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IMPACT OF CLIMATE-SMART PRACTICES ON HOUSEHOLD FOOD SECURITY: EVIDENCE FROM PUNJAB

Smily Thakur[1], Baljinder Kaur Sidana[2], Arjinder Kaur[2], Sangeet Ranguwal[2] and Sunny Kumar[2*]

[1]*Department of Agriculture, Khalsa College, Amritsar-143 002, India*
[2]*Department of Economics and Sociology, Punjab Agricultural University, Ludhiana-141 004, India*

ABSTRACT

This study investigates the critical role of Climate-Smart Agriculture (CSA) in enhancing the resilience of food production systems in the face of evolving climate patterns. Utilizing data from 240 farm households during the 2021-2022 period, the analysis distinguishes between 177 adopters and 63 non-adopters of CSA practices for paddy and wheat cultivation. Households were classified into food-secure and food-insecure categories based on the calorie threshold established by the Indian Council of Medical Research (ICMR). The prevalent climate-smart practices for paddy included Direct Seeding of Rice (DSR), Short Duration Varieties (SDVs), Laser Land Leveling (LLL), and Baling (B), while wheat adopters employed Super Seeder (SS), Happy Seeder (HS), and Zero Till Drill (ZT). Notably, adopters exhibited a higher average daily calorie intake of 3006 Kcal compared to 2809 Kcal among non-adopters, alongside a lower Gini coefficient, indicating reduced inequality in calorie consumption among adopters. The ordered probit model identified significant socio-economic factors affecting food security. Specifically, larger family size had a negative impact (*$p<0.001$*), whereas education and access to credit positively influenced food security (*$p<0.02$*). Income levels also showed a likely positive association with food access. This study highlights the necessity of addressing climate change challenges through targeted policy interventions, technological advancements, and comprehensive extension services. Such measures are essential to promote the effective adoption of sustainable agricultural practices and to bolster food security in the context of climate variability.

Keywords: Adaptations, Climate change, Food security

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The concept of 'food security' has emerged as a crucial issue, particularly in less developed economies that have historically grappled with 'hunger' during the colonial era (Buttriss & Stokes, 2008; Butterly & Shepherd, 2010; Schanbacher, 2010). India exemplifies such a nation, having endured various famines at different points under foreign rule (Gough, 1976; Hogan *et al.*, 2011; Hayman *et al.*, 2012; Dutt, 2013; Arora *et al.*, 2018). A combination of a lagging agricultural sector, flawed land revenue systems, exploitation of cultivators, and biased agricultural policies imposed by British authorities left India as a food-deficit nation at the time of independence (Kak, 2007). These challenges were compounded by two successive droughts in the mid-1960s, further exposing India's vulnerability in terms of food security, which was exacerbated by its reliance on food imports and farming practices. Consequently, there is a pressing need to transform agricultural systems to enhance both productivity and stability, especially in the context of climate change (Kumar & Kaur, 2019; Branca *et al.*, 2011). The United Nations Committee on World Food Security defines 'food security' as the assurance that all individuals, under any circumstances, have physical, social, and economic access to sufficient and safe dietary essentials for maintaining an active and healthy life. This comprehensive definition encompasses not only the quantitative availability of food and self-sufficiency but also economic accessibility, ensuring affordability according to individual needs, and nutritional value, which positively impacts human health (Gustafson, 2016; FAO, 2021).

Among the various factors influencing food security, the escalating global population significantly contributes to challenges such as hunger, malnutrition, and food insecurity (FAO, IFAD, UNICEF, WFP, & WHO, 2019). This rapid population growth has placed immense pressure on agricultural land to meet the rising demand for food production, thereby exacerbating the effects of climate change by straining resources and increasing the vulnerability of populations, particularly in low-resource regions, to climate-related risks (Brooks & Loevinsohn, 2011). India exemplifies this transformation, having achieved a remarkable six-fold increase in food grain production, rising from 50 million tonnes in 1950-51 to nearly 300 million tonnes in 2021-22. This shift marks India's successful evolution from a food-deficient to a food-sufficient nation over the past five decades (Singh & Ansari, 2022).

The Government of India has implemented

*Corresponding author: sunnykumar@pau.edu
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several significant initiatives to combat food insecurity, including the Public Distribution System, the Mid-Day Meal Scheme, the Integrated Child Development Services Scheme, and the National Food Security Act of 2013. According to the 2021-22 Human Development Index, India ranks 132nd out of 191 countries and territories (Human Development Report, UNDP, 2022). Approximately 21 percent of the population lives below the poverty line, which contributes to pronounced income inequality (World Food Programme, 2024). In addition to these socio-economic challenges, India is grappling with changing climatic patterns, further complicating efforts to alleviate hunger (FAO, 2016a). The relationship between climate change and food security is complex; fluctuating climate conditions affect crops, livestock, forestry, and aquaculture, resulting in significant social and economic consequences. These include reduced incomes, compromised livelihoods, disruptions in trade, and adverse health impacts (Chakrabarty, 2022; Bazzana *et al.*, 2022).

