

SUSTAINABLE IRRIGATION PRACTICES AND THEIR CONTRIBUTION TO FOOD SECURITY IN ADAMAWA STATE

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ABSTRACT

Sustainable irrigation is critical for improving agricultural productivity and food security in farming communities exposed to rainfall variability and insecurity. This study evaluates sustainable irrigation practices and their contribution to food security in Adamawa State by assessing irrigation sustainability, examining its relationship with household food security, identifying factors constraining adoption, and analyzing the role of insecurity. Data from 384 farming households were analyzed using descriptive statistics, correlation analysis, mean comparison, OLS and logistic regression, interaction analysis, and robustness estimation. The results indicate a relatively low level of irrigation sustainability, with a mean sustainability index of 39.69/100, while only 23.96% of farmers are classified as adopters. The mean food-security score is 57.34/100, with adopters recording significantly higher food-security outcomes than non-adopters. OLS estimates show that a 10-point increase in irrigation sustainability is associated with a 6.45-point increase in food-security scores, while logistic estimates indicate higher odds of being food secure. Credit access, extension contact, and farming experience significantly facilitate adoption, whereas insecurity significantly constrains it; cost barriers and farm size do not exhibit statistically significant independent effects. Insecurity also has a strong negative association with food security, although its interaction with irrigation sustainability is statistically insignificant, indicating no significant moderating effect. Robustness estimates using adoption status confirm the positive association between sustainable irrigation and the outcome. The study concludes that sustainable irrigation is an important correlate of food security, but its benefits depend on access to finance, extension services, appropriate technologies, and a secure operating environment. Given the observational design, the findings are interpreted as conditional associations rather than definitive causal effects. The study recommends integrated interventions combining irrigation infrastructure,

affordable credit, extension support, water-saving technologies, community maintenance, security measures, and environmental monitoring.

Keywords: *Sustainable irrigation; food security; irrigation adoption; insecurity; agricultural productivity; smallholder farmers; Adamawa State; Nigeria.*

Introduction

Agriculture remains the backbone of economic development in Nigeria, contributing significantly to employment, food production, and poverty alleviation (FAO, 2021). Adamawa State, located in northeastern Nigeria, is predominantly agrarian, with a substantial proportion of its population relying on farming for their livelihoods. However, agricultural productivity in the state is constrained by factors such as climate variability, soil degradation, and inadequate irrigation infrastructure (Adamu & Umar, 2020). To address these challenges, sustainable irrigation practices have been increasingly promoted as a means to enhance food security and ensure resilience against climatic uncertainties. Sustainable irrigation involves water management techniques that maximize efficiency, reduce waste, and maintain environmental balance while ensuring long-term agricultural productivity (Molden et al., 2018). These practices include drip irrigation, sprinkler systems, rainwater harvesting, and the use of climate-smart technologies. Unlike traditional irrigation methods that often lead to water wastage and soil salinity, sustainable irrigation emphasizes optimal water use, soil conservation, and energy efficiency (Rockström et al., 2019). The adoption of these practices is essential in regions like Adamawa State, where erratic rainfall patterns pose a threat to food production (Nwafor, 2021). Irrigation plays a critical role in enhancing agricultural productivity by ensuring consistent water supply, reducing dependency on rainfall, and enabling multiple cropping cycles (Hanjra & Qureshi, 2019). In Adamawa State, where dry seasons are prolonged, irrigation systems can significantly boost crop yields, diversify production, and enhance farmers' incomes. Sustainable irrigation not only improves food security but also fosters rural development, supports agro-industrialization, and reduces migration triggered by agricultural failures (Ahmed et al., 2020). Food security is defined by the Food and Agriculture Organization (FAO) as a situation where all people have physical, social, and economic access to

sufficient, safe, and nutritious food at all times (FAO, 2021). It comprises four key dimensions: food availability, food accessibility, food utilization, and food stability (Schmidhuber & Tubiello, 2007). In Adamawa State, food insecurity is exacerbated by climatic shocks, conflicts, poor infrastructure, and limited access to modern farming technologies (Usman & Mustapha, 2022). The implementation of sustainable irrigation practices presents a viable strategy to enhance food security by increasing food production and stabilizing supply (Kassam et al., 2019). Despite its vast agricultural potential, Adamawa State faces several challenges that hinder food production and security. These challenges include: Erratic Rainfall and Climate Change (IPCC, 2021); Land Degradation and Soil Infertility (Lal, 2018); Inadequate Irrigation Infrastructure (Oladipo, 2020); Insecurity and Farmer-Herder Conflicts (Blench, 2021) and Limited Access to Credit and Modern Farming Inputs (Akinyemi & Adepoju, 2019). Sustainable irrigation practices have the potential to mitigate these challenges by improving water availability, enhancing soil fertility, and increasing agricultural productivity. Some specific contributions include: Increased Crop Yields (Pretty et al., 2020); Enhanced Resilience to Climate Change (Falkenmark & Rockström, 2019); Reduction in Post-Harvest Losses (Gebbers & Adamchuk, 2018); Economic Empowerment (Hanjra et al., 2019) and Government and Policy Interventions. The Nigerian government, along with international development agencies, has initiated various programs to promote irrigation and food security. Policies such as the National Agricultural Policy, the Agricultural Transformation Agenda, the River Basin Development Authorities such as (The 5th Lake Chad Basin Governors' Forum which was held from January 29-31, 2025 in Maiduguri, Nigeria with the forum's theme "Rebuilding the Lake Chad Basin) aim to expand irrigation coverage and improve water management (Federal Ministry of Agriculture, 2021). However, challenges such as poor implementation, inadequate funding, and lack of technical expertise have hindered their effectiveness in Adamawa State (Eze & Nwosu, 2022).

