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Adaptation, Impact and Barriers to Climate-Smart Agriculture: Empirical Evidence from Arunachal Pradesh

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ABSTRACT

This study analyses how tribal farming communities in Arunachal Pradesh are adapting to Climate-Smart Agriculture (CSA), the impact it has on their livelihoods, and the key challenges they face. The study is based on primary data collected from 250 farmers through a structured schedule. The analysis employs binary logistic regression to identify the factors that drive adaptation and applies Propensity Score Matching (PSM) to measure its outcomes. A Problem Confrontation Index (PCI) is used to rank the barriers. The results show that 43% of farmers have adopted CSA practices. Adaptation is more likely among individuals with higher education levels, access to irrigation, younger household members, and involvement in institutions such as farmers' groups. Farmers who adopted CSA reported major gains: crop yields increased by 51%, farm income increased by 58%, and food security improved by 19%. However, CSA had limited effects on reducing greenhouse gas emissions and improving carbon sequestration. Despite its benefits, many farmers face serious obstacles. The biggest challenges include weak agricultural extension services, low awareness about CSA, high cost and poor availability of improved seeds, and limited access to institutional credit. The study suggests training on CSA, better agricultural extension support, and inclusive financial services for better CSA adaptation. CSA has the potential to enhance productivity and resilience in tribal farming systems, and with the right support. It can play a key role in promoting sustainable agriculture in the region.

INTRODUCTION

1.1 Global Context: Climate Change and Agriculture

Agriculture plays a pivotal role in ensuring global food security. The farming sector is increasingly under pressure from rapid population growth, urbanization, environmental degradation, and the intensifying impacts of climate change. Approximately 690 million people (8.9%) of the global population were undernourished in 2020 (FAO, 2020a, 2020b). Food production will need to increase by at least 60% to meet the demands of a projected global population of 9 billion by 2050. This is a formidable challenge, especially when one in every eight people currently suffers from food insecurity. Climate change is estimated to result in a minimum global welfare loss of $268 billion and a GDP loss of $265 billion by 2050 (FAO). Developing countries with predominantly agrarian economies are particularly vulnerable to the impacts of climate change. This has an adverse impact on agricultural productivity, exacerbates rural poverty, and undermines food security (Fischer et al., 2002; Mendelsohn, 2008). Developing countries are more susceptible to the impact of climate change than developed countries (Antônio et al., 2015; Saikia et al., 2024). South Asia, one of the most densely populated and agrarian regions of the world, is particularly susceptible to the impacts of climate change. The consequences for food security, poverty reduction, and broader development objectives could be severe without timely adaptation and mitigation strategies (IPCC, 2014).

Climate change causes rising temperatures, disrupts plant and animal life, and contributes to water supply constraints. It could pose serious and catastrophic impacts on agriculture and transportation systems. Water supply is also highly vulnerable to changes in the precipitation pattern. The disruptions in the water supply will adversely affect plant growth, the yield of crops, and the availability of the gestation period for crop production (Kaiser et al., 1993). The crop productivity rate is also directly conditioned by increased atmospheric carbon dioxide levels. The escalation in mean sea levels can lead to flooding, downsizing arable land, and eroding the most profitable production systems (Antle, 2008). The agriculture sector has great potential to adapt to climate change and has already shown its ability to adapt to many significant fluctuations. The boom of the 1970s for agriculture in the USA and the recession of the 1980s show that agriculture can respond to climatic aberrations. However, those changes have imposed many costs on producers and rural communities. Climate change is considered a greater threat to the sustainability of agriculture, as per IPCC AR 2023. Agriculture is both a contributor to and a victim of climate change. It accounts for approximately 19–29% of Global Greenhouse Gas (GHG) emissions, while also being highly sensitive to climatic variability and extreme weather events (IPCC, 2014).

1.2 The Indian Context: Agriculture and Climate Vulnerabilities

In India, the agriculture sector employs 54.6% of the workforce and contributes 17.8% to the national Gross Value Added (FAO, 2020a, 2020b). At the same time, it is responsible for around 14% of the country's cumulative GHG emissions (UNFCCC, 2021), primarily due to methane emissions from rice cultivation and livestock, and nitrous oxide emissions from fertilizer use (Pathak et al., 2010). Indian agriculture is highly resource-intensive. Nearly 80% of the country's freshwater usage and approximately 17.35% of total electricity consumption is in farming (CEA, 2023; Dhawan, 2017). India is particularly vulnerable to the impacts of climate change due to a combination of socio-economic and environmental factors.

Widespread poverty, the dependence of the population on agriculture for their livelihood, reliance on natural resources, and limited adaptive and resilience capacity contribute significantly to this climate vulnerability. Although the adoption of improved agricultural technologies in the mid-1960s—including high-yielding varieties, chemical fertilizers, and irrigation—initiated the Green Revolution and enabled unprecedented growth in food grain production, concerns have been raised regarding the long-term sustainability of this growth in light of increasing population pressure. Despite the Green Revolution's success in transforming Indian agriculture and achieving self-sufficiency in food grain production, issues like food insecurity, malnutrition, poverty, and hunger remain persistent due to increasing economic inequality and frequent climate-led natural disasters.

1.3 Anticipated Climate Challenges

The continued intensive use of the same agricultural technologies has led to significant environmental degradation. Problems such as groundwater depletion, declining water quality, and deteriorating soil health have had negative consequences on agricultural productivity. These factors are considered major contributors to the deceleration of crop production growth. Climate changes are expected to impact agriculture adversely by affecting crops, fisheries, and livestock systems. Consequently, the pressure on agriculture increases to meet the rising food demand from the same or even shrinking cultivable land (Aggarwal, 2008). Changes in temperature and precipitation patterns are likely to affect land and water regimes, with serious implications for agricultural productivity and the food and livelihood security of farming communities. India may experience a 10–40% reduction in crop production due to increased temperatures by 2080–2100 (Fischer, IPCC, 2007; Parry et al., 2004; Rosenzweig & Parry, 1994; Shah, & Velhizen, 2002). The Indian Council of Agricultural Research (ICAR) has projected a potential decline of 4.5–9.0% in food grain production in the medium term (2010–2039) as a result of climate change. Further, a rise in temperature could lead to a loss of wheat production (Aggarwal, 2008). Other studies (e.g., Aggarwal, 2003; Aggarwal & Mall, 2002; Aggarwal & Sinha, 1993; Saseendran et al., 2000) have similarly warned of the negative effects of climate change on agricultural output. While long-term climate change is likely to reduce the yields of most crops, short-term variability will contribute to greater fluctuations in production (Rao et al., 2011). Even moderate increases in temperature have been found to negatively affect yields of rice, wheat, and maize (Aggarwal et al., 2012; Aggarwal et al., 2009; Parry et al., 2004). Using panel data from 200 districts between 1969 and 2005, Birthal et al. (2014) observed that while increases in maximum temperature negatively impacted both kharif and rabi crop yields, increases in minimum temperature had a slightly positive effect, although not enough to compromise the negative consequences. Rainfall had a generally positive impact, but it also fell short of compensating for heat-related yield losses. Further, drought frequency and severity have been identified as major constraints to sustainable productivity in rain-fed agriculture (Birthal et al., 2015).

