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Enhancing Agricultural Productivity and Food Security Through Climate Smart Agriculture (CSA) Adoption: The Interplay of Social, Economic and Environmental in Tidal Swamp Farming

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Abstract

Food security is closely linked to agricultural productivity and the adoption of modern technologies. This study examines the socio-economic and environmental factors that drive the adoption of Climate-Smart Agriculture (CSA), enhance productivity, and improve food security in tidal swamp areas. The interrelationships between economic factors such as income and access to capital, and environmental factors like sustainable land management practices and water resource usage, all of which play a crucial role in the adoption of CSA technologies. The study was conducted with 180 farmers in Banyuasin Regency, specifically in Telang Makmur, Panca Mukti and Telang Jaya Villages, who provided data to assess how these factors influence food security outcomes. The findings indicate that both economic and environmental factors significantly affect the adoption of CSA technology, which subsequently leads to increased agricultural productivity and food security. Specifically, economic empowerment through higher income levels and enhanced access to capital enables farmers to invest in CSA technologies, while environmentally sustainable practices help mitigate climate risks and improve land and water management. The results underscore the importance of integrated approaches that address both economic and environmental dimensions to ensure long-term food security. This study provides valuable insights for policymakers, stressing the need for strategies that combine economic support, technological innovation, and environmental sustainability to enhance food security in regions like Muara Telang.

Keywords

Climate Smart Agriculture (CSA) technology, food security, productivity.

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Introduction

Food security is a crucial issue around the world, especially in developing countries (Pratama et al., 2024; Wakweya, 2023). In Indonesia, the agricultural sector plays a substantial role in the economy (Prihadyanti and Aziz, 2023; Yamin et al., 2024). However, this sector faces numerous challenges, particularly those induced by climate change. One of the areas most vulnerable to the impacts of climate change is the tidal swamp agricultural land, which often experiences fluctuations in salinity levels, flooding, and soil degradation (Wang et al., 2023). All of these factors directly affect agricultural yields and food security. Therefore, the implementation of environmentally -friendly agricultural technologies is essential to help farmers adapt to climate change and enhance their food security (Wakweya, 2023).

One of the strategies increasingly adopted to address climate change in the agricultural sector is CSA (Hussain et al., 2022). CSA encompasses a variety of agricultural practices aimed at strengthening resilience to climate change, reducing greenhouse gas emissions, and improving agricultural productivity in a sustainable manner (Zheng et al., 2024). Various CSA technologies, such as soil conservation, more efficient water management, and crop diversification, have been proven effective in enhancing agricultural productivity while reducing losses caused by the impacts of climate change (Yamin et al., 2025; Zizinga et al., 2022). Therefore, the implementation of CSA technologies in tidal swamp agricultural areas can serve as an effective solution to improve food security and the well-being of farmers (Kundu et al., 2024). (Tabe-Ojong et al., 2024) shows that the adoption of CSA practices can enhance agricultural yields, thereby contributing to food security. Furthermore, his research indicates that the adoption of CSA is not only advantageous for farmers who have already embraced it, but it could also offer benefits to those who have not yet adopted these practices, should they choose to do so.

However, socio-economic and environmental factors are critical determinants in this process. The socio-economic conditions of farmers have a significant impact on agricultural productivity (Gwambene et al., 2023). Education also plays a crucial role. Farmers with higher levels of education generally possess a better understanding of agricultural technologies and their associated benefits. They are more open to adopting new information and are better able to implement it in their daily practices. Moreover, a cohesive community structure can facilitate the exchange of information and experiences among farmers, which, in turn, fosters the adoption of new technologies (Thomas et al., 2023).

In addition, several economic factors significantly influence the adoption of new agricultural technologies (Smidt and Jokonya, 2022). A key determinant is farmers' income levels, as these directly affect their capacity to invest in innovative agricultural tools, improved seeds, and advanced farming practices (Kundu et al., 2024). Farmers with higher incomes are generally more able to allocate resources for technological adoption, thereby enhancing productivity. Furthermore, access to capital and credit plays a crucial role, as it enables farmers to invest in better agricultural technologies, thus improving their farming operations (Balana and Oyeyemi, 2022). In contrast, low-income farmers are often constrained by financial limitations, which prevent them from adopting more efficient practices and technologies (Khan et al., 2021). This economic disparity can perpetuate a cycle of poverty, making it difficult for these farmers to increase productivity or improve their livelihoods (Ulukan et al., 2022). Consequently, addressing income disparities and enhancing access to financial resources are essential for fostering the adoption of sustainable agricultural practices (Adisa et al., 2024).