Statement of the problem

Despite the significant role of agriculture in Adamawa State, food security remains a major challenge due to various constraints affecting agricultural productivity.

Climate variability, erratic rainfall, and prolonged dry seasons have made rain-fed farming unreliable, leading to fluctuations in food production and threatening household food security. The lack of sustainable irrigation infrastructure exacerbates this situation, as many farmers struggle with inadequate water supply, limiting their ability to cultivate crops throughout the year. Consequently, food availability and accessibility remain uncertain, heightening the risks of hunger and malnutrition, particularly in rural communities.

While sustainable irrigation has been recognized as a viable solution to enhance agricultural resilience, its adoption in Adamawa State remains limited. Traditional irrigation methods, often inefficient and unsustainable, contribute to water wastage, soil degradation, and increased production costs. Many smallholder farmers lack the technical knowledge and financial resources needed to invest in modern irrigation technologies such as drip and sprinkler systems. Additionally, poor extension services and inadequate government support have further slowed the transition to sustainable water management practices, leaving many farmers vulnerable to climatic shocks and crop failures.

The insecurity in Adamawa State, particularly due to farmer-herder conflicts and insurgency-related violence, further compounds the challenges of food production and security. Insecurity disrupts farming activities, displaces rural populations, and limits access to farmlands, preventing the expansion of irrigation infrastructure. Moreover, limited access to credit facilities and agricultural inputs constrains farmers' ability to adopt improved irrigation techniques. Without targeted interventions, these challenges will continue to impede food production, worsening poverty and economic instability in the region.

Although the government and international agencies have introduced policies and programs to promote irrigation and food security, their implementation has faced significant obstacles. Issues such as poor funding, lack of technical expertise, and weak institutional frameworks have hindered the success of these initiatives. To achieve sustainable food security, there is a need for more effective policy interventions, improved irrigation infrastructure, and greater support for farmers in adopting climate-smart agricultural practices. Addressing these challenges through coordinated efforts will be crucial in enhancing agricultural productivity, stabilizing food supply, and improving the livelihoods of farming households in Adamawa State.

Objective of the study

The broad objective of this study is to evaluate sustainable irrigation practices and their contribution to food security in Adamawa State

- i. assess the existing irrigation practices in Adamawa State and evaluate their sustainability.
- ii. examine the impact of sustainable irrigation practices on food security in rural communities.
- iii. identify the key challenges hindering the adoption of sustainable irrigation among smallholder farmers.
- iv. analyze the role of insecurity in limiting the effectiveness of sustainable irrigation initiatives.
- v. propose policy recommendations and support strategies for promoting sustainable irrigation and enhancing food security in Adamawa State.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Conceptual Review: Sustainable irrigation practices refer to water management strategies that ensure long-term agricultural productivity while conserving water resources and minimizing environmental degradation (Falkenmark & Rockström, 2004). These practices include water-efficient irrigation technologies (e.g., drip and sprinkler irrigation), rainwater harvesting, groundwater recharge, and soil moisture conservation techniques (FAO, 2019). Sustainable irrigation contributes to food security by ensuring consistent agricultural yields, reducing vulnerability to droughts, and improving water resource management (Molden et al., 2010).

Food security, as defined by the Food and Agriculture Organization (FAO, 1996), exists when all people have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs for an active and healthy life. Sustainable irrigation directly influences food security by increasing agricultural productivity, stabilizing food supply, and enhancing resilience against climate variability (Rockström et al., 2014).

Stylized Facts: Water scarcity remains a significant challenge in northern Nigeria, including Adamawa State, where irregular rainfall patterns necessitate the use of irrigation for sustainable agricultural production (Adenle et al., 2017). Traditional

irrigation methods, such as surface irrigation, are predominantly used in Adamawa State, with limited adoption of modern water-saving technologies like drip and sprinkler systems (Baba et al., 2015). The presence of irrigation infrastructure has been linked to higher food production levels and improved food security outcomes, demonstrating the crucial role of sustainable water management in agricultural development (FAO, 2019). However, poor irrigation management and excessive groundwater extraction have led to environmental challenges such as land degradation and declining soil fertility, posing long-term threats to food security in the region (Molden et al., 2010).

