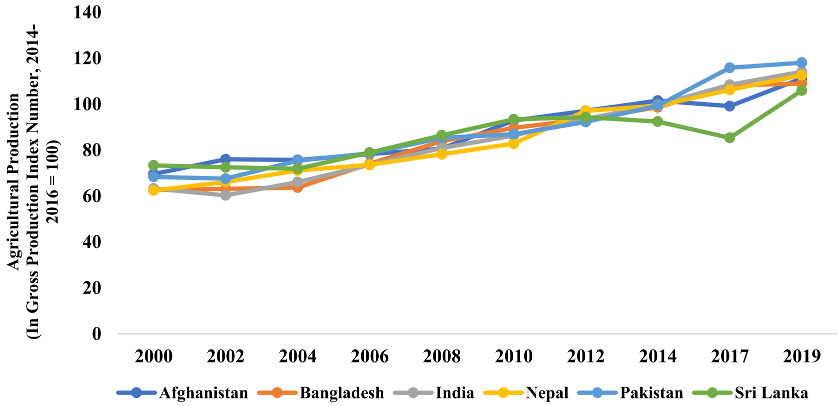

Fig. 2 Agricultural production in South Asia. *Source*: Food and Agricultural Organisation Statistics (2019), United Nations

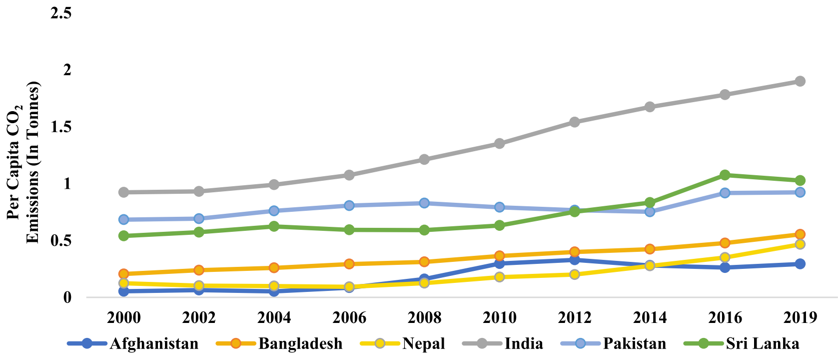

Fig. 3 CO_2 emission in South Asia. *Source*: Our World in Data (2019)

$$FSI = \frac{FAVI + FACI + FSTI + FUTI}{n = 4} \tag{3}$$

Furthermore, the recent trends of the primary variables, i.e., agricultural production and CO_2 emissions, in the South Asian countries are depicted in Figs. 2–3.

In Fig. 2, it is observed that agricultural production has increased dramatically in all the South Asian countries since 2004. This is because a sizeable portion of the South Asian population depends on agriculture as a primary source of living. Moreover, it has been observed that the gross agricultural production in each country was quite similar in 2019.

In Fig. 3, we observe that CO_2 emissions also show an increasing trend; however, compared to agricultural production, CO_2 emissions are observed to be increasing at a slow but steady pace in the South-Asian countries. This is mainly because South Asia is going through a transition phase from an underdeveloped or developing region to a more developed region, where industrialization, urbanization, and anthropogenic emissions are also increasing.

5.3 Model specification

Before the empirical estimation, all the variables are transformed into their natural logarithmic form. To explore the relationship between agriculture and food security amidst changes in the major climatic factors (CO_2, AAR, AAT), the following framework is expressed as given in the Eqs. (4–6).

$$AGP_{it} = \alpha + \beta_1 CO_{2it} + \beta_2 AAR_{it} + \beta_3 AAT_{it} + \varepsilon_{it} \tag{4}$$

$$CO_{2it} = \alpha + \beta_1 AGP_{it} + \beta_2 LUCP_{it} + \beta_3 FC_{it} + \varepsilon_{it} \tag{5}$$

$$FSI_{it} = \alpha + \beta_1 AGP_{it} + \beta_2 CO_{2it} + \beta_3 (AAR \times AAT) + \beta_4 AAR_{it} + \beta_5 AAT_{it} + \beta_6 LUCP_{it} + \beta_7 FC_{it} + u_{it} + \varepsilon_{it} \tag{6}$$