1.4 Climate-Smart Agriculture

The agricultural sector must adapt to changing climatic conditions. The transformation of the agricultural sector—including crops, livestock, forestry, and fisheries—should not occur at the cost of the natural resource base. This transformation is important for providing sufficient and nutritious food to a growing population while enhancing economic development and alleviating poverty. In this context, the concept of Climate-Smart Agriculture (CSA) was introduced by the FAO at the Hague Conference on Agriculture, Food Security, and Climate Change in 2010. According to FAO (2013, 2014) "Climate-smart agriculture (CSA) is an approach that helps guide actions to transform agri-food systems towards green and climate-resilient practices. CSA supports reaching internationally agreed goals such as the SDGs and the Paris Agreement. It aims to tackle three main objectives: sustainable agricultural productivity and incomes; adapting and building resilience to climate change; and reducing greenhouse gas emissions (See Fig. 1).

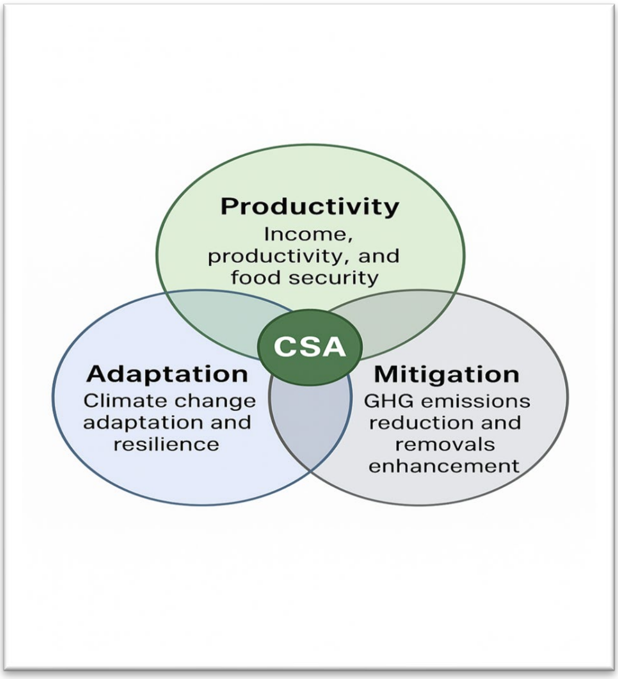

Fig 1: The Three Pillars of Climate-Smart Agriculture.

CSA practices include techniques such as crop rotation, integrated soil management, drought-resistant seed use, and conservation agriculture. It has a positive impact on crop yields, food security, household income, and environmental sustainability (Akter et al., 2022). The adaptation of CSA practices is influenced by various socioeconomic, institutional, and environmental factors. Socio-economic characteristics such as age, gender, education level, and perception of climate risk significantly influence decision-making (Aryal et al., 2018; Tran et al., 2024). Institutional factors—such as access to credit, secure land tenure, participation in farmers' organizations, and availability of agricultural extension services can play an important role in facilitating CSA adaptation. Digital advisory services (DAS) such as weather forecasting can enhance access to timely climate information, enabling farmers to adapt to climate-resilient technologies like zero tillage and climate-resilient crop varieties (Asante et al., 2024). Access to subsidies, training programs, and community-based support systems also improved the likelihood of CSA adaptation.

Despite increasing scholarly interest in CSA, several research gaps remain. First, empirical research focusing on tribal communities—especially in Northeast India—remains sparse, even though these regions are highly vulnerable to climate change due to geographical terrain. Second, most CSA studies emphasize adaptation drivers without quantitatively assessing the impacts on farm-level outcomes such as yield, income, and resilience. Third, existing work often lacks integrated barrier analysis using systematic indices that reflect local perceptions. This study makes an attempt to address this research gap by using an impact-focused approach.

One such region is Arunachal Pradesh. Agriculture in this region is largely rain-fed and subsistence-based, relying on indigenous knowledge systems and community-oriented practices. However, farmers face significant challenges like erratic rainfall, soil erosion, low productivity, limited land ownership, and restricted access to institutional support. CSA allows integrating traditional ecological knowledge with modern agricultural techniques such as agroforestry, organic farming, and water conservation. Successful adaptation depends on understanding the socio-economic, cultural, and institutional constraints specific to the region. Region-specific, inclusive approaches are required that build local capacity and provide equitable access to resources and decision-making platforms (Jost et al., 2016).

With this backdrop, the study aims to examine the adaptation of CSA. It aims to assess the impact of CSA on agricultural productivity, food security, and environmental sustainability while identifying key socio-economic and institutional barriers to adaptation. The study contributes to broader debates on sustainable development, climate adaptation, and inclusive agricultural policy by focusing on a climate-vulnerable and culturally distinct region (See Fig. 2).

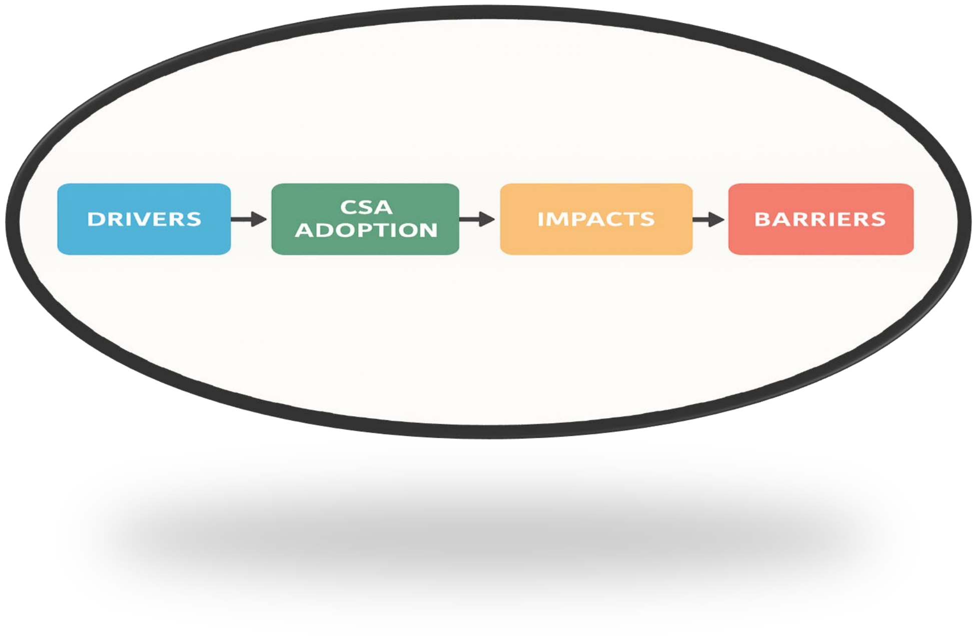

Fig 2: Core Objectives.