The physical environment, including climatic conditions and natural resources, plays a crucial role in determining agricultural productivity (Habib-ur-Rahman et al., 2022). Climate change, characterized by rising temperatures and erratic rainfall patterns, can significantly reduce crop yields and increase the risk of crop failure (Bedeke, 2023). In response to these challenges, CSA technology have been developed to assist farmers in adapting to and mitigating the impacts of climate change. However, the effectiveness of CSA technology is highly dependent on local conditions and biodiversity (Kassaye et al., 2022). The availability of natural resources, such as water and fertile soil, also affects productivity (Javed et al., 2022). Farmers residing in areas with limited access to these essential resources often face substantial difficulties in improving their agricultural yields (Mondal and Palit, 2022). Therefore, a comprehensive understanding of the interplay between environmental factors and agricultural practices is essential for developing effective strategies aimed at enhancing productivity and resilience to climate change.

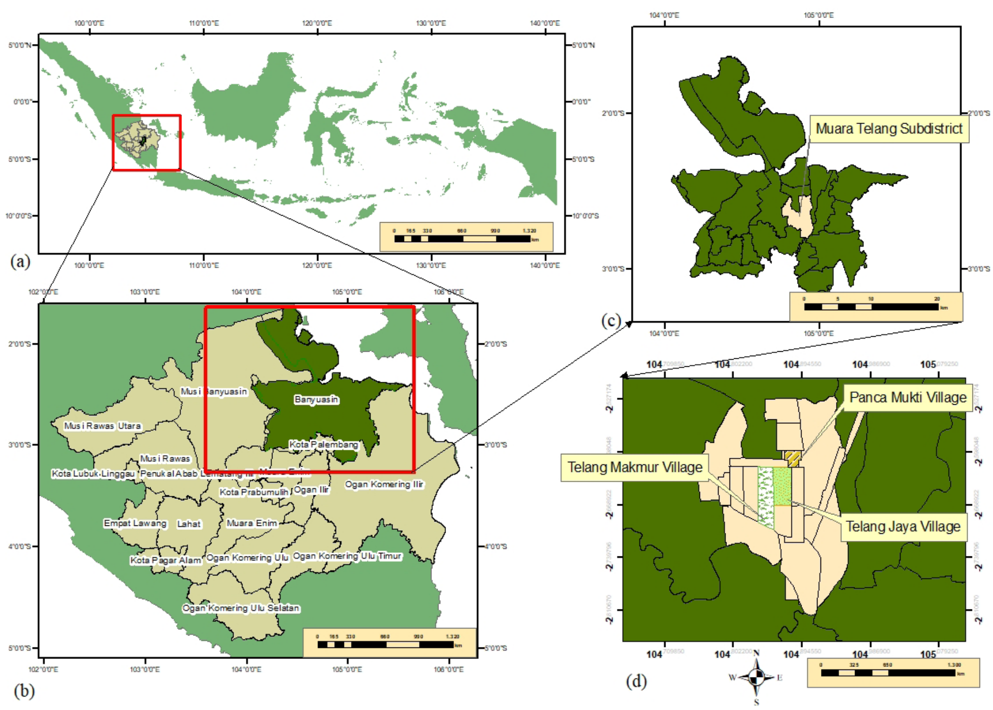
Food security is closely related to agricultural productivity and technology adoption. The adoption of CSA can make a significant contribution to food security by enhancing agricultural productivity and fostering greater stability in food resilience (Okolie et al., 2022). CSA practices have the potential to improve crop yields, mitigate losses caused by extreme weather events, and increase farmers' incomes. Consequently, this can lead to improved availability and accessibility of adequate and nutritious food for communities. Although extensive research has been conducted on the impact of CSA on agricultural productivity and food security, there has been limited focus on regions with tidal swamp typologies. These areas have unique characteristics, such as highwater salinity during the dry season and susceptibility to flooding, which influence the adoption of CSA. Therefore, this study aims to address the knowledge gap regarding how economic, social, and environmental factors play a role in the adoption of CSA in tidal swamp areas and their subsequent impact on productivity and food security. This research is of significant importance as it provides deeper insights into the factors influencing CSA adoption in tidal swamp regions. The study seeks to analyze the relationship between social, economic, environmental factors, as well as their effects on the adoption of CSA technologies, agricultural productivity and food security. The findings from this research are expected to form the foundation for the development of more effective policies aimed at promoting CSA adoption and enhancing food security in regions vulnerable to climate change.