where Eq. (4) shows the linear effects of climatic factors (CO_2, AAR, and AAT) on agricultural production. In Eq. (5), we assess the effects of agriculture-related factors (AGP, $LUCP$, and FC) on CO_2 emissions. Finally, in Eq. (6), we investigate the effects of both climatic factors and agricultural production on FSI. We have also incorporated the interaction term, $AAR \times AAT$ to capture the interaction effects of temperature and rainfall on the food security level. In the given model, α is the constant term, β is the coefficient, u is the control variable, ε is the error term, t is the time period, and i is the number of cross sections.

5.4 Methodology

The empirical analysis presupposes several diagnostic tests, which help in selecting the appropriate estimator to get robust results. To begin with, the variance inflation factor (VIF) is used to test for the multicollinearity problem in the model. The VIF test shows the changes in variance–covariance of the estimator with an increase in their pairwise partial correlation coefficient. Further, the Friedman (1937) and Breusch-Pagan (1980) cross-sectional dependency (CSD) tests are used to check the observed and unobserved common shocks between the cross-sections. The CSD test is crucial before moving towards further empirical investigation to avoid biased outcomes (Sharif et al., 2022). Following the CSD test, we use the second-generation unit-root tests, viz., "cross-sectionally augmented Im-Pesaran (CIPS) and covariate augmented Dickey Fuller (CADF)" by Pesaran (2007), to check for the stationarity level of the variables because the conventional unit root tests may give misleading and biased results in the presence of CSD (Haldar et al., 2023). Further, the Westerlund and Edgerton cointegration test, White's heteroskedasticity test, and Wooldridge autocorrelation test are used to check for the presence of long-run cointegration, heteroskedasticity, and serial autocorrelation among the variables, respectively. The diagnostic tests show the absence of multicollinearity while also confirming the presence of CSD, heteroskedasticity, and autocorrelation problems in the model. In addition, the Hausman test (1978) shows that the fixed effects model is appropriate for the empirical investigation. With this backdrop, we find that the PCSE and DSK estimators are appropriate for empirical estimation, given the sample size of our study with 20 time periods and 6 cross-sections.

For the estimation of fixed effect model with DSK, at first, all the variables of the model are within converted as illustrated in the Eq. (7).

$$\tilde{Z}_{it} = z_{it} - \bar{z}_i + \bar{z} \tag{7}$$

where $\bar{z}_i = T_i^{-1} \sum_{t=t_{i1}}^{T_i} z_{it}$ and $\bar{z} = \sum T_i^{-1}$

In Eq. (7), Z_{it} shows the "vector of model variables" and T shows the "time dimension." Next, the OLS estimation gives within estimation as mentioned in the Eq. (8), and the transformed model is then estimated using pooled OLS estimation with DSK.

$$\tilde{y}_{it} = \tilde{x}'_{it}\emptyset + \tilde{\varepsilon}_{it} \tag{8}$$

In Eq. (8), $\widetilde{y}_{it}$ and $\tilde{x}'_{it}$ are the "transformed variables" and $\widetilde{\varepsilon}_{it}$ is the "changed error term." The estimated standard errors are consistent with the panel cross-sectional dimension, as DSK covariance matrix depends on the cross-sectional averages. Equation (9) represents the pooled OLS estimates of $\varnothing$ as follows:

$$\hat{\emptyset} = (x'x)^{-1}x'y \tag{9}$$

DSK for the coefficient estimates, i.e., $V\left(\widehat{\varnothing}\right)$ is then obtained by taking the square root of the asymptotic covariance-matrix, as illustrated in Eq. (10).

$$V\left(\hat{\emptyset}\right) = (x'x)^{-1}\hat{S}_T(x'x)^{-1} \tag{10}$$

In Eq. (9) and (10), $\widehat{\varnothing}$ is the "vector of unknow coefficients" and $\widehat{\mathrm{S}}_{\mathrm{T}}$ in Eq. (10) is the Newey and West standard error (Newey & West, 1987). These standard errors are reliable with cross-sectional and temporal dependencies.