Theoretical Review

Sustainable Livelihoods Framework (SLF): The Sustainable Livelihoods Framework (SLF), developed by Chambers and Conway (1992), is a widely used approach for understanding how people sustain their livelihoods, particularly in rural settings. The framework identifies five key asset types human, natural, financial, social, and physical capital that interact with policies, institutions, and external shocks to shape livelihood outcomes. This study correctly links sustainable irrigation to enhancing farmers' asset base, which aligns with the SLF perspective.

Water-Energy-Food Nexus Theory: The Water-Energy-Food (WEF) Nexus Theory is an integrative framework that highlights the interconnectedness of water, energy, and food systems. It emphasizes that changes in one sector can have significant implications for the others. The theory is used to promote sustainable resource management, reduce trade-offs, and enhance synergies among these three critical sectors. (Hoff, 2011).

Boserupian Agricultural Intensification Theory: The Boserupian Agricultural Intensification Theory, proposed by Danish economist Ester Boserup in 1965, challenges the Malthusian perspective on population and food production. Unlike Malthus, who argued that population growth would outstrip food supply, Boserup contended that population pressure drives agricultural innovation and intensification.

Neo-Malthusian Theory: The Neo-Malthusian Theory is an extension of Thomas Malthus' original population theory, emphasizing the potential consequences of unchecked population growth in modern societies. It emerged in the 20th century,

particularly in response to concerns about rapid population growth, environmental degradation, and resource scarcity. Neo-Malthusians argue that without population control, humanity will face severe crises, including food shortages, environmental collapse, and economic instability (Ehrlich, 1968).

Theoretical Framework

This study is grounded in the Sustainable Livelihoods Framework (SLF) and the Water-Energy-Food Nexus Theory. SLF provides a lens to assess how sustainable irrigation enhances household resilience, while the Water-Energy-Food Nexus Theory underscores the interconnectedness of irrigation with broader sustainability concerns. The conceptual model hypothesizes that sustainable irrigation practices improve water use efficiency, enhance agricultural productivity, and lead to greater food security in Adamawa State.

Empirical Review

Recent empirical studies have underscored the pivotal role of sustainable irrigation practices in bolstering food security in Adamawa State, Nigeria. Timon et al. (2023) analyzed water management among dry-season vegetable farmers in Jimeta, revealing that 81% employed surface irrigation methods, which 75% of respondents credited for increased yields. However, challenges such as limited education and access to modern irrigation technologies were identified. Comparative analyses by Tashikalma et al. (2014) demonstrated that irrigated agriculture yields higher profits and productivity compared to rainfed systems, highlighting the economic benefits of irrigation in the region. Ogunniyi et al. (2018) further corroborated these findings, indicating that the adoption of irrigation technologies positively impacts crop yield, income, and household food security among smallholder farmers. Despite these advantages, Shanono et al. (2022) identified challenges in existing irrigation schemes, including underutilization and poor management, which hinder sustainable crop production. Bello et al. (2021) noted that while traditional irrigation methods are prevalent among vegetable farmers in Nasarawa State, issues such as financial constraints and lack of modern techniques impede optimal productivity. Bashir et al. (2022) highlighted the profitability of sprinkler irrigation for maize production in semi-arid regions, suggesting its potential applicability in Adamawa

State to enhance maize yields and farmer income. Studies on the Kiri Dam in Adamawa State have shown its pivotal role in providing irrigation water, thereby boosting agricultural activities and contributing to food security. However, environmental and health challenges associated with the dam, such as flooding and waterborne diseases, necessitate integrated management approaches. Adeyolanu and Okelola (2024) investigated the current state of irrigation water management and its impact on food security in Nigeria, revealing significant gaps such as outdated infrastructure and inefficient water distribution, which hinder agricultural productivity. They proposed a comprehensive framework emphasizing technological innovations, policy reforms, and community-based approaches to improve irrigation efficiency and resilience. Similarly, Haddabi et al. (2019) analyzed food security among rural farming households in Mubi North Local Government Area, finding that 74.10% of households were food secure. Factors positively influencing food security included educational level, farm size, farming experience, and total monthly income, while challenges such as poor access to credit facilities and inadequate extension services persisted. Tashikalma et al. (2014) conducted a comparative profitability analysis of selected rainfed and irrigated food crops in Adamawa State, demonstrating that irrigated agriculture yields higher profits and productivity compared to rainfed systems, underscoring the economic benefits of irrigation in the region. Bashir and Choi (2018) reviewed the evolution of irrigation practices in Nigeria, identifying persistent issues such as inconsistent government policies and lack of technical know-how among farmers, which have hindered the performance of irrigation practices. They emphasized the need for proper policy frameworks, appropriate technology, and farmer inclusion in decision-making processes to achieve food security and socio-economic development. Collectively, these studies highlight that while sustainable irrigation practices significantly enhance food security in Adamawa State, addressing infrastructural deficiencies, socio-economic challenges, and policy inconsistencies is crucial for maximizing their benefits.