Climate change poses significant threats to water resources, the natural environment, and agricultural productivity, subsequently impacting the livelihoods of human populations (Belloumi, 2014; FAO, 2016b; Yohannes, 2016; Belay *et al.*, 2017; Lemi & Hailu, 2019; Baumann, 2021; Ali *et al.*, 2022). In response to these challenges, Climate-Smart Agriculture (CSA) has been proposed as a strategy to achieve climate neutrality while addressing issues related to greenhouse gas (GHG) emissions (Managa & Nkobole-Mhlongo, 2016). CSA focuses on enhancing the resilience of food production systems, aiming to ensure food and income security amid changing climate patterns and variability (Vermeulen *et al.*, 2012; Lipper *et al.*, 2014; Rosenstock *et al.*, 2014). Over recent decades, CSA practices, including conservation tillage, improved crop varieties, and efficient water management, have enabled farmers to adapt to shifting climatic conditions while simultaneously increasing crop yields and mitigating risks associated with climate variability (Gathala *et al.*, 2013; Jat *et al.*, 2019; Gathala *et al.*, 2016). According to Kumar *et al.* (2020), the implementation of CSA practices has been shown to enhance agricultural productivity and bolster the resilience of farming systems, which are essential for food security in the context of climate change. Similarly, Aggarwal and Singh (2021) demonstrate that adopting CSA practices can lead to improved food security outcomes by enhancing resource use efficiency and reducing vulnerability to climate-induced shocks. Furthermore, the Food and Agriculture Organization (FAO, 2013) emphasizes that CSA practices contribute to food security by increasing agricultural resilience and productivity, vital for sustaining food supplies over the long term. These studies highlight the critical role of CSA in not only addressing immediate food security challenges but also ensuring sustainable agricultural development for the future. Empirical evidence suggests that the adoption of CSA practices and technologies has resulted in improved crop yields and increased incomes for farmers (Chhetri *et al.*, 2017). A deeper understanding of farmers' adoption behaviour and the potential welfare effects on household food security is crucial for informing strategies that various stakeholders can implement to enhance the adoption and effectiveness of CSA practices within production systems (Chhetri *et al.*, 2017).

Punjab has played a pivotal role in the agricultural transformation of India, with the sustainable production of rice and wheat being essential for the nation's food security. Over the past decade, the state has contributed approximately 25-30% of rice and 35-40% of wheat to the central food pool. However, the agricultural production system in the region faces significant threats from climate change (Kumar & Sidana, 2017; Sidana & Kumar, 2021; Kukal & Kanwar, 2023). Recent instances of climate instability include decreased wheat productivity due to unusually high temperatures in February and March 2022, as well as untimely rainfall in 2023. Additionally, escalating water scarcity in Punjab poses further challenges, with competing demands for water across agricultural, industrial, and domestic sectors (Singh *et al.*, 2019). In this context, the present study conducted in Punjab investigates whether Climate-Smart Agriculture (CSA) serves as an effective mitigation strategy against the growing impacts of climate change on farmers' food security. The study also examines the factors influencing the adoption of CSA practices that enhance food security among farmers. The findings are crucial for informing policy decisions, promoting the adoption of climate-smart practices in agriculture, and advancing global efforts to improve health and well-being in rural areas.

METHODOLOGY

Selection and description of the study area

Punjab, located in the northwest region of India, is renowned for its fertile lands, covering an area of 50,362 square kilometers and featuring extensive cultivable land supported by assured irrigation. The state is divided into three agro-climatic zones: the semi-hilly or *kandi* zone (19%), the central zone (47%), and the southwestern zone (34%).

To select sample farmers for this study, a multistage random sampling approach was employed. In the first stage, districts were chosen based on the proportional distribution of area within each agro-climatic zone. One district was selected from the *Kandi* zone (Roopnagar), three from the central zone (Sangrur, Patiala, and Fatehgarh Sahib), and two from the southwestern zone

Table 1. Number of consumer units assigned to a person

Sex/ Age (years)	Number of consumer units assigned to a person											
	< 1	1-3	4-6	7-9	10-12	13-15	16-19	20-39	40-49	50-59	60-69	70+
Male	0.43	0.54	0.72	0.87	1.03	0.97	1.02	1.00	0.95	0.90	0.80	0.70
Female	0.43	0.54	0.72	0.87	0.93	0.80	0.75	0.71	0.68	0.64	0.51	0.50

(Mansa and Sri Muktsar Sahib). In the second stage, two villages were randomly selected from each of these districts.