Furthermore, the PCSE estimator is feasible with a large time period (T) and small cross sections (N), while the DSK estimator is applicable to the model irrespective of the size of T and N, and both the estimators are robust in the presence of heteroskedasticity and autocorrelation in the model (Hoechle, 2007). However, the PCSE and Driscoll-Kraay estimators do not account for the potential endogeneity issue in the model. To address this issue, we have used the three-stage least square (3SLS) estimator for the robustness analysis because "it is the combination of multivariate and two-stage regression" (Zellner & Theil, 1962) and "allows correlation between unobserved disturbances across equations" (Bakhsh et al., 2017). Hence, this could possibly give robust results in the presence of endogeneity problems across error terms (Adewuyi & Awodumi, 2017). To sum up the econometric techniques used in carrying out the study, a methodological flowchart is presented in Fig. 4.

6 Empirical analysis and discussion

The analysis begins with the summary statistics for the variables and several diagnostic checks for choosing the appropriate estimator for regression analysis. Table 1 shows the outcomes of summary statistics as follows:

In Table 1, it is observed that the data are more dispersed from the mean value as the standard deviations in the summary statistics are quite high for all the variables. This is also evident from the S-Wilk and S-Francia normality test with p-value < 0.05, which indicates that the dataset is not distributed normally. Further, the correlation matrix outcome shows that all the variables are positively correlated with the Food Security Index (FSI), except for *AGP*, CO_2 emissions, *LUCP*, and *CPI*, as shown in Appendix Table 9. Next, we perform the diagnostic tests, and to begin with, we check for the multicollinearity problem

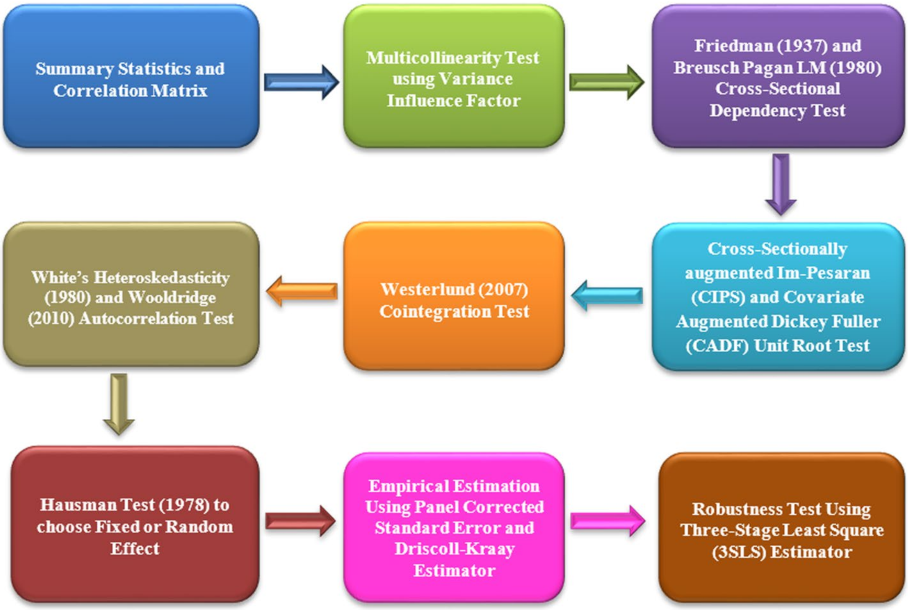

Fig. 4 Methodological flowchart

Table 2 Summary statistics

Variables	FSI	AGP	CO_2	FC	LUCP	AAR	AAT	CPI
Observations	120	120	120	120	120	120	120	120
Mean	0.50	4.51	10.53	4.17	15.79	6.78	3.01	4.53
Std. Dev	0.19	0.17	2.15	1.63	1.48	0.82	0.29	0.44
Min	0.17	4.1	6.65	0.31	13.53	5.25	2.57	3.60
Max	0.78	4.77	14.76	5.81	18.44	7.92	3.32	5.24
S-Wilk Prob	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-Francia Prob	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

in the dataset using the variance-inflation factor (VIF), which measures how much an independent variable is influenced by its interaction with other independent variables.