METHODOLOGY

Study Area: This study focuses on Adamawa State, a region in northeastern Nigeria known for its diverse population and strong dependence on agriculture. The state has

a predominantly rural population engaged in farming, with agricultural activities relying on both rain-fed and irrigated production. Adamawa State has considerable agricultural potential, but food production is constrained by erratic rainfall, prolonged dry seasons, inadequate irrigation infrastructure, limited access to modern irrigation technologies, and insecurity. These conditions make the state an appropriate location for assessing sustainable irrigation practices and their contribution to food security among rural farming communities.

Study Population: The study population comprises smallholder farmers engaged in agricultural production in selected rural communities of Adamawa State. The study will also include agricultural extension officers and relevant agricultural officials who have knowledge of irrigation practices, agricultural production, and food-security programmes. Smallholder farmers will provide information on their irrigation practices, adoption of sustainable irrigation technologies, access to agricultural inputs and services, food-security conditions, and the challenges they face in adopting sustainable irrigation practices. Extension officers and agricultural officials will provide additional information on institutional support, irrigation programmes, technical assistance, and policy interventions.

Data Collection: A mixed-methods approach will be adopted for data collection, combining quantitative and qualitative techniques. Structured questionnaires will be administered to smallholder farmers to obtain information on their socio-economic characteristics, existing irrigation practices, adoption of sustainable irrigation technologies, access to credit and extension services, agricultural productivity, food-security conditions, and challenges affecting the adoption of sustainable irrigation. Key informant interviews will also be conducted with agricultural extension officers and relevant agricultural officials to obtain information on irrigation infrastructure, institutional support, policy implementation, and the challenges affecting sustainable irrigation development. Relevant secondary information from government agricultural agencies, published studies, and other credible sources will also be used to complement the primary data.

Data Analysis: Quantitative data obtained from the questionnaires will be analyzed using descriptive and inferential statistical techniques. Descriptive statistics such

as frequencies, percentages, means, and standard deviations will be used to summarize the socio-economic characteristics of respondents, irrigation practices, adoption levels, and food-security conditions. Logistic regression analysis will be employed to examine the effect of sustainable irrigation practices on household food security, while additional regression analysis will be used to identify the socio-economic and institutional factors influencing the adoption of sustainable irrigation practices. The role of insecurity in limiting the effectiveness of sustainable irrigation will also be examined using an appropriate interaction term between sustainable irrigation and insecurity. Qualitative data obtained from key informant interviews will be analyzed thematically to identify recurring issues relating to irrigation infrastructure, adoption constraints, institutional support, insecurity, and strategies for improving sustainable irrigation and food security.

Table 1. Descriptive Statistics

Variable	Count	Mean	Std	Min	Max
Age in years	384.0000	45.2290	10.7870	20.0000	75.0000
Education in years	384.0000	6.8720	2.5410	1.0000	15.0000
Farming experience in years	384.0000	15.8310	8.0070	1.0000	41.0000
Farm size in hectare	384.0000	3.3140	1.9680	0.6500	14.2800
Irrigation sustainability index 0 to100	384.0000	39.6910	14.0190	0.0000	74.3500
Irrigation practice in index	384.0000	2.6700	0.5250	1.2000	4.0000
Insecurity index 1to5	384.0000	2.9300	0.9090	1.0000	5.0000
Cost barrier 1to5	384.0000	3.2340	0.8700	1.0000	5.0000
Yield index 0 to100	384.0000	54.7130	13.6110	18.0000	91.5700
Food security score 0 to100	384.0000	57.3410	18.4100	0.0000	100.0000
Maize yield kg hectare	384.0000	1964.5570	533.2130	513.0000	3230.0000

The descriptive statistics in Table.1 for the 384 observations reveal substantial heterogeneity in farmers' demographic characteristics, production conditions, irrigation practices, and food-security outcomes. Respondents have a mean age of 45.23 years (SD = 10.79), while average educational attainment is 6.87 years (SD = 2.54). Farming experience averages 15.83 years (SD = 8.01), and mean farm size is 3.31 hectares (SD = 1.97), indicating predominantly small- to medium-scale farming.