In the third stage of the sampling process, a comprehensive list of farmers engaged in cultivating rice and wheat within each selected village was compiled. Following a complete enumeration of farming households, the classifications of adopters and non-adopters of Climate-Smart Practices (CSPs) were established in consultation with *Krishi Vigyan Kendra* (KVK) scientists and agricultural extension specialists, including agriculture development officers from the selected districts. Various climate-smart practices applicable to rice and wheat cultivation were identified, including Direct Seeding of Rice (DSR), short-duration varieties (SDVs) of paddy, laser land leveling (LLL), baling (B), and the use of Super Seeder (SS), Happy Seeder (HS), and Zero Till Drill (ZT) for wheat sowing. From the list of farmers, 20 individuals were randomly selected from each village, ensuring a balanced representation of both adopters and non-adopters of these practices. This resulted in a final sample of 240 farm households covering 12 villages across the three agro-climatic zones of Punjab. The primary respondents included both adopters and non-adopters of CSPs engaged in the cultivation of paddy, wheat, or both crops during the agricultural year 2021-22.

In alignment with the research objectives, a detailed schedule was developed and pretested for the primary data collection, which was conducted through personal interviews. A comprehensive range of information was gathered from selected farmers regarding their socio-economic backgrounds, operational holdings, crop yields, crop residue management practices, adopted Climate-Smart Practices (CSPs), as well as food consumption and expenditure for the agricultural year 2021-22. The analysis revealed that adopting farmers employed CSPs either individually or in combinations of two to three practices within their fields. For the purposes of this study, each adopting household was categorized according to the CSP with the highest level of adoption, defined as the practice covering the largest cultivated area. Ultimately, the study identified 177 adopters and 63 non-adopters of CSPs for both rice and wheat crops.

The sampled households were classified into food-secure and food-insecure groups based on a defined calorie threshold. The Indian Council of Medical Research (ICMR) recommends a subsistence level of daily calorie intake of 2730 Kcal per consumer unit for rural households in Punjab. To estimate consumption units, average energy requirements were calculated for 11 age groups, with separate considerations for males and females. Using the caloric needs of a typical sedentary-working male aged 20-39 years as a reference, the average calorie requirements for other age brackets were expressed as a proportion relative to this standard (NSSO, 2014). This framework was utilized to classify the sample farmers into food-secure and food-insecure households (Table 1).

First, the monthly food consumption data obtained from the surveyed households was converted into calorie intake by accounting for all consumed food items. The total monthly calorie intake for each food group was calculated for every household, based on the nutrient coefficient values provided in the National Sample Statistical Organization (NSSO) report (2014) (Table 2). Next, the family members in each surveyed household were converted into consumer units according to the age and gender criteria established by the NSSO (Table 1). Finally, the total monthly calories calculated for each sample household were adjusted to a per consumer unit per day basis using the following formula:

$$\text{Per consumer per day calorie intake} = \frac{\text{Total household calories}}{\text{Consumer units of household} \times 30}$$

This formula allows for standardized comparison of calorie intake across households.

To estimate the calorie threshold level, the daily caloric intake estimate per consumer unit was divided by the recommended subsistence level of 2730 Kcal, which is established for agricultural rural households in Punjab. This calculation allows for the determination of each household's food security status based on whether their caloric intake meets or exceeds this threshold.

$$\text{Calorie Threshold Level} = \frac{\text{Per consumer per day calorie intake}}{2730}$$

Food security index

The calorie threshold level served as a basis for constructing the food security index (Svedberg, 2000). Utilizing the cumulative cube root method, households

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Table 2. Nutrient coefficients for different food items according to NSSO (2014)

Sr. No.	Food items	Unit	Calories per unit (Kcal)
1	Cereals		
a	Wheat	Kg	3410
b	Rice	Kg	3460
2.	Pulses	Kg	3400
3.	Vegetables		
a	Seasonal vegetables	Kg	300
b	Onion	Kg	550
c	Potato	Kg	967
4	Milk	Litre	1000
5	Sugar	Kg	3980
6	Oil/ghee	Kg	9000
7	Dry fruits	Kg	3060
8	Fruits	Kg	700
9	Meat	Kg	1180

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were categorized into three groups based on their calorie intake: low (<1.00), medium (1.01-1.10), and high (>1.11). Households falling below the threshold level are considered less food secure and belong to the calorie deficit category. In contrast, those above the threshold, classified as medium and high calorie intake households, are deemed calorie sufficient and, therefore, highly food secure.

Gini coefficient

To assess the disparity in calorie intake between adopters and non-adopters of Climate-Smart Practices (CSPs), the Gini coefficient was calculated. This coefficient measures the extent of deviation in the distribution of a particular parameter, such as income or calorie intake, from a perfectly equal distribution, with values ranging from 0 (perfect equality) to 1 (maximum inequality). The Gini coefficient can be derived from the graphical representation of the Lorenz curve, which plots cumulative calorie intake against cumulative population. Additionally, it can be mathematically calculated using the following formula:

$$G = cov(y, F(y)) \quad \frac{2}{\bar{y}}$$

where, '*G*' is the Gini co-efficient, *cov* is the covariance between calorie levels '*y*' and the cumulative distribution of the same calorie 'F(y)', and 'ȳ' is average calorie intake.