2. **METHODOLOGY**

The study has identified tribal dominated Arunachal Pradesh as a study area. Primary data was collected through a structured schedule in 2024. The sample consisted of 250 tribal households. Stratified random sampling is used that represent all agro-ecological variation across the state. Prior to final deployment, the questionnaire was pre-tested with 15 farmers to refine question wording, validate response categories, and ensure contextual relevance. For identification of climate-smart practices, a list of sustainable and environmentally friendly practices was prepared based on experiences and views of the researchers, extension workers, farmers and experts, and a review of literature. The questionnaire was designed to collect the information related to existing climate-smart practices based on the "CSA Tech Index" of the World Bank (2016) to measure and recognise the practice or technology as climate-smart or not in the earlier research work (Patra, 2017). All the existing crops and some important practices in the region are assessed with special reference to CSA". Indicators for identification and validation of existing crop production practices with reference to CSA are as follows: The practice improves yield and income, promotes crop and livelihood diversification, and supports local supply chains. It suits various agro-climatic zones—high/low altitudes, steep slopes, rainfed, high rainfall, and extreme temperatures. It reduces erosion, enhances soil fertility, improves water efficiency, and lessens groundwater use. It supports food security, gender equity, and drought resilience. For mitigation, it reduces energy use, enables IPM and INM, supports livestock and feed diversification, lowers GHG emissions, and enhances carbon sequestration. It allows zero tillage, and the crop residue serves as fodder without emitting harmful gases.

Formal institutional clearance was not obtained due to the non-invasive nature of the study. However, verbal informed consent was taken from all participants, and ethical norms such as voluntary participation, anonymity, and confidentiality were strictly followed.

The binary logistic regression model is used to identify and interpret the main socio-economic and demographic factors affecting the adaptation of climate-smart agriculture practices and their implications for food security. Besides, it also helps to identify the nature of the relationship between each of the identified factors and the dependent variables. Binary (binomial) logistic regression is the form of regression used when the dependent variable is a dichotomous variable and the predictor variables are of any type (Spicer, 2004). The model specification is a generalized linear model and can be written as:

$$\text{Logit}(\pi(xi)) = \log(\pi(xi)/1 - \pi(xi)) = \beta 0 + \beta 1x1i + \ldots + \beta pxpior.$$
$$\ln(p/1\text{-}p) = \beta 0 + \beta 1x1 + \beta 2x2 + \ldots + \beta pxp.$$

where, p =probability of event occurring, p/1-p =odds ratio.

In this study, the response (dependent variable) Y represents the adaptation of CSA practices. Farmers perceived that the adopted CSA practices contributed to both farm income and household food availability. It is measured as a dummy variable, a numeric value of 1 if the number of farmers adopts CSA, and 0 if no adopters. The explanatory (independent variables) in the regression model are hypothesized to affect the smallholder farmers' adaptation of CSA practices and the combined effects of various factors such as household demographic characteristics, socio-economic characteristics, and institutional characteristics. Based on the review of related literature, fourteen potential explanatory variables (sex of the HH, age of the HH, household size, education, farm size, farming experience, farming system, access to irrigation, farm income, off-farm income, access to credit, distance to market, and access to weather information) were considered as significant factors and examined for their effect on adaptation. To ensure robustness of estimates, multicollinearity diagnostics were conducted using the Variance Inflation Factor (VIF). All predictors had VIF values below 5, indicating no significant collinearity.

To assess the impact of CSA adaptation, the Propensity Score Matching (PSM) technique is used. This model estimates the average treatment effect of CSA on outcome variables such as soil health, economic stability, and food security by matching adopters and non-adopters with similar observable characteristics. First, a logit model is used to estimate propensity scores, which represent the probability of CSA adaptation given the covariates. Then, these scores are used to match each adopter with one or more non-adopters to evaluate the differences in outcomes that can be attributed to CSA adaptation. The outcome model includes CSA adaptation as a treatment variable along with control variables, and the impact is measured by comparing the matched samples.

Propensity Score Estimation (Logit Model):

$$P(T_i = 1 \mid X) = e^{(\gamma_0 + \sum \gamma_k X_{ik})} / (1 + e^{(\gamma_0 + \sum \gamma_k X_{ik})})$$

Where:
T_i = Treatment indicator (1 = CSA adopter, 0 = Non-adopter)
X_{ik} = Covariates (Landholding size, Farm income, etc.)
γ_k = Coefficients

Outcome Model
$Y_i = \alpha + \delta T_i + \sum \beta_k X_{ik} + \varepsilon_i$
Where:
Y_i = Outcome variables (Soil health, Economic stability, etc.)
δ = Treatment effect of CSA adaptation
ε_i = Error term
Matching quality was assessed using standardized mean differences. All covariates achieved balance (SMD < 0.1), confirming the effectiveness of the PSM process in reducing selection bias.

To identify and rank the barriers to CSA adaptation, the Problem Confrontation Index (PCI) method is employed. This approach quantifies farmers' perceived severity of different barriers using a 4-point Likert scale, where 0 represents no problem and 3 indicates a high-level problem. Farmers rate each barrier, and the PCI is calculated using the formula:

$$PCI = Pn\times0 + Pl\times1 + Pm\times2 + Ph\times3$$

where Pn, Pl, Pm, and Ph denote the number of farmers assigning the respective levels of severity. The PCI helps determine which barriers are most significant in obstructing the adaptation of CSA practices. This method has been effectively used in earlier studies to assess constraints in climate adaptation strategies. Each farmer rated the severity of these constraints using a four-point Likert scale. The PCI scores were calculated and used to rank the barriers accordingly.

3. RESULTS AND DISCUSSION

The average age of respondents is approximately 46 years, showing wide variation and participation from both younger and older individuals. Education levels are relatively modest, with an average of 6.2 years of schooling. Most respondents have only completed primary education. Household income remains low, averaging ₹20,500 and below ₹100,000. The average landholding size is about 1.25 acres, with all respondents owning less than 2 acres. The sample largely consists of marginal and small farmers. Gender representation is skewed, with 84% of respondents identifying as male. Household size averages 5.6 members. Climate-smart agriculture (CSA) practices are adopted by only 43% of households, indicating limited uptake despite environmental vulnerabilities. Access to formal credit is available to just 38% of respondents. The average climate risk perception score is 3.1 on a 1–5 scale, reflecting moderate awareness. Participation in agricultural training programs is low at 27%, potentially due to the average 8.5 km distance to such facilities. While 91% of the respondents own their land, only 35% report receiving support from agricultural extension services. Overall, the data reflect low land and income levels, modest education, and limited access to agricultural services (See Table 1.1).