In Table 2, the mean VIF value between 0 and 10 implies that multicollinearity between the variables is not an issue and is acceptable (He et al., 2016), which in our case is 1.85, 1.08, and 8.64 for the first, second, and third model, respectively. In the next step, we conduct a cross-sectional dependence (CSD) test, with the null hypothesis being "no cross-sectional dependence" across the countries. The Friedman and Breusch-Pagan CSD tests indicate the existence of cross-sectional dependency for all the variables in the model (Appendix Table 10). Following the CSD outcomes, we test for the order of stationarity for the variables in the model using the CADF and CIPS unit-root tests in Table 3.

In Table 3, the outcomes of the CIPS and CADF unit root tests imply that all the variables used for the study are stationary either at level (I-0) or at the first order difference

Table 3 Multicollinearity statistics result

Variable	Agricultural production		CO_2 emission		Food security	
	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF
AGP			1.03	0.97	10.11	0.1
CO_2	1.85	0.54			17.17	0.06
FC			1.12	0.89	4.94	0.2
LUCP			1.1	0.91	9.78	0.1
AAR	1.41	0.71			2.33	0.42
AAT	2.3	0.44			6.07	0.16
CPI					10.05	0.09
Mean VIF	1.85		1.08		8.64	

Table 4 CADF and CIPS Panel Unit root Test

Variables	CADF		CIPS	
	I (0)	I (1)	I (0)	I (1)
FSI	0.581	-3.770***	-1.486	-3.315***
AGP	− 5.270***	− 8.995***	− 3.946***	− 5.512***
CO_2	1.601	− 4.883***	− 1.057	− 3.783***
FC	− 0.997	− 5.511***	− 2.149	− 4.047***
LUCP	− 1.255	− 8.229***	− 2.258**	− 5.190***
AAR	− 5.335***	− 9.243***	− 3.973***	− 5.617***
AAT	− 4.939***	− 9.861***	− 3.807***	− 5.877***
CPI	− 5.403***	− 2.510***	− 4.002***	− 2.785***

*, ** and *** Shows 10%, 5% and 1% significance level

(I-1). Given this, we use Westerlund (2007) cointegration test to analyse the existence of long-run association between agricultural production, CO_2 emissions, and food security, as depicted in Table 4.

In Table 4, the outcome of the cointegration test with p-values > 0.05 implies that no long-run association can be established among these variables. Further, the results of other diagnostic tests are presented, in which the White Heteroskedasticity test and the Wooldridge Autocorrelation test (Wooldridge, 2010) with p-values < 0.05 indicate the presence of heteroskedasticity and autocorrelation in the error term, respectively (Appendix Table A3). Finally, by employing the Hausman test (1978), we find that fixed effects are present in the model (Fig. 5).

Following the diagnostic checks, we first estimated the single Eqs. (4–6) by employing PCSE and Driscoll-Kraay estimators and reported the results in Table 5. These estimators correct the problems of CSD, heteroskedasticity, and autocorrelation but do not consider the problems of endogeneity or reverse causality. As the independent variable CO_2 in Eq. (4) appears as the dependent variable in Eq. (5) and vice-versa, and both CO_2 and *AGP* appear as independent variables in Eq. (6), we have a simultaneous equation model. The problem of simultaneity is dealt with by using a 3SLS estimator, which is a more robust estimator in the presence of endogeneity. In both Table 5

Table 5 Cointegration Test Result

Statistic	AGP	CO_2	FSI
Gt	− 0.921(0.179)	− 0.031 (0.488)	2.118 (0.983)
Ga	0.350(0.637)	− 0.263 (0.396)	3.367 (1.000)
Pt	− 0.780(0.218)	− 0.883 (0.189)	2.537 (0.994)
Pa	− 0.569(0.285)	− 0.617 (0.269)	2.249 (0.988)

and 6, Model (I) represents the effects of CO_2, average annual rainfall, and average annual temperature, respectively, on agricultural production, while Model (II) shows the effects of agricultural production, *FC*, and *LUCP*, respectively, on carbon emissions. Furthermore, Model (III) shows the effects of the climatic (CO_2, *AAR*, and *AAT*) and non-climatic (*AGP*, *FC*, and *LUCP*) factors on food security.