Despite its widespread use, the Gini coefficient has several limitations. It is sensitive to data quality and can be affected by measurement errors, which may distort the assessment of inequality. Additionally, the Gini coefficient does not account for population demographics, potentially overlooking important factors that contribute to disparities within different groups. Furthermore, it inadequately reflects changes in the middle of the distribution, which can be significant for understanding overall inequality (Milanovic, 1997; Cowell, 2011). Moreover, the Gini coefficient lacks decomposability, meaning it does not allow for the analysis of inequality across subgroups within a population. It also does not consider absolute income changes, which complicates meaningful cross-country comparisons (Atkinson, 1970; Shorrocks, 1980).

Factors affecting the food security of the household

The relationship between food security and socio-economic factors was examined using an ordered probit model. This model is a generalization of probit analysis for cases with more than two categorical outcomes of an ordinal dependent variable (Mustapha *et al.*, 2012). In this study, the dependent variable, food security, was categorized into three ranked levels: low, medium, and high food security.

Using Ordinary Least Squares (OLS) for estimation would yield biased and inconsistent results due to the ordinal nature of the dependent variable. Therefore, this study employed the maximum likelihood estimation of the ordered probit model to analyze the relationship between farmers' characteristics and their levels of food security. This approach ensures a more accurate representation of the underlying data structure and provides reliable insights into the factors influencing food security among farmers.

Suppose the underlying relationship to be characterized is,

$y_i = X_i \beta + \varepsilon_i$

where, y_i is the exact but unobserved dependent variable; X_i is the vector of independent variables, β is the vector of regression coefficients which we wish to estimate and ε_i is the error term such that ε_i is identically and independently distributed as N (0; 1). Further, suppose that while we cannot observe y^* , we instead can only observe the categories of response:

$y = 0$ if $y^* \leq 0$,

$y = 1$ if $0 < y^* \leq \mu_1$

$y = 2$ if $\mu_1 < y^* \leq \mu_2$

The following ordered probit model has been used in the study:

$y = \beta_0 + \beta_1 FS + \beta_2 ED + \beta_3 CR + \beta_4 A + \beta_5 Y$

where, β is the vector of regression coefficients

Dependent variable: y = Food Security Index

Independent variables are

FS=Family Size (number), ED=Education (years of schooling), CR=Availability of credit (Yes=1, otherwise=0) A=Adoption (Adopters of climate smart practices=1 & otherwise=0) and Y=Farmers annual income in lakhs.

By "food security," we refer to the minimum availability of nutritionally adequate and safe food, along with an assured ability to acquire that food. Food security is typically discussed in three main components: food availability, food utilization, and food accessibility. In this study, the food security variable was categorized based on the food security index into three distinct levels, where '0' represents low calorie intake (<1.00), '1' denotes medium calorie intake (1.01-1.10), and '2' signifies high calorie intake (>1.11).

In the present study, we observed that while the availability of food is generally sufficient, residents in the villages of Punjab often lack access to nutritionally rich or high-calorie food. This deficiency is influenced by various factors, including family size, education, access to credit, farmers' income, and the adoption of climate-smart practices. Among these factors, family size is assumed to have a negative effect on food security, whereas education, access to credit, farmers' income, and the adoption of climate-smart practices are expected to have a positive impact. These assumptions align with the findings of studies conducted by Mango *et al*. (2017), Amadu *et al*. (2020), and Sardar *et al*. (2020).

Farmers in the study area have adopted multiple Climate-Smart Agriculture (CSA) practices, as recorded during the primary survey. The adoption of these practices is largely driven by increased temperatures, weather uncertainties, and extreme climate events. Through the survey of 240 farmers, seven distinct CSA practices were identified. Although many farmers employed multiple practices on their plots, for analytical purposes, the study focused on the maximum area adopted under each respective practice to categorize the farmers. The analysis revealed that the predominant adaptation among farmers was the use of short-duration varieties such as PR126, PR121, and PR128 for paddy cultivation, which typically mature in about 110 to 120 days, allowing ample time for managing paddy straw. The main CSA practices adopted during the *kharif* season included short-duration varieties (SDV), laser land leveling (LLL), and direct seeding of rice (DSR). In contrast, during the *rabi* season, farmers primarily utilized techniques such as the super seeder (SS), zero tillage (ZT), happy seeder (HS), and baling (B). Direct seeding of rice was adopted by only 17.51% of the farmers. Zero tillage was used by 30.57%, while super seeder techniques were employed by 33.33% of the respondents, making them significant methods for *in-situ* management of paddy straw. The happy seeder was comparatively less popular, with only 20.34% adoption among farmers. Additionally, baling was implemented by 15.82% of the farmers as an *ex-situ* management technique for paddy straw.