Material and methods

The research location in Telang Jaya, Banyuasin Regency, which is known for its tidal swamp land influenced by the fluctuations of sea tides. With its unique land characteristics, this study aims to explore how economic, social, and environmental factors play a role in the implementation of CSA (Climate-Smart Agriculture) technology in the tidal swamp agricultural area and how this impacts agricultural productivity and food security in the region. The detailed location of the study can be seen in the following Figure 1.

This study employs a quantitative approach using Structural Equation Modeling (SEM) with the Smart PLS application to examine the influence of economic, social, and environmental factors on the adoption of Climate-Smart Agriculture (CSA), agricultural productivity, and food security in the tidal swamp agricultural system with a Planting Index (IP) of 300 (IP300). The SEM model was chosen for its ability to test the relationships between interrelated variables simultaneously and in a complex manner, both in terms of direct and indirect relationships (Garrido et al., 2022; Qonita et al., 2025). The population of this study consists of farmers engaged in tidal swamp agriculture in three villages in Banyuasin Regency, South Sumatra, with a sample size of 180 farmers, selected using random sampling based on different levels of CSA adoption. This sampling technique ensures a fair representation of various levels of CSA technology adoption among the farmers.

Data were collected in 2024 through a structured questionnaire that included statements related to social factors (education, health, social interactions, and institutional support), economic factors (business diversification, income, production, and access to capital), and environmental factors (sustainable farming practices, environmental management, soil quality, water availability, and the use of chemical inputs) as they relate to productivity, CSA technology adoption, and food security. A five-point Likert scale, ranging from "strongly disagree" to "strongly agree", was developed for this study to measure these items. For more detailed information, the variables and indicators of the study can be seen in the following Table 1.



Source: Authors

Figure 1: Site study sampling: a) Indonesia, b) South Sumatra, c) Muara Telang Subdistrict, d) Telang Makmur, Panca Mukti and Telang Jaya Village.

Variable	Indicator
Social (X1) (Al-Maskari et al., 2022)	X1.1. Education
	X1.2. Health
	X1.3. Social Interaction
	X1.4. Institutional
Economy (X2) (Arru et al., 2021; Rafique et al., 2022)	X2.1. Business Diversification
	X2.2. Income
	X2.3. Production
	X2.4. Access to Capital
Environment (X3) (Aulakh et al., 2022)	X3.1. Sustainable Agricultural Practices
	X3.2. Environmental Treatment
	X3.3. Soil Quality
	X3.4. Water Availability
	X3.5. Use of Production Inputs from Chemicals
Productivity (Y1) (Leul et al., 2023; Zheng et al., 2024)	Y1. Farming Experience
	Y2. Soil Quality Last 5 Years
	Y3. Land Size
Adoption of CSA Technology (Y2) (Hussain et al., 2022; Okolie et al., 2022)	Y2.1. Land Cultivation
	Y2.2. Planting Technology
	Y2.3. Organic Control
	Y2.4. Irrigation
	Y2.5. Organic Fertilizer
	Y2.6. Superior Variety
	Y2.7. Planting Calendar
	Y2.8. Harvesting Technology
Food Security (Y3) (Ghufran et al., 2024)	Y3.1. Food Stock
	Y3.2. Food Access
	Y3.3. Food Utilization
	Y3.4. Food Stability

Source: Authors

Table 1: Research variables and indicators.

Results and discussion

Characteristic of respondent

The diverse characteristics of respondents reflect both the potential and challenges in adopting Climate-Smart Agriculture (CSA) technologies among farmers. Gender, etnicity, education, farmers experience and land size are key factors that can influence farmers' decisions to transition to more sustainable agricultural practices. Detailing the characteristics of respondents is crucial for understanding the context of the findings. Here's a typical framework for presenting the characteristics of respondents in a study in Table 2.