Table 6 PCSE and DSK estimator results

Estimators	PCSE estimator result			Driscoll and kraay estimator result		
Variables	I	II	III	I	II	III
	AGP	CO_2	FSI	AGP	CO_2	FSI
AGP		1.515***	0.278**		1.515***	0.278***
		(0.000)	(0.012)		(0.000)	(0.002)
CO_2	0.022**		− 0.178***	0.023**		− 0.178***
	(0.016)		(0.000)	(0.029)		(0.000)
*AAR*AAT*			− 0.149**			− 0.149
			(0.024)			(0.136)
FC		0.486***	0.065***		0.486***	0.065***
		(0.000)	(0.000)		(0.000)	(0.016)
LUCP		1.099***	0.088***		1.099***	0.088***
		(0.000)	(0.000)		(0.000)	(0.000)
AAR	0.001		0.444**	0.001		0.444
	(0.913)		(0.022)	(0.909)		(0.132)
AAT	− 0.113**		1.511***	− 0.113**		1.511*
	(0.039)		(0.006)	(0.038)		(0.063)
CPI			− 0.029			− 0.029
			(0.515)			(0.141)
Constant	4.541***	− 15.591***	− 4.879***	4.541***	− 15.591***	− 4.879*
	(0.000)	(0.000)	(0.004)	(0.000)	(0.000)	(0.054)
Observations	120	120	120	120	120	120
Countries	6	6	6	6	6	6

*, ** and *** Shows 10%, 5% and 1% significance level. Parenthesis () shows the *P*-value

6.1 Findings

The outcome of the single equation estimation using PCSE and DSK estimators is provided in Table 5.

In Table 5, it is observed that agricultural production is positively affected by CO_2 emissions at 5% level of significance (Model I). Moreover, *AGP* is observed to be positively but insignificantly affected by the average annual rainfall, whereas the effect of the average annual temperature on *AGP* is found to be negative at 0.05 level of significance. In Model II, it is observed that agricultural production, fertilizer consumption, and *LUCP* have a favourable impact on CO_2 emissions. Interpretively, a 0.01 increase in *AGP*, *FC*, and *LUCP* will increase CO_2 emissions by 1.515, 0.486, and 1.099 percentage points, respectively. In Table 5, the effects of climatic (CO_2, *AAR*, and *AAT*) and non-climatic (*AGP*, *FC*, and *LUCP*) factors on food security are also presented in Model-III. It is observed that CO_2 emissions have a significantly negative impact on food security, whereas the effects of average annual rainfall and average annual temperature on food security are found to be significantly positive. However, we found that the interaction effect of *AAR* and *AAT* on the food security level is negative and statistically significant in South Asian countries. Furthermore, agricultural production, fertilizer consumption, and *LUCP* are found to have a significantly positive impact on food security, whereas the effect of the control variable, i.e., *CPI*, is found to have a negative (−0.029) impact on the South Asian country's food security level.

6.2 Robustness check

Since Eqs. (4–6) show the presence of reverse causality, we have performed the robustness test using a simultaneous equation estimator, i.e., 3SLS, to confirm the outcomes we get using the single equation estimators (PCSE and DSK). The outcome of the 3SLS estimator is presented in Table 6 as follows:

In Model-I of Table 8, it is observed that agricultural production is positively influenced by CO_2 emissions, whereas it is negatively influenced by average annual rainfall and average annual temperature in the South Asian countries. Furthermore, in Model-II of Table 6, we found that agricultural production (1.654), fertilizer consumption (0.486), and *LUCP* (1.095) significantly induce CO_2 emissions in the South Asian countries. This result confirms the outcomes of the PCSE and DSK estimators in Table 5. Lastly, in Model-III of Table 6, we found that the effect of CO_2 emissions on food security is significantly negative, whereas the effect of average annual rainfall and average annual temperature on food security is found to be significantly positive. However, the interaction effect of *AAR* and *AAT* on food security is found to be negative at 0.05 level of significance in the South Asian countries. Furthermore, we found that agricultural production, fertilizer consumption, and *LUCP* positively influence food security levels. Additionally, food security in South Asian countries is observed to be negatively but insignificantly influenced by the control variable, i.e., *CPI*, which confirms the results of the PCSE and Driscoll-Kraay estimators in Table 5.