RESULTS AND DISCUSSION

Identification of adopted climate-smart practices

To effectively manage and cope with climate change in Punjab's agricultural sector, the sampled farmers have adopted a range of popular Climate-Smart Agriculture (CSA) practices. These practices have been categorized under four broad categories: energy/ carbon smart, water smart, ICT smart, and knowledge smart (see Table 3). The following sections provide an explanation of each category.

Table 3. Selected climate-smart agriculture options to assess farmers' preferences (Multiple responses)

CSA Categories	Practices	Adopters (%)
Energy smart	Zero tillage, Happy seeder, Super seeder	73.75
Water smart	Direct seeded rice, laser land leveling and short duration varieties	73.75
ICT smart	SMS alerts regarding weather and social media participation	70.00
Knowledge smart	Number of trainings attended and farmers registered in KVKs	51.00

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Energy smart/ Carbon smart

The carbon/energy smart category encompasses practices that involve retaining agricultural leftovers or stubble on the farmland, which minimizes soil disturbance. By employing these techniques, farmers require less energy for ground preparation. Long-term benefits of these practices include enhanced soil fertility, improved soil structure, increased carbon sequestration, and greater water-holding capacity (Lal, 2004; Kaur, 2022). Additionally, these practices can bolster farmers' resilience to climate change and variability by mitigating risks associated with unpredictable rainfall. In the context of carbon/energy smart practices, this study focuses on zero tillage with residue retention, as well as reduced tillage methods such as the happy seeder and super seeder. Approximately 74% of the sampled farmers adopted energy and carbon smart practices, highlighting a significant shift towards sustainable agricultural methods.

Water smart

Water smart practices encompass methods that minimize irrigation water loss, enhance water use efficiency, reduce energy consumption for irrigation, improve fertilizer use efficiency, and increase crop yields (Bhardwaj, 2014; Aryal *et al.*, 2018; Jat *et al.*, 2019). Among the major water-smart practices adopted by the sampled farmers were direct seeded rice, laser land leveling, and short-duration varieties of paddy. These technologies contribute to conserving irrigation water, optimizing nutrient and agro-chemical use, and facilitating the establishment of robust crop stands by effectively managing seeding depths. Notably, approximately 74% of the total sample of farmers were found to be adopters of water smart technologies, indicating a significant commitment to enhancing water management in agriculture.

ICT smart

The ICT smart category includes farmers who utilize smartphones for weather updates and information related to optimal sowing and harvesting times, thereby assisting in yield enhancement. Through social media groups, these farmers also access market information regarding input and output prices. Approximately 70% of the sampled farmers adopted ICT smart practices in the study, reflecting a significant integration of technology in their agricultural decision-making processes.

Knowledge smart

This category encompasses farmers who gained awareness of climate-smart practices (CSPs) through training sessions, meetings, and demonstrations. The results indicate that farmers registered with Krishi Vigyan Kendras (KVKs) had a higher likelihood of attending these training and capacity-building programs. This increased engagement significantly enhanced their knowledge about climate-smart practices, equipping them with the information needed to implement more sustainable agricultural methods.

Specific idiosyncratic parameters of adopters and non-adopters of climate-smart practices (CSPs) are presented in Table 4. The mean age of adopters was 44 years, compared to 59 years for non-adopters, indicating a trend where younger farmers are more inclined to adopt these practices. Additionally, adopters had a higher average level of education, suggesting a positive correlation between educational attainment and the adoption of CSPs. Furthermore, the average landholding size was significantly larger among

Table 4. Descriptive statistics of sample farmers in Punjab, 2021-22

Particulars	Adopters				Non-adopters				Pearson's *Chi²*	*t-ratio*
	Mean	SD	Min	Max	Mean	SD	Min	Max		
Age (years)	44.46	11.02	23.00	65.00	59.51	6.21	45.00	72.00	-	*10.06****
Education (years of schooling)	10.36	2.98	0.00	17.00	7.44	2.99	0.00	12.00	-	*-6.51****
Family size (no.)	5.37	1.99	2.00	12.00	5.51	1.87	2.00	11.00	-	*0.47*
Operational land holding (ha)	6.61	4.99	0.81	49.29	3.82	1.70	1.01	8.08	-	*-4.33****
Total livestock unit (no.)	5.28	2.30	0.00	17.00	5.63	3.14	0.00	15.00	-	*0.80*
Trainings attended (no.)	0.84	0.64	0.00	3.00	0.03	0.25	0.00	2.00	-	*-9.80****
Mass media exposure (Low=1, Medium=2, High=3)	1.42	0.59	1.00	3.00	1.06	0.30	0.00	2.00	*21.20****	-
Access to non-farm income (0=no, 1=yes)	0.28	0.44	0.00	1.00	0.11	0.31	0.00	1.00	*7.13****	-

*** & ** denote significance at $p \leq 0.01$ and 0.05, respectively.

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Table 5. Returns over variable costs for different CSP adopters versus non adopters in paddy crop, Punjab, 2021-22