Based on the data presented, this study illustrates he demographic and socio-economic characteristics of the respondents, the majority of whom are male farmers from Java. Most of the respondents have low levels of education, with an average education of only 8.84 years, which primarily corresponds to middle school and high school levels. Only a small percentage have higher education, such as a diploma or bachelor's degree. This suggests that the respondents' education levels are generally limited, which may affect their knowledge and skills in managing agricultural enterprises (Devkota et al., 2023). In terms of farming experience, the average respondent has approximately 21.81 years of experience, with most falling within the 31-40 years range. This indicates that they possess significant knowledge in running farming businesses, although a small number are relatively new to the field (0-10 years). Such extensive experience can be a valuable asset in facing challenges within the agricultural sector (Haque et al., 2023).

Variabel (n = 180)	Persentage (%)	Average	Standard Deviation (±)
Gender			
Male	100.00	-	-
Female	0.00		
Etnicity			
Local (Sumatra)	0.00	-	-
NonLocal (Jawa)	100.00		
Education (Year)			
0-6 Year	41.11		
7-9 Year	26.67	8.84	2.96 (18;3)
10-12 Year	27.78		
> 12 (Diploma, Bachelor)	4.44		
Farmers Experience (Year)			
0-10 Year	22.22		
11-20 Year	25.56		
21-30 Year	12.22	21.81	11.91 (50;1)
31-40 Year	32.22		
> 40 Year	7.78		
Land Size (Ha)			
0-1	35.00	2.19	1.71 (10;0.50)
> 1-2	36.11		
> 2	28.89		

Source: Authors

Table 2: Characteristic of respondent.

Regarding land size, the average respondent owns around 2.19 hectares of land. Most own land between 1 and 2 hectares, with 35% owning less than 1 hectare. This suggests that the majority of these farmers fall into the smallholder category, with limited access to land and capital. The diversity in land size also reflects varying potential in managing their agricultural production (Yu et al., 2022). This data portrays a population of experienced farmers, yet they face challenges in terms of education and land size. Approaches that support improving access to education and empowering small farmers would be highly beneficial in enhancing their well-being.

Analysis of type I and type II construction models

The analysis of the construction model in type I shows the results of the analysis of social (X1), economic (X2) and environmental (X3) influences on productivity (Y1), technology adoption (Y2) and food security (Y3). This model adopts the Climate-Smart Agriculture (CSA) theory, where each variable is measured using specific indicators. The results of the data analysis conducted are presented. It can be observed that the outer loading value represents the relationship between the latent variable and the manifest variable. The test criterion applied requires that the outer loading value must be greater than 0.7. After conducting the test, it was concluded that some of the outer loading values did not meet the required criterion. Specifically, the outer loading values that were less than 0.7 include farmers' perceptions of social interaction, income, water availability, planting technology, superior varieties and Harvesting Technology. For more detailed information, please refer to the following Table 3.

Indicator	Notation	Outer Loading Value
Social Interaction	X1.3	0.393 < 0.7
Income	X2.3	0.617 < 0.7
Water Availability	X3.4	-1.30 < 0.7
Planting Technology	Y2.2	0.351 < 0.7
Superior Variety	Y2.6	-0.109 < 0.7
Harvesting Technology	Y2.8	0.50 < 0.7

Source: Authors

Table 3: Outer loading value on indicators not greater than 0.7.

Several factors influencing the adoption of Climate-Smart Agriculture (CSA) technologies demonstrate weaker-than-expected relationships, even though these factors are anticipated to play crucial roles. Social interaction among farmers, while theoretically important for accelerating knowledge transfer and technology adoption, has not proven to be a strong driver in CSA implementation. This is likely due to low levels of trust among farmers or a lack of shared understanding regarding the benefits of CSA technologies. Economic factors, such as income, although positively correlated with CSA adoption, are not sufficiently significant to drive widespread adoption. Farmers with greater financial resources may have better access to CSA technologies (Bojago and Abrham, 2023), but economic factors alone are limited in facilitating broader technological change, given other barriers such as knowledge or access to the technologies themselves.

Water availability shows an unusual inverse relationship, where areas with limited water resources are more likely to adopt water-saving technologies. However, despite the potential for water scarcity to drive adoption, its impact on CSA adoption remains relatively insignificant. Planting technologies and the use of superior varieties, although highly promising in improving agricultural productivity, are not being applied optimally, likely due to inadequate access to the required technologies or a lack of understanding of their potential benefits. Harvesting technologies, while showing potential to reduce post-harvest losses and improve product quality, are still limited in application to a small subset of farmers with access to them. Overall, these findings indicate that more effective CSA adoption requires a more integrated approach that considers economic, social, and technological factors in greater depth, alongside policies that improve the distribution of information and technology access among farmers, particularly in areas most vulnerable to climate change (Tanti et al., 2022).