Table 1.1: Descriptive Statistics of Socioeconomic and Agricultural Characteristics of Respondents.

Variable Name	Mean	Std. Dev.	Min	Max
Age (Years)	45.7	12.3	21	78
Education Level (Years)	6.2	4.1	0	16
Household Income (Rs.)	20,500	12,000	20,000	99,000
Landholding Size (Acres)	1.25	0.45	0.3	1.99
Gender (1=Male, 0=Female)	0.84	0.36	0	1
Household Size	5.6	2.2	2	12
CSA Adaptation (1=Yes)	0.43	0.49	0	1
Access to Credit (1=Yes)	0.38	0.49	0	1
Climate Risk Perception[1]	3.1	0.8	1	5
Training Participation	0.27	0.44	0	1
Distance to Training (km)	8.5	4.6	1.0	25.0
Land Ownership (1=Yes)	0.91	0.28	0	1
Extension Access (1=Yes)	0.35	0.48	0	1

Source: Author's Calculation

3.1 Adaptation

There is a balanced pattern of adaptation across practices, with no single method overwhelmingly dominant or ignored. The highest adaptation rates, each at 52%, are observed for efficient chemical fertilizer application, water management, and livelihood diversification. This suggests a relatively greater recognition of these practices' benefits in coping with climate variability and improving resilience. Improved livestock feed practices (50%), conservation agriculture (50.8%), and improved crop varieties (49.2%) also exhibit relatively high uptake, indicating an integrated approach among some households toward both crop and livestock management under climate stress. Practices such as mulching, compost and manure management, and crop residue management show adaptation levels clustered around 47.6 %, reflecting a moderate but widespread interest in soil fertility and organic matter preservation.

Table 1.2: Adaptation of Climate-Smart Agricultural Practices

CSA Practice	Frequency	Percent (%)
Crop rotation	115	46.0
Cereals and legumes crops intercropping	121	48.4
Efficient chemical fertilizer application	130	52.0
Improved crop varieties	123	49.2
Pest-resistant crop varieties	120	48.0
Drought and heat tolerant crop varieties	121	48.4
Post-harvest technologies	123	49.2
Conservation agriculture	127	50.8
Crop residue management	119	47.6

Mulching	119	47.6
Compost and manure management	119	47.6
Water management	130	52.0
Agro-forestry	120	48.0
Improved livestock feed and feeding practices	125	50.0
Early-warning weather information	116	46.4
Livelihood diversification	130	52.0

Source: Author's Calculation

Similarly, adaptation of drought- and pest-resistant crop varieties, intercropping of cereals and legumes, and agroforestry fall in the 48–49% range, implying an awareness of the importance of biodiversity and climate-resilient crops. Lower adaptation levels are seen in early-warning weather information (46.4%) and crop rotation (46%), possibly pointing to gaps in information dissemination or infrastructure support for early climate advisories. Overall, the results suggest that while awareness and use of CSA practices are moderately high and fairly evenly distributed, no single practice dominates the landscape. There are opportunities for more targeted promotion, education, and policy support to improve uptake across multiple CSA domains (See Table 1.2).

Table 1.3: Factors Impacting the Adaptation of CSA

Independent Variable	**B**	**S.E.**	**Wald**	**Sig.**	**Exp(B)**	**95 % CI Lower**	**95 % CI Upper**
Sex	-0.24	0.213	1.264	0.261	0.787	0.517	1.197
Age	-0.015	0.01	2.25	0.134	0.985	0.966	1.005
Education level	0.502	0.168	8.936	0.003*	1.652	1.182	2.308
Marital status	0.178	0.244	0.532	0.466	1.195	0.742	1.924
Household size	0.202	0.067	9.091	0.003*	1.224	1.07	1.4
Dependency ratio	-0.133	0.105	1.604	0.205	0.875	0.708	1.082
Youth presence in household	0.389	0.193	4.071	0.044*	1.476	1.012	2.153
Farm size (in ha)	0.158	0.094	2.828	0.093	1.171	0.973	1.41
Soil quality perception	0.421	0.182	5.366	0.021*	1.523	1.066	2.176
Irrigation access	0.982	0.343	8.189	0.004*	2.67	1.392	5.119
Crop diversification index	0.312	0.115	7.383	0.007*	1.366	1.092	1.709
Livestock ownership	0.041	0.023	3.21	0.073	1.042	0.997	1.09
Use of farm implements	0.675	0.277	5.936	0.015*	1.964	1.139	3.388
Organic certification status	0.789	0.321	6.049	0.014*	2.202	1.171	4.14
Land tenure	0.337	0.216	2.439	0.118	1.401	0.918	2.138
Annual farm income	-4E-05	1E-05	11.392	0.001*	0.99996	0.99994	0.99998
Annual off-farm income	3E-05	1E-05	7.215	0.007*	1.00003	1.00001	1.00006
Access to institutional credit	0.384	0.245	2.455	0.117	1.468	0.91	2.369

Membership in SHG/FPO	0.642	0.281	5.214	0.022*	1.9	1.097	3.292
Participation in government schemes	0.711	0.298	5.693	0.017*	2.037	1.139	3.647
Ownership of smartphone	0.477	0.226	4.47	0.034*	1.611	1.038	2.499
Access to savings facility	0.359	0.219	2.684	0.101	1.432	0.931	2.203
Extension contact frequency	0.552	0.248	4.961	0.026*	1.737	1.07	2.82
Received CSA training	0.894	0.312	8.191	0.004*	2.445	1.312	4.558
Awareness of CSA techniques	0.789	0.298	7.006	0.008*	2.201	1.231	3.937
Access to early warning info	0.619	0.268	5.339	0.021*	1.857	1.095	3.148
Access to market info	0.472	0.235	4.028	0.045*	1.603	1.01	2.544
Distance to nearest market	-0.044	0.017	6.589	0.01*	0.957	0.926	0.99
Access to crop insurance	0.331	0.234	2.01	0.156	1.392	0.878	2.206
Perceived climate risk	0.741	0.304	5.956	0.015*	2.099	1.16	3.801
Exposure to past shocks	0.592	0.263	5.07	0.024*	1.808	1.084	3.015
Perceived yield loss (%)	0.019	0.007	7.412	0.006*	1.019	1.006	1.033
Attitude toward risk	0.468	0.211	4.922	0.027*	1.597	1.057	2.412
Climate adaptation awareness	0.853	0.295	8.366	0.004*	2.347	1.295	4.256