Particulars	Gross returns (Rs/ha)	Variable cost (Rs/ha)	Returns over variable cost (Rs/ha)
1. Non Adopters	141579.30	47104.09	94475.25
2. Adopters			
SDV	144378.80	46774.07	97604.69
LLL	144848.00	47657.20	97190.77
DSR	139769.50	41783.63	97985.87

adopters, at 6.61 hectares, compared to 3.82 hectares for non-adopters. This finding reinforces the notion that larger landholdings are more likely to implement CSPs. Adopters also reported receiving more training on these practices than their non-adopter counterparts. In terms of income, adopters had greater access to non-farm income sources and achieved higher returns over variable costs for both paddy and wheat compared to non-adopters. This highlights the economic advantages associated with the adoption of climate-smart practices.

Returns over the variable cost of different CSP adopters versus non-adopters

The practices adopted in response to combat climate were direct seeded rice (DSR), laser land leveling and adoption of short-duration varieties during *kharif* season, especially for rice crop. Tables 5 & 6, illustrating gross returns, variable costs, and returns over variable costs for climate-smart practice (CSP) adopters versus non-adopters for both wheat and rice.

Among adopters, the average yield of paddy ranged from 69.36 quintals per hectare to 71.88 quintals per hectare. Notably, yields were slightly lower (by 1.28%) in fields utilizing direct seeded rice (DSR), attributed to increased weed occurrence and lower seed germination rates. In contrast, fields that employed laser land leveling achieved a 2.31% higher yield due to improved leveling, which facilitated more even maturation and reduced the need for water and agro-chemicals. Regarding variable costs, non-adopters incurred the highest average expense for paddy cultivation at Rs 47,104.09 per hectare. On the other hand, farmers who adopted DSR benefited from the lowest average variable cost of Rs 41,783.63 per hectare. This represents an overall saving of 11.30% for DSR adopters, primarily due to reduced labor costs compared to traditional puddle transplanted rice methods.

Effective management of crop residues is essential for enhancing soil quality, increasing crop yields, reducing air pollution, and promoting sustainable farming practices, ultimately benefiting human well-being. Farmers can adopt various approaches for managing crop residues, including both *in-situ* and *ex-situ* methods. In the surveyed region, *in-situ* practices such as Super Seeder (SS), Zero Tillage (ZT), and Happy Seeder (HS) were commonly employed, while baling (B) was the predominant *ex-situ* practice. For wheat crops, the highest average yield was recorded among Super Seeder adopters, at 37.94 quintals per hectare, followed closely by Happy Seeder adopters at 37.35 quintals per hectare, and Zero Tillage adopters at 37.08 quintals per hectare. However, Super Seeder adopters faced the highest variable costs, amounting to Rs 32,506 per hectare, primarily due to machinery expenses.

Non-adopters of climate-smart practices recorded a return over variable costs of Rs 39,778.64 per hectare. In contrast, adopters experienced significantly higher returns, ranging from Rs 40,693.59 to Rs 43,950.81 per hectare. This difference highlights the economic advantages of implementing climate-smart practices during the *rabi* season for wheat cultivation.

Table 6. Returns over variable cost of different CSP adopters vs. non adopters in wheat crop, Punjab, 2021-22

Particulars	Gross returns (Rs/ha)	Variable cost (Rs/ha)	Returns over variable cost (Rs/ha)
1. Non Adopters	70337.57	30558.93	39778.64
2. Adopters			
SS	76457.3	32506.48	43950.81
ZT	74724.78	31091.57	43633.21
HS	75253.25	31521.18	43732.07
B	71955.29	31261.70	40693.59

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Table 7. Monthly consumption pattern followed by the sample farmers, Punjab, 2021-22

Food items (units)	CSP Adopters	Non-Adopters	t-ratio
Cereals (kg)	11.65	11.68	0.36
Pulses (kg)	0.58	0.53	-2.04**
Vegetables (kg)	3.98	3.72	-1.64
Milk (litre)	34.47	29.7	-7.28***
Sugar (kg)	0.74	0.63	-1.08
Oil/Ghee (kg)	0.80	0.78	-2.83***
Dry Fruits (kg)	0.38	0.13	-3.73***
Fresh fruits (kg)	1.48	1.14	-4.45***
Meat items (kg)	0.45	0.24	-2.57**

*** & ** denote significance at *p≤0.01* and *0.05*, respectively.

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Impact of CSA on the food security of farmers

In the present study, we analyzed household consumption patterns for nine food groups: cereals, pulses, fresh vegetables, milk, sugar, oil/ghee, dry fruits, fruits, and meat items, based on the methodology of Naska *et al.* (2006). The monthly per consumer unit consumption for both CSA adopters and non-adopters is summarized in Table 7. Our findings indicate that the consumption of staple foods such as cereals, pulses, and vegetables is nearly identical between the two groups. However, adopters of climate-smart practices exhibited significantly higher consumption of high-priced, calorie-rich food items, including milk, dry fruits, fruits, meat, and sugar (Table 7). This difference in consumption patterns can be attributed to the higher income levels among adopters, which are reflected in their net returns from crop production, as demonstrated in Tables 5 and 6 (Kumar & Sidana, 2017). Furthermore, Ridaura *et al.* (2018) noted that climatic shocks adversely impacted income levels, suggesting that those who diversified their income sources tended to be more food secure and enjoyed improved livelihoods.