The next step involves reconstructing the model to achieve a proper fit, ensuring that there are no manifest variables or models that fail to meet the analyst's specified criteria. The results of this model reconstruction can be observed in the Figure 2.

Validity

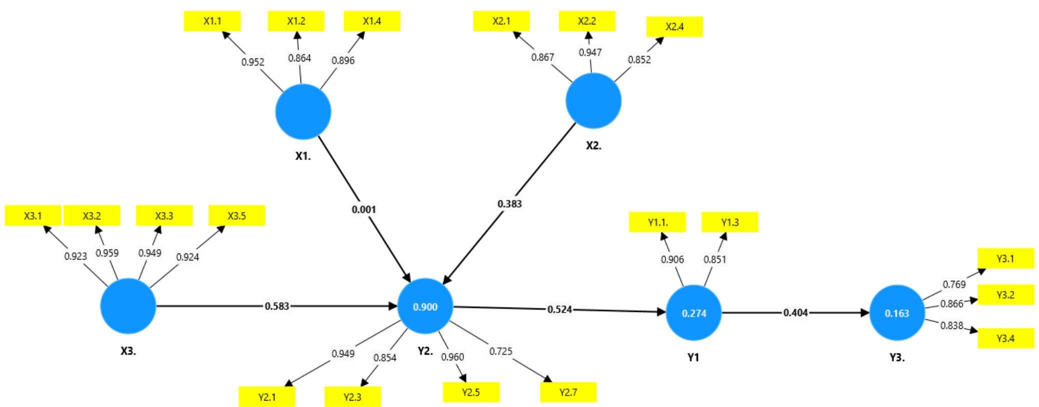
To measure the validity of convergence, it was done by looking at the Average variance extracted (AVE) value. Convergent validity is related to the principle that the indicators or manifest variables of a construct have a strong correlation. The AVE shows the proportion of variance that can be explained by these latent construct indicators, compared to the variance caused by measurement errors. If the AVE value is greater than 0.5, the items or indicators used in the SEM-PLS model meet the validity criteria or are declared valid. The following are the average variance extracted (AVE) values in the SEM-PLS model with the help of the Smart PLS 4.0 program on Table 4.

Variable	Average Variance Extracted (AVE)
X1	0.818
X2	0.792
X3	0.882
Y1	0.773
Y2	0.769
Y3	0.681

Source: Authors

Table 4: The result of Average Variance Extracted (AVE).

It can be seen that all the variables used in the SEMPLS model have an AVE value of > 0.5 so it can be concluded that the SEMPLS model



Source: Authors

Figure 2: Results of type II data analysis (after reconstruction).

built is valid. Apart from the value of loading factor and AVE to see the validity of convergence, SEM-PLS must also meet the criteria of discriminatory validity. The validity of discrimination from the outer model uses the cross loading value criterion. Indicators that have a cross loading value of > 0.7, these indicators meet the criteria for the validity of discrimination.

R-square test

Models in the SEM-PLS can be tested for fit or fit through Goodness of fit (GoF). The value of GoF is obtained through the root of the multiplication of the R-square mean (R2) and the communality mean. The R-square value of each construct is obtained through the bootstrapping procedure while the communality value is obtained through the blindfolding procedure. The following are the average values of R2 and communality respectively presented in Table 5.

Variable	R-square	R-square adjusted
Y1	0.274	0.270
Y2	0.900	0.898
Y3	0.163	0.159

Source: Authors

Table 5: R-square result.

Hypotesis testing

Hypothesis testing is conducted to examine the relationships between latent variables or constructs in the structural model of SEM-PLS. The bootstrapping method is used for hypothesis testing in this study, as it is more efficient than the jackknifing method, which does not account for confidence intervals. The significance level applied in this analysis is 5%, and the findings are based on the results from the SmartPLS 4 program. The following are the outcomes of the analysis, providing insights into how different factors influence the model variables.

The analysis on table above shows that social factors like education and health do not significantly influence the adoption of CSA technology, likely due to limited awareness and trust among farmers. However, economic factors such as income and financial capacity play a crucial role, as wealthier farmers can afford the costs of adopting CSA technologies. Environmental factors, particularly water availability, strongly drive the adoption of CSA, especially in areas facing water scarcity.