Source: Author's Calculation; Note: *** = $p < 0.05$**

The logistic regression model demonstrates a good fit, with a McFadden's pseudo R^2 value of 0.312, indicating that the model explains approximately 31.2% of the variance in CSA adaptation decisions. Education significantly increases the likelihood of adaptation. Highly educated farmers are more likely to adopt new and sustainable farming techniques. Larger household sizes also have a positive contribution. Possibly due to the availability of more family labor. The presence of youth in the household further enhances adaptation. This suggests their role in bringing innovation and openness to modern practices. Farmers who perceive their soil quality to be good are more likely to adopt CSA. This implies a positive feedback loop between perceived natural resource quality and the willingness to invest in climate-smart methods. Access to irrigation is strongly associated with higher adaptation. A diverse cropping pattern, as indicated by the crop diversification index, is positively linked to CSA uptake. This shows the role of ecological resilience and production flexibility. Use of farm implements and possession of organic certification also positively influence adaptation. This indicates the significance of mechanization and compliance with environmental standards. Livestock ownership and farm size show positive trends. However, their effects are not statistically strong enough to be conclusive. Income variables display mixed results, i.e., higher annual farm income slightly reduces adaptation likelihood, potentially due to risk aversion or satisfaction with conventional practices. Off-farm income shows a mild positive effect, possibly offering financial stability to support innovation. Institutional factors such as membership in farmer groups or self-help groups, participation in government schemes, and ownership of smartphones significantly enhance the probability of adaptation. These variables show access to information, collective learning, and direct or indirect support mechanisms. Regular extension contact and receipt of CSA-related training are among the most impactful variables, emphasizing the crucial role of capacity building and knowledge transfer.

Awareness of CSA techniques and access to early warning information significantly increase the odds of adaptation, showing that informed farmers are better prepared to mitigate risks and adapt their practices accordingly. Access to market information also plays a positive role. A greater distance to the market has a negative effect. This indicates that logistical and infrastructural barriers can limit the feasibility of CSA adaptation. Psychological and experiential factors such as perceived climate risk, exposure to past shocks, and perceived yield loss contribute positively and significantly to adaptation. Farmers who are motivated by past vulnerabilities are more likely to take preventive or adaptive action. A proactive attitude toward risk and higher awareness of climate adaptation options also promote CSA adaptation. Hence, mental preparedness and an adaptive mindset are important. There is relatively balanced and moderate adaptation of various CSA technologies in the study area, with practices such as efficient chemical fertilizer use, livelihood diversification, and water management recording the highest uptake at 52%. Awareness of CSA benefits exists among farming households. However, the extent of implementation remains fragmented and context-dependent (FAO, 2016).

Education, household size, the presence of youth, perceived soil quality, access to irrigation, the use of farm implements, organic certification, and participation in farmer organizations all contribute positively to the likelihood of CSA adaptation. These findings reinforce long-standing arguments regarding the enabling role of human capital, institutional access, and infrastructural support in driving the uptake of sustainable technologies (Aryal et al., 2018). Education emerges as a crucial determinant, enhancing farmers' ability to comprehend and apply complex agroecological practices such as conservation tillage, crop diversification, and integrated pest management (Diro et al., 2022). Larger household sizes, particularly those with youth members, suggest that the availability of labor and the openness to innovation are vital for the successful implementation of labor-intensive CSA practices. Meanwhile, access to irrigation and mechanization points to the infrastructural backbone required for adapting water-efficient techniques and reducing drudgery in difficult terrains (Rockström et al., 2010) (See Table 1.3)

Positive associations are found between CSA adaptation and variables such as membership in self-help groups or farmer-producer organizations, participation in government schemes, and ownership of smartphones. These factors facilitate information access, collective bargaining, and exposure to agricultural advisories, all of which are essential for making informed decisions under climate uncertainty (Liu et al., 2023; Teklewold et al., 2013). Extension services and training related to CSA technologies stand out as particularly influential. Continuous farmer education and capacity building are foundational to driving long-term change in behavior and practices (Aryal et al., 2018). At the same time, the findings caution against an overly deterministic view of institutional access. For example, while credit availability is often assumed to be an enabler, its influence on CSA adaptation in this study is statistically insignificant. This shows the reality that credit in rural areas is frequently diverted toward non-agricultural uses such as household expenses, education, or health emergencies

(Aryal et al., 2018). The case of Arunachal Pradesh is illustrative of a broader phenomenon where formal financial inclusion does not automatically lead to productive investment in agriculture, especially when informal networks and consumption needs dominate household priorities (Teklewold et al., 2013).

Psychological and experiential factors also play a key role. Farmers' perceptions of climate risk, their experiences with past climatic shocks, and perceived yield losses significantly influence their decision to adopt CSA practices. Lived experiences of vulnerability often act as catalysts for change (Issahaku and Abdulai, 2020). However, it is important to recognize that the motivation due to risk perception may lead to short-term coping strategies rather than long-term adaptation, especially when resources and institutional support are lacking. The relatively low adaptation of improved crop varieties, including pest-resistant, drought-tolerant, and heat-resilient genotypes, reveals persistent structural and informational barriers. Despite the recognized potential of these technologies to enhance resilience and sequester carbon, their uptake remains limited due to factors such as limited varietal availability, lack of machinery suited for hilly terrains, inadequate market incentives, and minimal on-ground promotion. Conservation agriculture, although conceptually ideal for hill farming systems, faces multiple barriers such as labor intensity, equipment costs, and unfamiliarity with techniques like mulching and zero tillage.

Agroforestry, similarly, stands out as a high-potential CSA practice, particularly for upland regions, due to its role in carbon sequestration, biodiversity enhancement, and integrated livelihood support. However, its relatively low adaptation emphasizes critical gaps in training, market support, and interdepartmental coordination, similar to the experiences reported in Sub-Saharan Africa and Northeast India. This reinforces the need for capacity-building programs, incentive structures, and demonstration plots that can encourage replication. Water harvesting and small-scale irrigation—crucial for climate-resilient farming in erratic rainfall zones—require more public investment and local capacity-building to realize their potential. These technologies help stabilize yields and reduce dependency on unpredictable monsoons but are often underutilized due to capital constraints and lack of technical support (Akinnagbe and Irohibe, 2014; Hillel, 2005).

Arunachal Pradesh shows promising levels of CSA awareness and initial adaptation across a broad spectrum of technologies; the scaling of these practices requires support. Policy should focus on improving credit delivery, mechanization access, extension reach, training relevance, and participatory innovation platforms. CSA interventions to local agro-ecological and socio-cultural conditions are vital. Regional success will depend on multi-stakeholder coordination, sustained investment in farmer education, and leveraging youth as change agents in promoting long-term sustainability and climate resilience.