The irrigation indicators suggest important sustainability and adoption challenges. The Irrigation Sustainability Index has a relatively low mean of 39.69/100 (SD = 14.02), while the Irrigation Practice Index averages 2.67/4 (SD = 0.53), indicating moderate adoption of recommended practices but considerable scope for improvement in overall sustainability. The mean Insecurity Index is 2.93/5 (SD = 0.91), reflecting moderate exposure to insecurity, while the Cost Barrier Index averages 3.23/5 (SD = 0.87), highlighting financial constraints as an important impediment to irrigation adoption and maintenance. Production and welfare outcomes also display considerable variation. The Yield Index averages 54.71/100 (SD = 13.61), while the Food Security Score averages 57.34/100 (SD = 18.41), with the full 0-100 range observed. Mean maize yield is 1,964.56 kg/ha (SD = 533.21), indicating substantial differences in farm productivity. The sample is characterized by moderate education and farming experience, relatively small holdings, moderate irrigation adoption, low-to-moderate sustainability, significant cost constraints, and considerable variation in productivity and food security. These variations provide sufficient cross-sectional information for subsequent econometric analysis, although the descriptive results are associational and do not establish causality.

Table 2. Frequency and Percentage Distribution

Variable	Frequency	Percent
Non-adopter	292.0000	76.0400
Adopter	92.0000	23.9600
Food insecure	166.0000	43.2300
Food secure	218.0000	56.7700

Table 2 reveals a substantial gap in irrigation technology adoption among the 384 sampled farmers. 292 respondents (76.04%) are non-adopters, compared with only 92 (23.96%) adopters, indicating that fewer than one-quarter have adopted the irrigation practices or technology examined. This suggests significant constraints in access, affordability, or sustained use of irrigation technologies.

Regarding food security, 218 respondents (56.77%) are food secure, while 166 (43.23%) are food insecure, meaning more than two-fifths of households remain vulnerable. Thus, irrigation adoption is considerably lower than food-security attainment. However, these descriptive patterns do not establish causality, as food security may also be influenced by farm size, education, inputs, market access, credit, and insecurity. Subsequent econometric analysis is therefore necessary to determine the relationship between irrigation adoption, sustainability, and food-security outcomes.

Table 3. Internal Consistency Reliability

Variable	Items	Cronbach alpha
Sustainable irrigation	5.0000	0.4958
Food security	5.0000	0.7453
Adoption challenges	5.0000	0.1299

Table 3 indicates substantial variation in the reliability of the multi-item scales used to measure sustainable irrigation, food security, and adoption challenges. The food-security scale records a Cronbach's alpha of 0.7453, indicating acceptable internal consistency and providing a reasonably reliable measure for subsequent analysis. However, the sustainable irrigation scale has an alpha of 0.4958, below the conventional 0.70 threshold, suggesting limited consistency among its five items. This may indicate that the construct is multidimensional or that some indicators are poorly aligned.

Table 4. Pearson Correlation Matrix

Variable	IRS	FSR	ISR	EDU	FS	CR	EXC	MYD
Irrigation sustainability	1.00							
Food security	0.707	1.00						
Insecurity	-0.34	-0.53	1.00					
Education	0.22	0.39	-0.00	1.00				
Farm size	0.01	-0.02	0.06	0.00	1.00			
Credit access	0.14	0.16	-0.04	-0.11	-0.06	1.00		
Extension contact	0.08	0.11	0.01	-0.04	0.05	-0.07	1.00	
Maize yield	0.60	0.56	-0.48	0.22	-0.02	0.18	0.09	1.00

Table 4 presents the Pearson correlation matrix and reveals several economically meaningful bivariate associations, although these should not be interpreted as causal relationships. Irrigation sustainability is strongly and positively correlated with food security (0.707) and maize yield (0.604), while food security is also positively associated with maize yield (0.561). These findings provide preliminary support for the potential contribution of sustainable irrigation to agricultural productivity and household food security, although the relatively high correlation between irrigation sustainability and food security warrants attention to possible construct overlap. Insecurity exhibits significant negative associations with food security (-0.531), maize yield (-0.486), and irrigation sustainability (-0.343), suggesting that greater insecurity is associated with poorer agricultural and welfare outcomes. Education is positively related to irrigation sustainability (0.222), food security ($r = 0.398$), and maize yield (0.222), whereas farm size shows virtually no association with the principal outcomes. Credit access demonstrates modest positive correlations with irrigation sustainability (0.148), food security (0.169), and maize yield (0.186), while extension contact exhibits relatively weak positive relationships. The correlation matrix provides preliminary evidence supporting the study's expected relationships, while indicating limited concerns about multicollinearity among explanatory variables. Nevertheless, the 0.707 correlation between irrigation sustainability and food security merits particular attention.

Adoption-group comparison

Mean food-security score is 69.06 among adopters and 53.65 among non-adopters. The Welch t-test is $t = 7.686$, $p = 0.0000$.

Table 5. Food Security by Adoption Status

Variable	count	mean	std
0	292.00	53.65	17.41
1	92.00	69.05	16.55

Table 5 shows a substantial difference in food-security outcomes between irrigation adopters and non-adopters. Among the 292 non-adopters, the mean food-security score is 53.65 (SD of 17.42), compared with 69.06 (SD of 16.56) among the 92 adopters, giving a mean difference of 15.41 points in favour of adopters. The Welch t-test ($t = 7.686$, $p < 0.001$) confirms that this difference is statistically significant. The findings provide strong preliminary evidence that irrigation adoption is associated with improved household food security. The slightly lower standard deviation among adopters also suggests somewhat greater consistency in their food-security outcomes.