6.3 Discussion

From the empirical analysis, it has been observed that the outcomes of the PCSE, Driscoll-Kraay, and 3SLS estimators are quite similar, as depicted in Tables 5 and 6.

The outcome of the study reveals that agricultural production has a significantly positive effect on food security. This result supports the conclusion drawn by some of the existing studies (Gregory et al., 2012; Rasul, 2021a). We can conclude that the food security level of a country directly depends upon its agricultural production, which feeds people in unfavourable situations. Hence, sustainable agricultural practices are needed to achieve sustainable food security in South Asian countries. Moreover, the impact of land under cereal production and fertilizer consumption is also found to have a statistically significant and positive impact on *FSI*. This is because both *LUCP* and *FC* affect the food security level by enhancing agricultural production, which is consistent with the conclusion drawn by prior studies (Zhai et al., 2017; Dogan, 2018; Chandio et al., 2020b). Nonetheless, the findings contradict the study of Guntukula (2019), who posits that areas under cereal production may affect food security negatively by depleting agricultural output. This may be possible since the agricultural land area is fixed, and exploiting the land under cultivation to get more output through excessive use of fertiliser and agricultural machinery may adversely affect food security by depleting agricultural production (Baig et al., 2022).

Nonetheless, CO_2 emissions found to have a positive (0.022) impact on agricultural production at 0.05 level of significance. This result is in line with the earlier studies (Ahsan et al., 2020; Chandio et al., 2020a; Kumar et al., 2021). They conclude that CO_2 levels may increase crop yield by decreasing transpiration rates, and plants with higher CO_2 levels utilises water more efficiently, leading to higher cereal production. To the contrary, studies have also found that the rising CO_2 emission level in the atmosphere adversely affects the nutritional contents of numerous crops, which have an unfavourable impact on human health (Myers et al., 2015; Rasul, 2021b). In this context, in Tables 5 and 6, it has been observed that CO_2 emissions negatively affect the food security level (Model-III), which is in line with the conclusion drawn by earlier studies (Qureshi et al., 2016; Chandio et al., 2020b).

Furthermore, while the impact of average annual rainfall on agricultural production is found to be positive, the effect of average annual temperature on *AGP* is found to be negative (Model-I). Our result is in line with the findings of some previous studies (Attiaoui & Boufatech, 2019; Kumar et al., 2021). They concluded that rainfall significantly improves agricultural production, whereas an increase in temperature due to rising global warming lowers the agricultural production. However, the findings contradict the earlier studies (Kumar et al., 2021; Baig et al., 2022); they posit that the effects of varying rainfall and temperature may differ according to geographical locations, such that in tropical and subtropical regions, agricultural production gets adversely affected by higher temperatures, whereas in cold climatic zones, it favourably affects agricultural production and the availability of food supply. Furthermore, we found that although the individual effects of *AAR* and *AAT* on food security are positive, the interaction effect of *AAR* and *AAT* on food security is negative and significant (Model-III). This could be interpreted as varying rainfall coupled with rising temperatures adversely affecting agricultural production and, consequently, the level of food security (Table 7). It is argued that the varying rainfall and temperature patterns due to climate change have resulted in the escalating occurrence of cyclones, floods, droughts, and heat waves (Hussain et al., 2020; Quandt & Kimathi, 2017), which affect not only agricultural production but also food security and human health in many ways (Ammani et al., 2012; Fanzo et al., 2018; Pickson & Boateng, 2022).