3.2 Impact of CSA

Table 1.4: Impact of CSA

CSA Theme	Indicator	ATT (Difference)	t-value	p-value
Productivity	Increase in crop yield	+0.51	3.12	0.002**
Increase in farm income	+0.58	3.45	0.001	**
Promote crop diversification	+0.48	2.89	0.005	**
Diversify livelihoods	+0.58	3.30	0.001	**

Support local/regional production chains	+0.53	3.10	0.002	**
Resilience	Enhance soil fertility	+0.23	2.90	0.005**
Increase water use efficiency	+0.21	2.70	0.008	**
Address food security	+0.19	2.40	0.018	*
Increase resilience to drought	+0.18	2.20	0.029	*
Mitigation	Enhance carbon sequestration	+0.14	1.80	0.074*
Reduce greenhouse gas (GHG) emissions	+0.12	1.60	0.112	ns
Integrated Pest Management (IPM)	+0.11	1.50	0.136	ns
Integrated Nutrient Management (INM)	+0.09	1.20	0.234	ns
Zero tillage potential	+0.06	0.80	0.425	ns

Source: Author's Calculation

Note: * = $p < 0.01$; ** = $p < 0.05$; *** = $p < 0.10$; ns = not statistically significant ($p \geq 0.10$).

PSM was conducted using the Nearest Neighbor Matching method with a caliper of 0.2 to ensure comparability between treated (CSA adopters) and control (non-adopters) groups. Kernel and radius matching were also tested for robustness.

The increase in crop yield associated with CSA adaptation is both substantive and statistically significant (ATT = 0.51, p = 0.002). This reflects measurable improvements in on-farm productivity. A similar pattern is observed for household income, where CSA participation corresponds to a gain of 0.58 points (p = 0.001), reinforcing the argument that such practices contribute directly to economic gains among farming households. CSA adopters also reported a notable shift toward greater crop diversification (ATT = 0.48, p = 0.005) and increased livelihood diversification (ATT = 0.58, p = 0.001). These practices offer broader economic flexibility and reduce dependence on a single source of income. These outcomes are especially relevant in regions affected by variable climatic conditions, where diversified agricultural portfolios can reduce risk exposure. In addition, a positive association was observed between CSA adaptation and support for local and regional agricultural value chains (ATT = 0.53, p = 0.002). This implies a wider systemic benefit that extends beyond the farm level.

On the dimension of environmental resilience, CSA appears to contribute to improvements in both soil fertility (ATT = 0.23, p = 0.005) and water use efficiency (ATT = 0.21, p = 0.008). These outcomes point to better resource conservation and more efficient use of available inputs, both of which are crucial for long-term sustainability in farming systems with limited ecological carrying capacity. Food security and drought resilience also appear to benefit from CSA interventions, though to a lesser extent. The gains observed in food security (ATT = 0.19, p = 0.018) and drought resistance (ATT = 0.18, p = 0.029) are statistically meaningful, reflecting the stabilizing effect of CSA practices during periods of environmental stress. In contrast, the evidence relating to climate mitigation is less conclusive. While there is a slight increase in carbon sequestration potential (ATT = 0.14, p = 0.074), the effect does not meet conventional thresholds for statistical significance. Other indicators—such as the reduction in greenhouse gas emissions (ATT = 0.12, p = 0.112), adaptation of integrated pest and nutrient management practices (ATT = 0.11 and 0.09, respectively), and potential for zero tillage (ATT = 0.06)—also remain statistically insignificant. These findings suggest that, within the scope of this study, the environmental mitigation aspects of CSA are not as pronounced or may take longer to manifest. It is also plausible that the limited scale or partial adaptation of such technologies may dilute their observable impact.

The adaptation of climate-smart agriculture (CSA) practices has shown substantial benefits across diverse agroecological contexts, particularly in improving productivity, resilience, and environmental sustainability. A growing body of empirical research demonstrates that CSA interventions enhance agricultural outcomes without compromising ecological integrity. For example, adaptation integrated soil management and crop rotation in Eastern India resulted in increased paddy yields and agricultural income due to their capacity to transform subsistence farming into a more market-oriented model. Similarly, smallholder maize farmers in Ghana experienced gains in yield and net farm income when utilizing CSA practices such as drought-resistant seeds, row planting, and zero tillage (Asante et al., 2024). CSA implementation has also been positively linked to livestock productivity and income. Evidence from Kenya indicates that the combination of climate-smart feed concentrates and fodder significantly boosted dairy milk yield and commercialization potential. Beyond production, the intensity of CSA adaptation has been associated with improved household income and income diversity. In China, for instance, more educated farmers and those residing in conducive geographies demonstrated higher adaptation intensity, leading to better economic outcomes.

The relationship between CSA adaptation and farm-level productivity has been explored through composite indices. A high Climate-Smart Score (CSS) based on 34 weighted indicators positively correlates with the yields of staple crops such as paddy, wheat, and maize, when practices like zero tillage, intercropping, crop diversification, and integrated nutrient management were deployed in India. The economic rationale behind CSA adaptation is further emphasized in research conducted in Rwanda. By integrating CSA technologies such as biogas plants and improved barns into livestock donation programs, households achieved up to 3.5 times greater net benefits compared to traditional schemes. Additional advantages included reduced respiratory health risks and lower GHG emissions, positioning CSA as both an economic and environmental solution. In terms of input use and substitution, CSA's influence varies by context. Findings from Nigeria indicate that zero or minimum tillage, residue retention, and organic manuring shifted resource allocation among smallholder rice farmers. Although labour and fertilizer demand remained price inelastic, mechanization services were used to substitute labour when costs increased, and organic inputs contributed to pesticide reduction. Agroforestry, interestingly, emerged as labor-neutral, contrasting with the labor-intensive nature of most CSA practices.

Balancing tests using **standardized mean differences (SMDs)** were conducted before and after matching. All covariates achieved balance with SMDs below 0.1 post-matching, indicating effective bias reduction and reliable estimation of CSA impact. Taken together, these findings collectively affirm the multidimensional benefits of CSA technologies. While yield and income improvements show strong incentives for adaptation, environmental and resource-use efficiencies further strengthen the rationale for their integration into smallholder systems.