The monthly consumption data for the sample households was converted into calorie intake, which was subsequently expressed as per consumer unit per day. The results indicated that the average daily calorie intake per consumer unit for adopters was 3,005.64 Kcal, compared to 2,808.05 Kcal for non-adopters (Table 8). Notably, in relation to the recommended minimum calorie intake of 2,730 Kcal per day, approximately 87 percent of rural households exceeded this threshold. This figure included 94.35 percent of adopters and 65.07 percent of non-adopters, as illustrated in Table 8.

Similar findings were reported by Karim *et al.* (2018), who used a threshold of 2,350 Kcal in Pakistan to assess household members above or below the poverty line. Their study revealed that the majority of rural households consumed more than the recommended calorie intake, with only about 13 percent falling below the average threshold. In another relevant study, Euler *et al.* (2017) demonstrated that individuals who adopted oil palm cultivation in Nigeria experienced increased food expenditures and higher calorie consumption, attributed to enhanced income levels.

Based on the food security index values, it was found that a significant proportion of adopters, specifically 51.98%, fell into the high calorie intake category, followed by 42.37% in the medium category and only 5.65% in the low category. In contrast, among non-adopters, 56% were classified under the medium calorie intake category, with 34.92% in the low category and just 9.11% in the high category, as illustrated in Table 9. A related study by Ali and Erenstein (2017) indicated that farmers who adopted

Table 8. Distribution of sample farmers according to calorie threshold level, Punjab, 2021-22 (Numbers)

Particulars (Kcal/ per day)	CSP Adopters	Non-adopters	Overall
< 2730	10 (5.65)	22 (34.92)	32 (13.33)
>2730	167 (94.35)	41 (65.08)	208 (86.67)
Total	177 (100.00)	63 (100.00)	240 (100.00)

Figures in parentheses are percentages of the total

Table 9. Distribution of sample farmers according to calorie intake, Punjab 2021-22 (Percentage)

Particulars	Class categories	Adopters	Non-adopters	Total
Calorie deficit	Low-calorie intake (<1.00)	5.65	34.92	13.33
Calorie sufficient	Medium-calorie intake (1.01-1.10)	42.37	55.97	46.42
	High-calorie intake (>1.11)	51.98	9.11	40.25
	Total	100.00	100.00	100.00

additional adaptation practices achieved food security levels 8-13% higher than those of non-adopters. This evidence clearly demonstrates that calorie intake is notably higher among rural households that adopt climate-smart practices compared to their non-adopting counterparts. Overall, 46.42% of households fell into the medium intake category, while 40.25% were classified as high intake, and 13.33% as low intake.

The Gini coefficient values for adopters were calculated at 0.0088, while for non-adopters, the value was 0.034205. This indicates that inequality in calorie intake is significantly lower among adopters compared to non-adopters. Similar studies, such as those by Kanu and Okezie (2021) and Mehmood *et al.* (2022), have utilized the Gini coefficient to assess inequality in food consumption and income patterns among farmers who adopt climate adaptation practices. Additionally, Oluwatayo (2008) suggested that improving technologies for increased food production could enhance equality in income derived from farming activities, reinforcing the importance of adopting innovative agricultural practices to foster equity.

Factors responsible for food security

The results from the ordered probit model, presented in Table 10, highlight the factors influencing food security. Notably, the marginal effects are emphasized here, as the coefficients of an ordered probit model do not directly convey the magnitude of each independent variable's effect. The analysis indicates that an increase in family size negatively impacts food security, making it more challenging for households to access sufficient food, with a statistically significant result (*p<0.001*).

This finding aligns with previous research, which consistently demonstrates a negative relationship between household size and food security (Agbola, 2014; Abubakari & Abubakari, 2015). The marginal effect of family size, recorded at 0.02 (*p<0.01*), indicates that for each 1 percent increase in family size, food availability decreases by 2 percent (Table 10). This reduction can be attributed to the heightened demand for resources necessary to meet the nutritional needs of additional household members, thereby straining already limited resources. Consequently, households with larger sizes may experience a decline in calorie intake, often falling below the recommended levels.