Table 7 3SLS estimator result

Estimators	3SLS Estimator Result		
Variables	I	II	III
	AGP	CO_2	FSI
AGP		1.654***	0.278**
		(0.000)	(0.031)
CO_2	0.022**		− 0.178***
	(0.023)		(0.000)
*AAR*AAT*			− 0.149**
			(0.011)
FC		0.486***	0.065***
		(0.000)	(0.000)
LUCP		1.095***	0.088***
		(0.000)	(0.000)
AAR	− 0.002		0.444***
	(0.903)		(0.010)
AAT	− 0.103		1.511***
	(0.214)		(0.001)
CPI			− 0.029
			(0.565)
Constant	4.536***	− 16.156***	− 4.879***
	(0.000)	(0.000)	(0.001)
Observations	120	120	120
Countries	6	6	6

*, ** and *** Shows 10%, 5% and 1% significance level. Parenthesis () shows the *P*-value

Apart from the climatic and non-climatic factors, the control variable, i.e., the *CPI*, is also found to have adverse effects on food security. In general, rising food prices adversely affect the purchasing power of the people, which eventually dampens the food accessibility dimension, resulting in a higher level of food insecurity in the country. This result is in line with the conclusion drawn by the earlier studies (Kumar & Sharma, 2013; Erokin & Gao, 2020; Faharuddin et al., 2022).

7 Conclusion and policy implications

This study has analysed the effect of climatic factors (temperature, rainfall, and CO_2 emissions) and non-climatic factors (agricultural production, fertilizer consumption, and land under cereal production) on food security in South Asian countries. For the empirical investigation, we have used a balanced panel data set of six South Asian countries over the period from 2000 to 2019. Moreover, to address the CSD, autocorrelation, and heteroskedasticity issues in the model, we have used the PCSE and Driscoll-Kraay estimators for the empirical analysis. In addition, considering the potential endogeneity issue and simultaneity bias in the model, we have used the 3SLS estimator for robustness analysis in the current study.

The findings of the study validate the *first hypotheses*, that an increase in agricultural production has a favourable impact on the food security level of South Asian countries. Furthermore, prior studies have shown that food security is more susceptible to climate change, especially with the increasing concentration of CO_2 in the atmosphere (Belloumi, 2014; Rasul, 2021a). In this regard, we have found that CO_2 emissions negatively affect food security in South Asian countries, which validates our *second hypotheses*. Moreover, the varying rainfall patterns coupled with rising temperatures due to climate change are intensifying the occurrence of extreme events, which dampen food security by affecting crop yield (Agovino et al., 2018; Arora, 2019; Aryal et al., 2019b). With this backdrop, we found the interaction effect of *AAR* and *AAT* on food security to be negative and significant, which validates our *third hypotheses*.

The increasing climate change issues in South Asian countries are ravaging the agricultural sector and consequently giving rise to food insecurity. Moreover, with one-third of the world's poor population, achieving sustainable food security with growing climate change is a major cause of concern in these countries. Hence, it is suggested that the government train the farmers regarding climate-related problems and the adoption of climate-resilient agricultural practices, which will enhance both agricultural yield and food security. Secondly, it is observed that factors related to agriculture and land use are substantially inducing CO2 emissions in South Asian countries. Therefore, to sustainably increase agricultural productivity while mitigating the detrimental effects of agricultural production on the environment, the government should promote the use of renewable energy in the agricultural sector by providing subsidies and by creating awareness among farmers about sustainable agricultural practice. And finally, the governments in the South Asian nations are suggested to encourage regional cooperation for promoting integrated policy planning and institutional harmonization in order to ensure a sustainable environment, resilient agro-production systems, and food security in this region. To conclude, it can be suggested that policy choices should be made in a certain way to address urgent needs by resolving climate change issues as well as ensuring sustainable agriculture and food security in the long-run.

Furthermore, this study may be extended by incorporating the role of renewable energy consumption, electricity consumption in the agriculture sector, and political factors in achieving food security in the South Asian nation. Moreover, a comparative analysis between countries or different regions could make an insightful contribution to the climate change-food security literature. In addition, considering the growing importance of Information and Communication Technology (ICT) in the economy, future studies may incorporate the role of ICT in determining the food security level across countries. This problem has significant policy implications and warrants further investigation since the world is undergoing the long-term adverse impacts of climate change.

Appendix

See Fig. 5 and Tables, 8, 9 and 10.