Moreover, increased productivity directly enhances food security, showing the importance of improving farming methods through CSA. Finally, CSA adoption boosts productivity, reinforcing the link between technology use and better food security (Wakweya, 2023). These findings highlight the need for targeted policies that address economic constraints and environmental challenges to promote CSA adoption.

SEM-PLS analysis also provides valuable insights into the indirect relationships between variables, commonly referred to as specific indirect effects (Hair, 2022). These indirect effects are essential for understanding the pathways through which one variable influence another, offering a deeper understanding of the causal relationships within the model. This information is instrumental in identifying the most relevant paths for further investigation and ensuring that the structural model is robust and accurate. The following table presents the results of the specific indirect effects analysis, conducted with the SmartPLS 4.0 program, which helps to highlight the key indirect relationships in the model and provides a clearer view of the variables' interdependencies as follows (Table 7).

The specific indirect effects analysis highlights the critical roles of environmental and economic factors in driving the adoption of Climate-Smart Agriculture (CSA) technologies, enhancing agricultural productivity, and improving food security. Environmental factors, especially related to water availability and climate resilience, are essential in encouraging CSA adoption, as these

Variable	Original sample (O)	Sample mean (M)	Standard deviation (stdev)	t-statistics (stdev)	P values
X1 -> Y2	0.001	-0.007	0.130	0.007	0.994
X2 -> Y2	0.383	0.375	0.146	2.630	0.009
X3 -> Y2	0.583	0.600	0.114	5.113	0.000
Y1 -> Y3	0.404	0.413	0.067	6.014	0.000
Y2 -> Y1	0.524	0.527	0.068	7.736	0.000

Source: Authors

Table 6: Path analysis (direct effects).

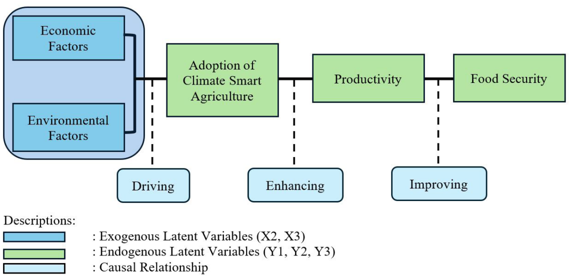
Variable	Original sample (O)	Sample mean (M)	Standard deviation (stdev)	t-statistics (stdev)	P values
X3 -> Y2 -> Y1	0.305	0.317	0.073	4.160	0.000
Y2 -> Y1 -> Y3	0.212	0.222	0.060	3.511	0.000
X2 -> Y2 -> Y1 -> Y3	0.081	0.083	0.040	2.030	0.042
X1 -> Y2 -> Y1 -> Y3	0.000	-0.002	0.030	0.007	0.995
X3 -> Y2 -> Y1 -> Y3	0.123	0.133	0.046	2.695	0.007
X1 -> Y2 -> Y1	0.001	-0.003	0.069	0.007	0.994
X2 -> Y2 -> Y1	0.201	0.198	0.081	2.476	0.013

Source: Authors

Table 7: Results of bootstrapping procedure on the SEM-PLS model (indirect effects).

technologies help mitigate the impacts of climate change. Economic factors, such as financial resources and access to markets, also play a significant role in enabling farmers to invest in CSA technologies, thereby boosting productivity and food security.

On the other hand, social factors like education and health, while important, have a less direct influence on CSA adoption. This may be due to limited access to information, low levels of trust among farmers, or the lack of social networks that support the adoption of technology (Dadzie et al., 2022). Additionally, farmers tend to prioritize economic factors, such as financial capability, and environmental challenges, such as water availability, when deciding to adopt CSA. Therefore, while social factors do play a role, their influence is limited unless supported by more fundamental economic and environmental factors. This suggests that although social capital can help raise awareness, it is not enough on its own to drive significant technological change without sufficient economic and environmental support. Therefore, a multi-dimensional approach is required: policies should integrate economic empowerment and environmental sustainability, alongside social initiatives (Falah et al., 2025), to effectively promote CSA adoption and improve food security. By addressing these key factors, CSA technologies can become more accessible and impactful for farmers, fostering long-term agricultural resilience.



Source: Authors

Figure 3: Critical roles of environmental and economic factors.