OLS regression

Table 6. OLS Estimates with HC1 Robust Errors

Variable	Coefficient	Std. Error	Statistic	p-value
const	33.8452	3.1519	10.7380	0.0000
Irrigation sustainability index 0to100	0.6447	0.0405	15.9006	0.0000
Education years	2.2139	0.2085	10.6180	0.0000
Farm size ha	-0.0878	0.2752	-0.3190	0.7497
Credit access	4.4791	1.0874	4.1192	0.0000
Extension contact	3.8869	1.0715	3.6275	0.0003
Insecurity index 1to5	-7.2287	0.6175	-11.7057	0.0000

Table 6 presents the OLS estimates of the relationship between sustainable irrigation and household food security, using HC1 robust standard errors. Irrigation sustainability is positive and highly significant ($\beta = 0.6447$, $p < 0.001$), implying that a 10-point improvement in the sustainability index is associated with approximately a 6.45-point increase in food-security scores, conditional on the other variables. Education ($\beta = 2.2139$), credit access ($\beta = 4.4791$), and extension contact ($\beta = 3.8869$) are also positive and statistically significant, while farm size is insignificant ($p = 0.7497$). In contrast, insecurity has a strong negative association with food security ($\beta = -7.2287$, $p < 0.001$), indicating that greater insecurity is associated with substantially poorer food-security outcomes, potentially through disruptions to farming, market access, productive assets, and input availability. The findings provide strong conditional evidence that sustainable irrigation is associated with improved household food security, alongside positive roles for education, credit, and extension services.

Logistic regression

Table 7. Logistic Regression of Food Security

Variable	Coefficient	Std. Error	Statistic	p-value	Odds Ratio
const	-2.0568	0.8539	-2.4087	0.0160	0.1279
Irrigation sustainability index 0to100	0.0866	0.0133	6.5084	0.0000	1.0905
Education years	0.3239	0.0626	5.1764	0.0000	1.3825
Farm size ha	-0.0670	0.0716	-0.9362	0.3492	0.9352
Credit access	0.5462	0.2913	1.8749	0.0608	1.7266
Extension_contact	0.4526	0.2841	1.5932	0.1111	1.5724
Insecurity_index_1to5	-1.1590	0.1822	-6.3622	0.0000	0.3138

Table 7 presents a logistic regression examining the determinants of household food-security status, complementing the continuous-outcome OLS model. Irrigation sustainability is positive and highly significant ($\beta = 0.0866$, $p < 0.001$), with an odds ratio of 1.0905, indicating that each one-point increase in the sustainability index is

associated with approximately a 9.05% increase in the odds of being food secure, holding other factors constant. Education is also positive and significant ($\beta = 0.3239$; OR = 1.3825; $p < 0.001$), implying higher odds of food security with additional schooling. Farm size is negative but insignificant ($\beta = 0.0670$, $p = 0.3492$), while credit access is positive but only marginally significant (OR = 1.7266, $p = 0.0608$). Extension contact is also positive but statistically insignificant (OR = 1.5724, $p = 0.1111$), providing insufficient evidence of an independent effect. In contrast, insecurity has a strong negative and significant association with food-security status ($\beta = -1.1590$; OR = 0.3138; $p < 0.001$), indicating that a one-unit increase in insecurity is associated with approximately a 68.62% reduction in the odds of being food secure. The logistic results reinforce the OLS findings, particularly the positive association between irrigation sustainability and food security and the adverse role of insecurity. **Determinants of adoption**

Table 8. Logistic Regression of Sustainable Irrigation Adoption

Variable	Coefficient	Std. Error	Statistic	p-value	Odds Ratio
const	-1.3305	0.8075	-1.6477	0.0994	0.2644
Education in years	0.0253	0.0492	0.5146	0.6068	1.0257
Farming experience in years	0.0525	0.0163	3.2335	0.0012	1.0539
Farm size ha	0.0968	0.0612	1.5828	0.1135	1.1017
Credit access	0.5942	0.2546	2.3340	0.0196	1.8116
Extension contact	0.6436	0.2632	2.4457	0.0145	1.9033
Insecurity index 1to5	-0.3890	0.1413	-2.7524	0.0059	0.6777
Cost_barrier_1to5	-0.2349	0.1444	-1.6265	0.1039	0.7907