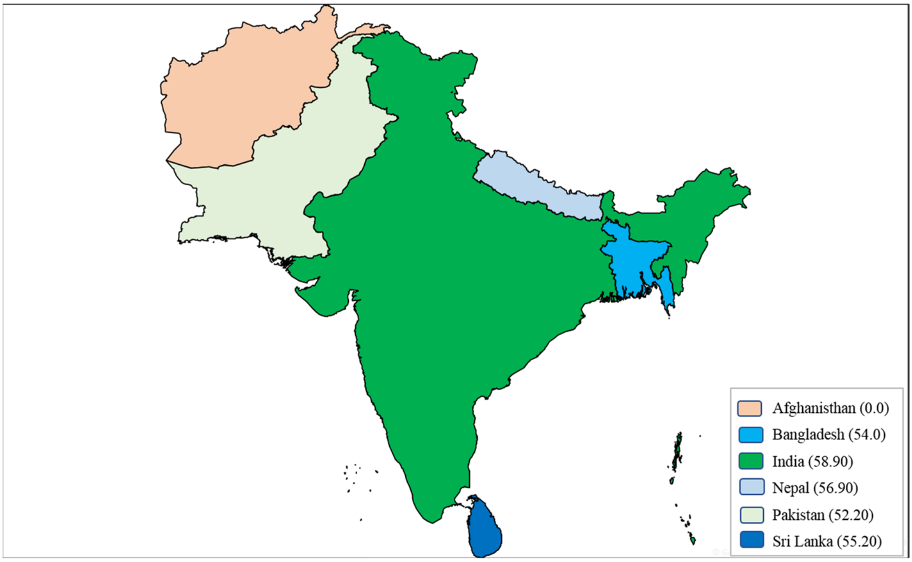

Fig. 5 Study area map *Notes*: The map shows the food Security index score of the selected South Asian countries as per the Global Food Security Index (GFSI). The score for Afghanistan is indicated as zero because GFSI does not have the data for Afghanistan. Source: Global Food Security Index, 2022.

Table 8 Food security indicators. Source: Food and Agricultural Organisation Statistics (2019), United Nations

Dimensions of Food Security	Indicators
Food Availability	Average Dietary Energy Supply Adequacy
	Average Value of Food Production
	Average Protein Supply
	Average Supply of Protein of Animal Origin
	Share of Dietary Energy Supply Derived from Cereals, Roots and Tubers
Food Accessibility	Prevalence of Undernutrition
	Depth of Food Deficit
	Gross Domestic Product
Food Stability	Cereal Import Dependency Ratio
	Percentage of Arable Land Equipped for Irrigation
	Value of Food Imports over Total Merchandise Exports
	Political Stability & Absence of Violence Index
	Per Capita Food Production Variability
	Per Capita Food Supply Variability
Food Utilization	Percentage of Population Accesses to Least Basic Drinking Water Sources
	Percentage of Population Accesses to Least Basic Sanitation Sources
	Prevalence of Obesity in the Adult Population
	Prevalence of Anaemia among Women of Reproductive Age

Table 9 Correlation matrix

Variables	FSI	AGP	CO_2	FC	LUCP	AAR	AAT	CPI
FSI	1							
AGP	− 0.072	1						
CO_2	− 0.535***	0.158*	1					
FC	0.220**	0.142	0.611***	1				
LUCP	− 0.617***	− 0.025	0.864***	0.297***	1			
AAR	0.466***	− 0.065	0.038	0.494***	− 0.050	1		
AAT	0.152*	− 0.012	0.624***	0.851***	0.303***	0.442***	1	
CPI	− 0.116	0.925***	0.198**	0.139	0.072	0.064	− 0.032	1

*, **, and *** indicate the 10%, 5% and 1% level of significance respectively

Table 10 Diagnostic test result

Test statistic	AGP	CO_2	FSI
Friedman Cross Sectional Dependency	107.781***	22.514***	19.286***
Breusch-Pagan LM Test for CSD	163.420***	60.920***	31.014***
Hausman Test	70.240***	12.720***	94.08***
White's Heteroskedasticity Test	15.880*	30.860***	2.990*
Wooldridge Autocorrelation Test	2.737**	40.014***	328.50***

*, ** and *** Shows 10%, 5% and 1% significance level

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Data availability The dataset has been compiled from the following secondary sources: https://climateknowledgeportal.worldbank.org/download-data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. https://databank.worldbank.org. https://www.fao.org/statistics/en/.

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