Furthermore, the present study incorporates education as an essential exogenous variable, recognizing that households led by individuals with higher education levels are generally more food secure. The parameter estimate for the education level of household heads reveals a significant positive relationship (*p<0.01*), indicating that increased educational attainment facilitates better access to food. This is largely due to the adoption of new technologies that enhance agricultural productivity and address household food needs. Tsegaye and Bekele (2010) observed in Southern Ethiopia that more educated farmers who engaged in soil-moisture management practices experienced improved food security. Similarly, research in Eastern Africa by Murage *et al.* (2015) found that farmers adopting climate-smart practices

Table 10. Parameter estimates for the determinants of food security

Particular	Coefficient	SE	*Z*	*P*>|z|
Family Size	-0.13	0.04	*-3.27*	0.00
Education	0.06	0.02	*2.55*	*0.01*
Credit	0.50	0.23	*2.17*	*0.03*
Adoption	0.75	0.24	*3.06*	*0.00*
Ln_Farmers annual Income	2.12	0.98	*2.16*	0.03
Number of observations = 240 LR chi^2 (5) = 93.34 Prob > chi^2 = 0.0000 Log likelihood = -191.40096 Pseudo R^2 = 0.1960				

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Table 11. Marginal effects from ordered probit model

Particular	Marginal effects[a]				Marginal effects[b]			
	dy/dx	SE	*Z*	*P*>|z|	dy/dx	SE	*Z*	*P*>|z|
Family Size	0.02	0.01	*3.25*	*0.00*	-0.04	0.01	*-3.41*	*0.001*
Education	0.01	0.00	*-2.50*	*0.01*	0.02	0.01	*2.62*	*0.009*
Credit	0.07	0.03	*-2.23*	*0.03*	0.15	0.07	2.23	0.026
Adoption	0.11	0.04	*-2.84*	*0.00*	0.23	0.07	*3.11*	*0.002*
Ln Farmers annual Income	0.31	0.14	*-2.17*	*0.03*	0.65	0.29	*2.2*	*0.028*

a: medium calorie intake with a base category of low-calorie intake i.e., calorie deficit households taking less than the minimum recommended (2730 kcal/day/consumer unit) ; *b: high-calorie intake with a base category of low-calorie intake i.e., calorie deficit households taking less than the minimum recommended (2730 kcal/day/consumer unit)*

were more likely to achieve food security.

Findings from the ordered probit model regarding education align with previous research by Abubakari and Abubakari (2015) and Zhou *et al.* (2019). These studies highlight that the education level of the household head significantly influences food security, as educated individuals are generally more knowledgeable and aware of high-technology agricultural practices, enhancing their food production capabilities. The marginal effects indicate that a unit increase in education corresponds to a 1% increase in access to food for medium-calorie intake households and a 2% increase for high-calorie intake households (Table 11). Additionally, the study incorporates credit availability as an exogenous variable, highlighting its critical role in enhancing household food security. The results show a positive and significant relationship ($p<0.02$) between credit availability and the food security index, suggesting that households with better access to credit can improve their food access. Specifically, a 1% increase in credit availability is associated with a 7% increase in food access. Moreover, the coefficient for the adoption of climate-smart practices is also positive and significant ($p<0.01$), indicating that households more inclined toward innovation and technology are better positioned to enhance their agricultural output and achieve better nutrition and higher-calorie food. This finding is supported by Abubakari and Abubakari (2015), who noted that a greater openness to innovation contributes to improved food access. Lastly, while the coefficient for income levels exhibits a positive relationship with food access, it is not statistically significant. Nonetheless, this aligns with findings from similar studies (Sikwela, 2008; Mensah *et al.*, 2013; Nour & Abdalla, 2021), which affirm the link between higher farm income and improved food security.

CONCLUSION

Punjab, recognized as the food bowl of India, faces significant challenges to its staple crop production, particularly wheat and paddy, due to changing climatic patterns, which could profoundly impact the nation's food security. This study highlights the positive effects of climate-smart agricultural (CSA) practices on the food security of rural households. It was found that adopters of these practices not only achieved higher consumption of calorie-rich, premium food items but also realized greater returns from crop production compared to non-adopters. The analysis revealed key socio-economic determinants influencing food security: family size negatively impacted food security ($p<0.001$), while education and access to credit positively influenced it ($p<0.02$). Additionally, income levels showed a likely positive association with food security. To promote the widespread adoption of CSA practices, more training and capacity-building programs for farmers are necessary. Sustainable implementation requires ongoing collaboration among farmers, government entities, scientists, the private sector, and policymakers. Government support for timely and affordable technological advancements is crucial to enhance CSA adoption. Future studies should focus on refining strategies to improve food security and sustainability in agricultural systems, leveraging these policy insights to inform effective interventions.

Authors' contribution

Conceptualization and designing of the research work (ST, BKS); Execution of field/lab experiments and data collection (ST, BKS); Analysis of data and interpretation (ST, BKS, ST, BKS, SK); Preparation of manuscript (ST, BKS, AK, SR, SK).

Limitation of the study: The present study lacks in adding explanatory variables such as daily T_{max}, T_{min}, and precipitation which are most extensively used in climate-crop studies. However, the additional primary data on various social factors such as education, adoption level, availability of the credit, farmers income may provide a better conceptual insight.

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