3.3 Barriers to CSA Adaptation :

Table 1.5: Barriers to CSA Adaptation

Sl. No.	Barrier	Pn	Pl	Pm	Ph	PCI	Rank
1	Poor extension services	7	24	121	98	560	1

2	Low level of awareness of CSA practices	8	25	119	98	557	2
3	Unavailability and high cost of improved crop varieties	10	27	118	95	548	3
4	Lack of access to productive farm inputs	8	30	120	92	546	4
5	Lack of access or inadequate access to credit or government support	9	34	112	95	543	5
6	Limited user-friendliness of CSA practices	10	40	100	100	540	6
7	Taboos and values of community	22	18	109	101	539	7
8	Incidences of pests and diseases	11	32	116	91	537	8
9	Limited access to ready markets and market information	14	28	116	92	536	9
10	Lack of enforcement by traditional authorities	23	20	108	99	533	10
11	Challenge with bulky nature of manure	19	26	110	95	531	11
12	Insecure land tenure system	21	22	113	94	530	12
13	Lack of knowledge and education on CSA practices	13	31	120	86	529	13
14	Lack of or limited access to weather and climate information	14	35	110	91	528	14
15	Some practices are time-consuming	16	30	114	90	528	14
16	Limited information about CSA options	12	36	115	87	527	16
17	High illiteracy level of smallholder farmers	18	26	118	88	526	17
18	Limited access to agricultural technologies	17	33	110	90	523	18
19	Insufficient organic materials for composting	18	29	115	88	523	18
20	Practice not compatible with farmers' crop of interest	19	29	115	87	520	20
21	Shortage of timely labor / high cost of labor	15	38	110	87	519	21
22	Lack of or inadequate land	20	28	125	77	509	22

Source: Author's Calculation

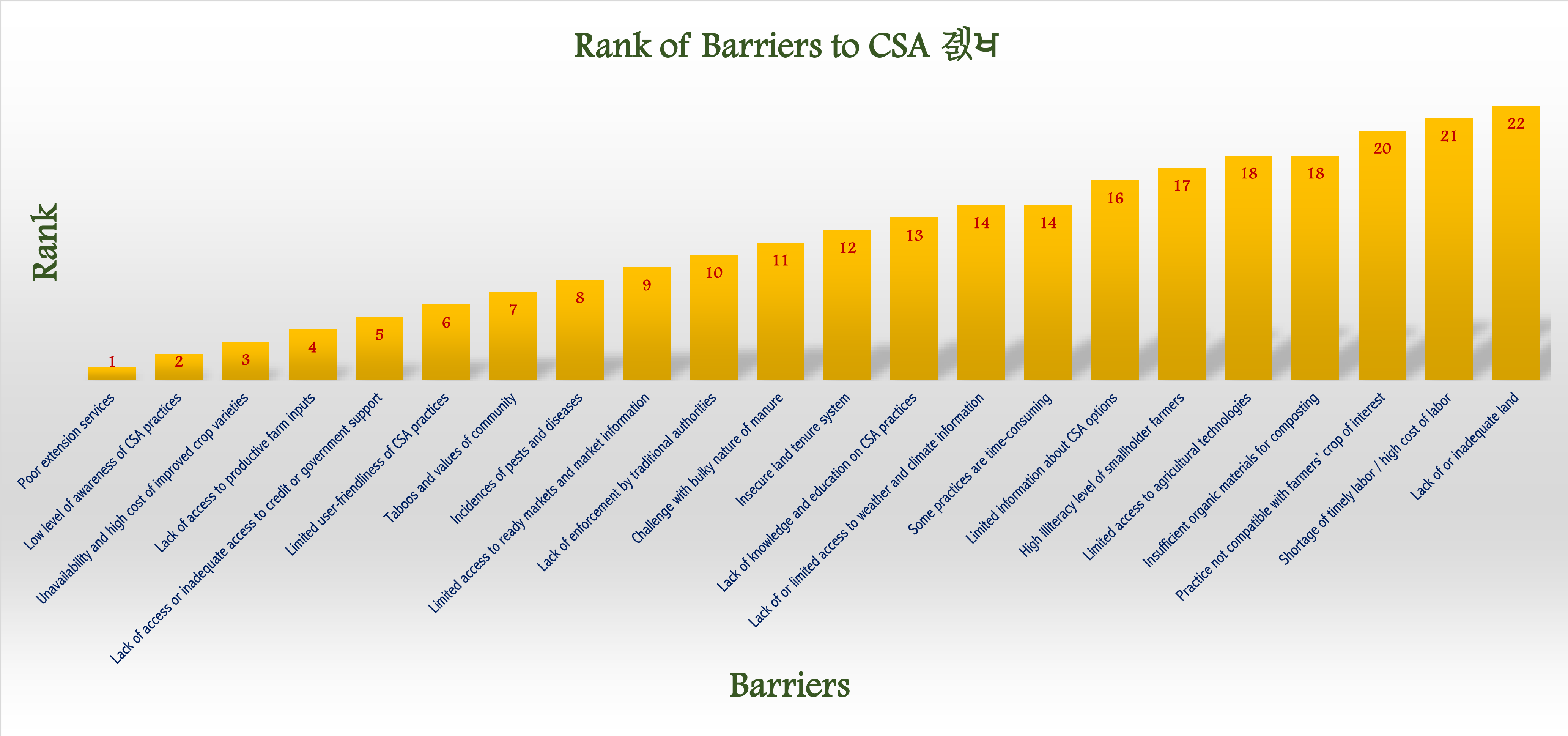

Fig 3: Rank of Barriers to CSA Adaptation.

The most pressing barriers to CSA adaptation in the region are poor extension services, low levels of awareness of CSA practices, the unavailability and high cost of improved crop varieties, lack of access to productive farm inputs, and limited access to credit or government support. Institutional and informational challenges dominate the constraint landscape in the study area. Extension systems in hilly and tribal regions such as Arunachal Pradesh face logistical, financial, and infrastructural challenges. Limited outreach and lack of technical support severely restrict farmers' access to updated agricultural knowledge. Effective CSA scaling depends heavily on strong extension frameworks that give continuous engagement, capacity-building, and technology transfer (Aryal et al., 2018). When these systems are underfunded or inadequately trained, adaptation rates for complex, knowledge-intensive practices like CSA decline. Awareness is foundational for behavioral change in agricultural systems. In this study, the low awareness levels among respondents significantly constrained CSA adaptation. Farmers are less likely to adopt CSA without a clear understanding of its short- and long-term benefits. Information asymmetry, exacerbated by remote geographies and literacy barriers, results in widespread disengagement from innovation pathways.

High-yielding, drought-tolerant, and pest-resistant seeds are key enablers of CSA. However, the results show that many farmers struggle with both the cost and availability of these improved varieties. Such constraints disproportionately affect marginalized farmers who cannot afford initial investments or lack access to certified seed networks. In tribal settings, where traditional seed systems dominate, bridging this gap is essential through public-private partnerships or community seed banks. CSA practices often rely on timely and adequate access to fertilizers, composting materials, mulching sheets, and water-saving technologies. The barrier identified in this study mirrors global patterns. Access to inputs is one of the strongest predictors of CSA adaptation success (Lipper et al., 2014). Inadequate input delivery systems and high input prices deter sustained engagement with CSA interventions. Access to finance is central to the adaptation of capital-intensive technologies. The results of this study show a clear financing gap that disrupts investment in CSA among smallholders (Khatri-Chhetri et al., 2017). The lack of inclusive financial infrastructure, particularly in tribal areas, remains a core constraint to sustainable transitions. Illiterate farmers struggle to interpret advisory messages, comprehend CSA technologies, or engage in extension-based capacity-building. Thus, illiteracy indirectly amplifies other barriers by limiting access to enabling resources.