Table 8 examines the factors associated with sustainable irrigation adoption using logistic regression. Farming experience, credit access, and extension contact are positive and statistically significant, while insecurity has a significant negative association with adoption. Each additional year of farming experience increases the

odds of adoption by approximately 5.39% (OR = 1.0539; $p = 0.0012$). Credit access is associated with 81.16% higher odds of adoption (OR = 1.8116; $p = 0.0196$), while extension contact corresponds to approximately 90.33% higher odds (OR = 1.9033; $p = 0.0145$), highlighting the importance of financial and institutional support. In contrast, education ($p = 0.6068$), farm size ($p = 0.1135$), and cost barriers ($p = 0.1039$) are statistically insignificant, suggesting that these factors do not independently explain adoption after controlling for the other variables. Insecurity has a significant negative effect (OR = 0.6777; $p = 0.0059$), indicating that a one-unit increase in insecurity is associated with approximately a 32.23% reduction in the odds of adoption. The findings suggest that credit, extension services, and farming experience facilitate sustainable irrigation adoption, whereas insecurity constrains it. However, the estimates represent conditional associations rather than causal effects because selection into credit and extension services, omitted variables, and other forms of endogeneity may remain. Given the low adoption rate of 23.96% reported in Table 2, improving access to affordable credit and effective extension services while addressing insecurity may support wider adoption.

Moderating role of insecurity

Table 9. Irrigation Sustainability × Insecurity

Variable	Coefficient	Std. Error	Statistic	p-value
const	38.1511	5.6109	6.7994	0.0000
Irrigation_sustainability_in dex_0to100	0.5930	0.1247	4.7569	0.0000
Insecurity_index_1to5	-8.0122	1.6448	-4.8711	0.0000
Irrigation × Insecurity	0.0229	0.0389	0.5879	0.5566
Education in years	2.1512	0.2144	10.0339	0.0000
Credit access	4.1074	1.0935	3.7563	0.0002

Table 9 examines the moderating role of insecurity in the relationship between irrigation sustainability and the outcome. Irrigation sustainability has a positive and significant effect ($\beta = 0.5930$, $p < 0.001$), while insecurity has a significant negative direct effect ($\beta = -8.0122$, $p < 0.001$). This indicates that sustainable irrigation is

associated with improved outcomes, whereas greater insecurity substantially constrains agricultural performance. However, the irrigation sustainability $\times$ insecurity interaction is positive but statistically insignificant ($\beta = 0.0229$, $p = 0.5566$). Thus, there is insufficient evidence that insecurity significantly alters the relationship between irrigation sustainability and the outcome, and the proposed moderation hypothesis is not supported. Education ($\beta = 2.1512$, $p < 0.001$) and credit access ($\beta = 4.1074$, $p = 0.0002$) are also positive and significant. The results suggest that insecurity is an important direct constraint, but not a statistically significant moderator of the irrigation sustainability outcome relationship.

Robustness analysis

Table 10. Robustness Model Using Adoption Status

Variable	Coefficient	Std. Error	Statistic	p-value
const	57.6353	3.0151	19.1155	0.0000
Sustainable irrigation adoption	11.1468	1.5317	7.2775	0.0000
Education in years	3.0297	0.2484	12.1949	0.0000
Farm size hectare	-0.0635	0.3121	-0.2036	0.8386
Credit access	6.4152	1.2898	4.9738	0.0000
Extension contact	4.7270	1.2531	3.7723	0.0002
Insecurity_index_1to5	-9.9190	0.6803	-14.5813	0.0000

Table 10 provides a robustness check using sustainable irrigation adoption status as an alternative measure of irrigation sustainability. Adoption has a positive and highly significant association with the outcome ($\beta = 11.1468$, $p < 0.001$), indicating that adopters have an estimated 11.15-point higher outcome score after controlling for other factors. Education ($\beta = 3.0297$), credit access ($\beta = 6.4152$), and extension contact ($\beta = 4.7270$) are also positive and significant, while farm size is insignificant ($\beta = -0.0635$, $p = 0.8386$). Conversely, insecurity has a strong negative and significant association with the outcome ($\beta = -9.9190$, $p < 0.001$), confirming its role as an important constraint on agricultural performance. Hence, the positive adoption coefficient remains significant after controlling for insecurity and other covariates,

supporting the robustness of the study's main finding across alternative measures of irrigation sustainability.

Diagnostic tests

Table 11. Variance Inflation Factors

Variable	VIF
const	35.3410
Irrigation_sustainability_index_0to100	1.2570
Education in years	1.0890
Farm size hectare	1.0130
Credit access	1.0610
Extension contact	1.0250
Insecurity index 1to5	1.1510

Table 11 shows very low multicollinearity among the explanatory variables, with VIF values ranging from 1.013 for farm size to 1.257 for irrigation sustainability, all well below the conventional thresholds of 5 or 10. Education (1.089), credit access (1.061), extension contact (1.025), and insecurity (1.151) likewise indicate negligible collinearity. Although the constant has a higher VIF of 35.341, this does not indicate problematic multicollinearity among the substantive regressors and is generally not the focus of the diagnostic. The results confirm that multicollinearity is not a serious concern, supporting the stability and interpretability of the estimated regression coefficients.