Economic variables (X2) → CSA technology adoption (Y2)

The challenges faced by farmers in tidal swamp lands, along with the Agricultural Performance Index (IP) 300, underscore the critical role of economic factors in enabling the adoption of Climate-Smart Agriculture (CSA) technologies. Economic variables such as business diversification, income, production capacity, and access to capital significantly influence farmers' ability to implement CSA practices. Diversification of livelihoods, such as engaging in horticultural activities (vegetables and fruits) before the rice planting season, helps mitigate economic risks by providing additional sources of income.

This, in turn, strengthens the financial resilience of farmers, enabling them to invest in CSA technologies, such as more efficient irrigation systems or salt-tolerant seeds. Higher income levels facilitate the purchase of essential agricultural equipment (Peng et al., 2022), such as water pumps and tractors, which are crucial for managing the environmental challenges of tidal swamp lands. Additionally, achieving higher production capacity reaching 8-9 tons per hectare per planting season allows farmers to reinvest their agricultural outputs into more efficient technologies. Finally, access to capital is vital, as it enables farmers to finance the necessary tools and machinery, ensuring their capacity to adapt to unpredictable land conditions (Tabe-Ojong et al., 2024). Therefore, strengthening these economic factors is crucial for enhancing farmers' resilience to climate change and promoting widespread adoption of CSA technologies, ensuring sustainable agricultural practices in this challenging environment.

Environmental variables (X3) → CSA technology adoption (Y2)

Sustainable agricultural practices, effective environmental management, and the use of environmentally friendly production inputs are highly relevant to SDGs Goal 13: Climate Action

(Rehman et al., 2022), which emphasizes the global need to address climate change. In the agricultural context, the adoption of CSA technologies plays a crucial role in mitigating the negative impacts of climate change, enhancing resilience to natural disasters, and reducing greenhouse gas emissions (Hussain et al., 2022). Practices such as crop rotation and the use of straw as mulch help to improve soil fertility, which is particularly significant in areas with tidal swamp lands. Additionally, the use of crop varieties that are resistant to salinity and drought is essential in such regions, where these environmental stresses are prevalent. Moreover, effective environmental management, such as the sustainable use of natural resources, can optimize the use of water and land (Li et al., 2022).

The implementation of efficient irrigation systems and prudent resource management helps farmers adapt to erratic rainfall patterns, a growing phenomenon caused by climate change. Maintaining soil quality is also critical, as it directly influences agricultural yields and ensures the sustainability of food production (Qiao et al., 2022), even in the face of climate impacts. By reducing the excessive use of chemicals and replacing them with organic inputs or environmentally friendly technologies, the agricultural sector can minimize its carbon footprint.

Overall, the adoption of CSA directly contributes to SDGs Goal 13: Climate Action by mitigating the effects of climate change, reducing carbon emissions, and improving food security through more sustainable and eco-friendly practices. The application of CSA by farmers in climate-vulnerable areas, such as tidal swamp regions, is pivotal in achieving global sustainability goals, given its contribution to building agricultural resilience against the ever-evolving challenges posed by climate change.

Adoption of CSA technology (Y2) → Productivity (Y1)

The adoption of CSA technologies plays a critical role in enhancing agricultural productivity, not only by promoting environmental sustainability but also by improving production efficiency and resilience to external challenges such as climate change. Key CSA practices, such as the use of superior seeds, integrated pest and disease management through techniques like mulch fences (Figure 4a), efficient irrigation systems for water management (Figure 4b, 4c), and the application of lime to improve soil quality (Figure 4d), are all pivotal in boosting agricultural productivity. In addition to these practices, the use of water pumps to ensure consistent water supply during the dry season stands out as a vital aspect of CSA. By integrating such technologies, CSA not only fosters environmental sustainability but also equips farmers with the necessary tools to enhance their crop yields, even in challenging environments such as tidal swamp areas (Chiang et al., 2024).

In the research area, which is characterized by tidal swamp land, the adoption of CSA has been shown to significantly boost rice productivity, with yields reaching up to 8-9 tons per hectare per planting season. This serves as a clear example that CSA technology can help farmers overcome environmental challenges, such as soil salinity and water scarcity, while achieving higher yields compared to traditional farming methods. This success underscores the potential of CSA to improve productivity even in regions that face severe climatic and environmental pressures (Mpala and Simatele, 2024). Overall, the adoption of CSA technologies highlights that sustainable and productive agriculture is not solely reliant on economic factors but also on the implementation of technologies that integrate environmental sustainability with increased output (Abegunde and Obi, 2022).