Climate information services are integral to CSA decision-making (Mwongera et al., 201). The inability to access real-time weather forecasts, agro-advisories, or early warning systems reduces adaptive capacity. Many farmers identified this as a significant constraint. Without timely information, farmers cannot implement water-efficient irrigation or adjust planting schedules, resulting in lower resilience. The labor-intensive nature of many CSA practices, such as composting, mulching, and agroforestry, poses a significant burden on smallholder households. In tribal regions, where youth often migrate for wage labor, the aging agricultural workforce struggles to implement CSA. Tribal customs, land tenure insecurity, and community-level taboos were also reported. Practices like agroforestry or manure application are sometimes resisted due to deep-rooted traditional beliefs. Moreover, land tenure insecurity discourages long-term investment in CSA, particularly those practices with delayed benefits like carbon sequestration or soil regeneration. Wildlife intrusion, destruction by bushfires, and unregulated grazing also emerged as site-specific barriers. These factors exacerbate the risks associated with investing in CSA and lead to disadaptation in high-conflict zones. As shown by Bryan et al. (2012), ecosystem-based risks need tailored land-use governance and compensation strategies. To address these multifaceted constraints, a systems-level intervention is required. Investment in local agro-extension agents and mobile outreach technologies is necessary. Gender-sensitive training programs and tribal language materials can improve outreach. Development of CSA-specific microfinance instruments, crop insurance, and targeted subsidies can lower entry barriers. Climate information services should be integrated into mobile platforms, radio programs, and community-based advisories. Government and NGO partnerships should ensure the timely delivery of improved seeds and CSA kits, especially in remote blocks. Inclusive land reforms and engagement with tribal councils are essential to designing culturally sensitive CSA interventions.

The study gives meaningful insights into the adaptation of CSA in the tribal regions of Arunachal Pradesh. There are a few important limitations that should be acknowledged. First, the data is cross-sectional, meaning it captures a snapshot in time. This makes it difficult to determine cause-and-effect relationships—for example, whether CSA practices directly led to increased income or improved food security. Although Propensity Score Matching (PSM) helped reduce selection bias by comparing similar adopters and non-adopters, there may still be other unmeasured factors—like farmers' motivation levels, land quality, or access to informal knowledge networks—that influenced both their decision to adopt CSA and the outcomes they experienced. Another key limitation lies in the gender composition of the sample. With 84 percent of the respondents being male, the study may not fully reflect the views, roles, and challenges faced by women farmers. In tribal communities, women often play a central role in agricultural labor and household decision-making. Their underrepresentation limits the study's ability to explore gender-specific barriers or opportunities in the adaptation of climate-smart practices. Additionally, while CSA adaptation showed clear benefits in terms of yield, income, and household food security, its environmental impacts—such as reducing greenhouse gas emissions or improving carbon storage—appeared limited. This may be because many farmers only adopted a few CSA components rather than applying them comprehensively. It could also reflect the small landholdings common in the region, which reduce the scale at which environmental improvements can be observed. Moreover, the timeframe of the study may have been too short to capture the long-term ecological benefits of CSA.

The successful adaptation of CSA in regions like Arunachal Pradesh depends on carefully designed, locally relevant policies. Strengthening extension services—especially those that communicate in tribal languages and reach remote areas—is essential to improving awareness and technical support. Making CSA inputs like drought-resistant seeds and organic fertilizers more affordable and accessible can also help. In addition, introducing financial tools such as weather-based insurance and climate-linked credit can reduce risks for farmers and encourage long-term investment. Youth-focused training programs, better support for farmer groups, and greater inclusion of women in CSA initiatives can further strengthen adaptation. To be effective, these efforts must be aligned with Arunachal Pradesh's broader climate and agricultural policies. Only then can CSA truly become a practical and sustainable solution for tribal farmers facing the twin challenges of climate change and rural poverty?

4. Conclusion and Future Dimension

The adaptation of Climate-Smart Agriculture (CSA) among tribal farming communities in Arunachal Pradesh remains limited, with only 43 percent of surveyed households engaging in such practices. While there is growing awareness, the uptake of CSA is shaped by enabling factors such as educational attainment, youth presence in households, access to irrigation, and institutional engagement. These drivers support the implementation of practices like efficient water use, improved crop varieties, conservation agriculture, and soil fertility management. Tangible benefits include increased yields, higher farm incomes, improved food security, and better natural resource use. Despite these gains, widespread CSA adaptation is constrained by multiple challenges. Poorly equipped extension services, especially in remote areas, hinder timely knowledge dissemination. High input costs, lack of access to quality seeds and fertilizers, and limited awareness among elderly and less-educated farmers restrict implementation. Financial barriers are especially acute—many smallholders rely on informal credit sources unsuitable for long-term investment, while formal loans are often inaccessible or diverted. Additional constraints such as insecure land tenure, absence of crop insurance, limited market access, youth outmigration, and ecological fragility further dampen adaptation potential. Moreover, while CSA contributes to adaptation and productivity, its climate mitigation benefits—such as carbon sequestration—remain modest due to the low scale of adaptation.

Policymakers should begin by prioritizing youth-targeted CSA training programs to leverage the region's demographic potential and encourage innovation among younger farmers. Expanding and localizing extension services is equally important, with an emphasis on delivering content in tribal languages and utilizing ICT tools to improve outreach in remote areas. Ensuring affordable and timely access to CSA inputs—such as drought-resilient seeds, organic fertilizers, and climate-resilient technologies—will help remove key material barriers to adaptation. Financial instruments also play a crucial role; promoting climate-linked credit and crop insurance schemes can reduce the risks associated with new practices and support long-term investment in sustainable agriculture. Finally, CSA strategies should be fully integrated into broader state-level agricultural and climate policies to ensure that efforts toward improving productivity and resilience are aligned with environmental sustainability goals.

Community involvement must remain central. Strengthening farmer-producer organizations, self-help groups, and youth-led initiatives can enhance trust, facilitate innovation, and ensure that interventions reflect local needs and knowledge systems. Future research should include longitudinal studies to monitor the long-term impacts of CSA adaptation on productivity, resilience, and household well-being over a 3–5 year period. Comparative studies across tribal regions in Northeast India could help evaluate the scalability and contextual adaptability of CSA practices. Additionally, qualitative research into community-level perceptions of innovation, risk, and institutional trust would provide deeper insight into behavioral barriers to adaptation. Through inclusive, locally grounded strategies and sustained policy support, CSA can become a transformative pathway for making agriculture in Arunachal Pradesh more resilient, productive, and environmentally sustainable.

JEL Classification: Q01, Q16, Q18, Q54

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