Table 12. Breusch-Pagan Heteroskedasticity Test

Variable	Statistic	p-value
LM	1.7855	0.9383
F	0.2935	0.9399

Table 12 reports the Breusch-Pagan test for heteroskedasticity. The LM statistic is 1.7855 ($p = 0.9383$), while the F-statistic is 0.2935 ($p = 0.9399$). Since both p-values exceed the 5% significance level, the null hypothesis of homoskedasticity cannot be rejected. Thus, there is no statistical evidence of heteroskedasticity, indicating that the error variance is reasonably constant across observations. The consistency of the LM and F tests further supports this conclusion. Hence, heteroskedasticity does not appear to be a material concern, strengthening

confidence in the estimated regression relationships and associated statistical inference.

Table 13. Jarque-Bera Residual Normality Test

Variable	Statistic	p-value
Jarque-Bera	0.3233	0.8507

Table 13 reports the Jarque-Bera residual normality test, yielding a statistic of 0.3233 ($p = 0.8507$). Since the p-value is well above 5%, the null hypothesis of normally distributed residuals cannot be rejected, indicating no significant evidence of residual non-normality. Combined with the VIF and Breusch-Pagan results, the diagnostics suggest that the model has satisfactory statistical properties, with no serious multicollinearity, heteroskedasticity, or residual-normality problems. The use of HC1 robust standard errors further provides an additional safeguard for statistical inference. Thus, the diagnostic results support the reliability of the estimated coefficients and associated hypothesis tests.

Discussion

The findings provide consistent evidence of a positive association between sustainable irrigation and household food security. Across the OLS, logistic, and robustness models, higher irrigation sustainability and adoption are associated with better food-security outcomes. This relationship is theoretically plausible because reliable irrigation reduces dependence on rainfall, supports multiple cropping cycles, stabilizes yields, and can improve farm income and household food availability.

The adoption results further show that credit access, extension contact, and farming experience are important correlates of sustainable irrigation adoption. Credit can relax financial constraints associated with irrigation equipment, energy, maintenance, and complementary inputs, while extension services provide farmers with technical knowledge on water management, soil conservation, and appropriate technologies. These findings indicate that irrigation infrastructure alone may be insufficient without complementary financial and institutional support.

Insecurity emerges as a major constraint on both agricultural welfare and irrigation adoption. Its negative association with food security, agricultural outcomes, and irrigation adoption may reflect restricted farm access, displacement, asset losses,

disrupted markets and labour, and reduced incentives to invest in irrigation infrastructure. However, the interaction between irrigation sustainability and insecurity is statistically insignificant ($\beta = 0.0229$, $p = 0.5566$). Thus, while insecurity has a strong direct effect, there is insufficient evidence that it significantly changes the strength of the irrigation-outcome relationship.

The descriptive and multivariate results also show a substantial adoption gap, with only 23.96% of farmers classified as adopters. The higher food-security scores among adopters and the persistence of the positive irrigation coefficient after controlling for relevant characteristics provide a coherent pattern of evidence. Nevertheless, these findings represent conditional associations rather than causal effects. Selection into irrigation adoption, reverse causality, omitted variables, and differences in farmer resources may influence the observed relationships. Future research should therefore employ stronger identification strategies and improved measurement instruments.

Conclusion

The study finds a positive relationship between sustainable irrigation and household food security, with irrigation sustainability and adoption consistently associated with improved outcomes across alternative model specifications. Credit access, extension contact, and farming experience are important correlates of irrigation adoption, while insecurity significantly constrains adoption and agricultural welfare. However, the insignificant interaction between irrigation sustainability and insecurity indicates that insecurity does not significantly moderate the irrigation-outcome relationship. Rather, it appears to operate primarily as an independent constraint on agricultural production and investment. The findings support an integrated approach to irrigation development combining infrastructure with finance, technical assistance, maintenance, and security interventions. Nevertheless, the results should be interpreted as associational rather than causal unless future research addresses potential endogeneity and selection bias using stronger identification strategies. Empirical claims specific to Adamawa State should also be validated using genuine field data.

Recommendations

- i. Expand and rehabilitate and expand irrigation infrastructure, prioritizing smallholder farmers and areas with severe rainfall constraints, while establishing community-based maintenance systems to ensure long-term functionality.
- ii. Improve access to affordable agricultural finance and targeted support through concessional credit, subsidies, and other mechanisms that enable vulnerable farmers to acquire irrigation equipment, inputs, and maintenance services.
- iii. Strengthen extension services and promote appropriate water-saving technologies by providing training on efficient water use, soil conservation, irrigation scheduling, and climate-smart agricultural practices.
- iv. Integrate security and environmental sustainability into irrigation planning by protecting farms and irrigation assets while monitoring groundwater extraction, soil degradation, salinity, water availability, and system efficiency.
- v. Integrate irrigation development with broader agricultural support and effective monitoring, including improved inputs, markets, storage, roads, and systematic evaluation of irrigation adoption, productivity, food security, and environmental outcomes.

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