Source: Authors

Figure 4a: Efficient irrigation systems for water management.

Source: Authors

Figure 4b: Key CSA practices through techniques like mulch fences.

Source: Authors

Figure 4c: Efficient irrigation systems for water management.

Source: Authors

Figure 4d: The application of lime to improve soil quality.

Productivity (Y1) → Food security (Y3)

Increasing agricultural productivity directly contributes to food security by enhancing the availability and stability of food stocks (Mutungi et al., 2023). As farmers achieve higher yields, they are able to allocate a portion of their harvest typically 15-25% toward ensuring food security for their households. This reserved portion serves as a safeguard against periods of food scarcity, such as during seasonal fluctuations or unexpected agricultural setbacks. In regions where rice productivity reaches 8-9 tons per hectare per planting season, reserving 15-25% of the harvest translates to an approximate 1.2 to 2.25 tons (or 1,200 to 2,250 kg) of dry rice. This surplus is essential for maintaining a reliable food supply, especially during lean months, adverse climatic events, or when market conditions cause food prices to spike (Nyathi & Mlambo, 2024). It provides farmers with the ability to feed their families even when other food sources may be limited or unaffordable.

Furthermore, this practice reinforces the resilience of rural communities by reducing their reliance on external markets, which can be volatile and subject to disruptions (Zhou and Gu, 2025). By maintaining a strategic reserve of food, farmers are better equipped to withstand external shocks and avoid food insecurity. This approach also complements Climate-Smart Agriculture (CSA) practices, which further enhance productivity through the use of innovative technologies such as efficient irrigation systems, pest management techniques, and drought-resistant crop varieties. Ultimately, setting aside 15-25% of the harvest not only strengthens food security at the household level but also contributes to broader regional food stability (Aryal et al., 2019) .This aligns with the objectives of SDGs 2: Zero Hunger, promoting food availability, reducing vulnerability to climate-related risks, and fostering self-sufficiency. By supporting farmers' ability to produce and secure food for their families, this practice plays a pivotal role in achieving sustainable and long-term food security in the face of an increasingly uncertain climate (Chao, 2024).

Conclusion

This study provides compelling evidence that the adoption of Climate-Smart Agriculture (CSA) technologies is a factor in increasing agricultural productivity and food security, particularly in ecosystems highly vulnerable to climate change, such as tidal wetlands. Respondent characteristics indicate that although most farmers have farming experience, they have limited education and land size, which prevents them from adopting new methods without external support. Structural model analysis indicates that social factors, such as education and health, do not significantly impact CSA adoption due to limited awareness and weak trust networks. Instead, economic and environmental factors emerge as the strongest drivers. Economic means—in terms of diverse income sources, higher production levels, and the availability of funds—enable farmers to invest in CSA innovations such as efficient irrigation equipment, machinery, or high-yielding seeds. Natural factors, particularly water and soil management and climate-resilient technologies, play a key role in facilitating CSA adoption because these technologies have a direct impact on pressing local issues such as salinity, drought, and irregular rainfall.

The findings also show that CSA adoption has a direct and significant impact on agricultural productivity, as rice yields with CSA can reach 8–9 tons per hectare in tidal swamps, compared to traditional farming. This increased productivity translates into improved household and local food security, as farmers can store 15–25% of their harvest—1.2–2.25 tons of rice per growing season—as a safety buffer against market fluctuations, seasonal deficits, and climate-related risks. By extending beyond immediate food needs, this buffer boosts community resilience by reducing dependence on external food markets and creating a secure food buffer.

It is important to emphasize that, in this study, CSA adoption is not only an agro-innovation but also a strategic pathway towards achieving broader sustainability goals. By effectively utilizing resources, reducing greenhouse gas emissions, and increasing resilience to climate shocks, CSA directly contributes to SDG 2 (Zero Hunger) and SDG 13 (Climate Action). This highlights the need for a multifaceted policy response that integrates economic empowerment, environmental sustainability, and social protection systems. Improving access to capital, enhancing knowledge diffusion, promoting farmer networks, and ensuring equitable access to CSA technology are key steps to facilitate adoption. This way, CSA can be scaled up into a viable solution for resilient agriculture, vulnerability reduction, and sustainable agricultural resilience in the most climate-vulnerable regions.

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