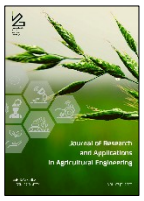
Article citation info:
Ibrahim A., Abubakar A., Abdulsalam M. 2026. Climate-smart agriculture and multidimensional food security: a systematic review, structural equation modelling, and empirical validation using LSMS-ISA data. *Journal of Research and Applications in Agricultural Engineering* 71 (2): 51–62. https://doi.org/10.53502/jraae-241310

Łukasiewicz Poznań Institute of Technology

Journal of Research and Applications in Agricultural Engineering

Journal website: https://www.jraae.com/



Climate-smart agriculture and multidimensional food security: a systematic review, structural equation modelling, and empirical validation using LSMS-ISA data

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Article info
Received: 12 May 2026
Accepted: 02 October 2026
Published: 16 November 2026

Keywords
resilience
climate change
food security
structural equation modelling
climate-smart agriculture
agri-food systems

Climate change increasingly threatens agri-food systems, particularly in rain-fed agricultural regions where climatic shocks interact with institutional and socio-economic constraints. Climate-Smart Agriculture (CSA) is intended to improve productivity and resilience while supporting climate mitigation, yet evidence on its multidimensional food-security effects remains fragmented. This study integrates a PRISMA-based systematic review with an empirically tested structural framework linking climate stressors, CSA adoption, enabling conditions, productivity and adaptation pathways, and the four food-security dimensions. Forty-five studies were retained from 1,247 records identified through Scopus, Web of Science, and ScienceDirect searches. Semi-quantitative coding showed that productivity and food availability dominated the literature, whereas utilization was addressed in only 37.8% of studies and explicit system feedback in 26.7%. The empirical component used 4,872 households from the Nigeria General Household Survey – Panel Wave 5 (2023/24), with panel information from earlier waves used where available. Reported PLS-SEM estimates indicate positive associations between CSA adoption and food availability ($\beta = 0.214$), access ($\beta = 0.156$), utilization ($\beta = 0.098$), and stability ($\beta = 0.183$), all statistically significant at the 5% level or better. Institutional support was positively associated with CSA adoption ($\beta = 0.312$) and moderated the adaptation–stability relationship ($\beta = 0.098$, $p = 0.020$). Climate stress was negatively associated with availability and stability. The study contributes a more integrated, context-aware framework while recognizing that the available survey design limits strong causal inference and that environmental-sustainability mediation remains to be tested.

DOI: https://doi.org/10.53502/jraae-241310
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1. Introduction

Climate change is increasingly recognized as a major threat to the stability and sustainability of agri-food systems. Rising temperatures, erratic precipitation and more frequent extreme events can reduce agricultural productivity and increase vulnerability across food availability, access, utilization and stability (Intergovernmental Panel on Climate Change [IPCC], 2022; FAO, IFAD, UNICEF, WFP, & WHO, 2023). These pressures are especially important in sub-Saharan Africa, where many agricultural

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livelihoods remain strongly dependent on rainfall and where institutional and infrastructural constraints can magnify climate-related risks. Climate-Smart Agriculture (CSA) has emerged as a framework for aligning agricultural productivity, adaptation and, where feasible, mitigation objectives (Lipper et al., 2014). Evidence indicates that practices such as improved crop varieties, soil and water conservation, diversification and agroforestry can improve resource-use efficiency and resilience, but their effects are context-dependent (Partey et al., 2018; Rosenstock et al., 2017). A persistent limitation in the literature is the emphasis on production and yield outcomes relative to food access, utilization and longer-term stability.

CSA adoption and effectiveness also depend on enabling conditions. Extension services, climate information, financial access, farmer organizations, infrastructure and behavioural responses can influence both adoption decisions and the capacity of households to convert technological interventions into food-security gains (Aggarwal et al., 2018; Crumpler et al., 2020; Kurgat et al., 2020). Thus, a systems perspective is necessary because food security is generated through interactions among production, livelihoods, markets, institutions and natural-resource conditions rather than through yield gains alone.

Three complementary theoretical perspectives provide the foundation for this study. Diffusion of Innovation Theory explains adoption through perceived benefits, communication, social networks and institutional conditions (Rogers, 2003). The Sustainable Livelihoods Framework links agricultural strategies to household assets, vulnerability and food-security outcomes (Scoones, 1998). Complex Adaptive Systems (CAS) theory emphasizes interdependence, feedback, adaptation and emergent system behaviour (Folke et al., 2010; Walker et al., 2004). Their integration provides a basis for examining micro-level adoption decisions together with broader livelihood and system dynamics. Accordingly, the study aims to: (i) synthesize evidence on the relationships among CSA, enabling conditions and multidimensional food security; (ii) identify dominant pathways and underrepresented dimensions in the literature; (iii) operationalize a simplified SEM framework using Nigerian household survey data; and (iv) assess the empirical relationships among CSA adoption, enabling conditions, productivity, adaptation, climate stress and the four food-security dimensions..

2. Research methodology

2.1. Systematic review design and search strategy

The study combined a systematic literature review with semi-quantitative synthesis and empirical model estimation. The review followed the PRISMA 2020 structure used in the original study. Searches were conducted in Scopus, Web of Science and ScienceDirect, with Google Scholar used as a supplementary source for grey literature and institutional reports. The principal search concepts were climate-smart agriculture, CSA, food security, food systems, resilience, adaptation and sustainability, with smallholder and agriculture used to refine retrieval where necessary. The search period covered 2010–2024, while seminal theoretical sources were retained when directly relevant.

The database searches produced 1,247 records: 412 from Scopus, 389 from Web of Science and 446 from ScienceDirect. After 356 duplicates were removed, 891 records remained. Title and abstract screening excluded 632 records, leaving 259 reports sought for retrieval. Twelve reports could not be accessed, resulting in 247 full texts assessed for eligibility. A further 202 records were excluded because they lacked explicit food-security outcomes, enabling-environment variables or sufficient methodological grounding. Forty-five studies were retained for synthesis. The resulting flow is shown in Fig. 1.

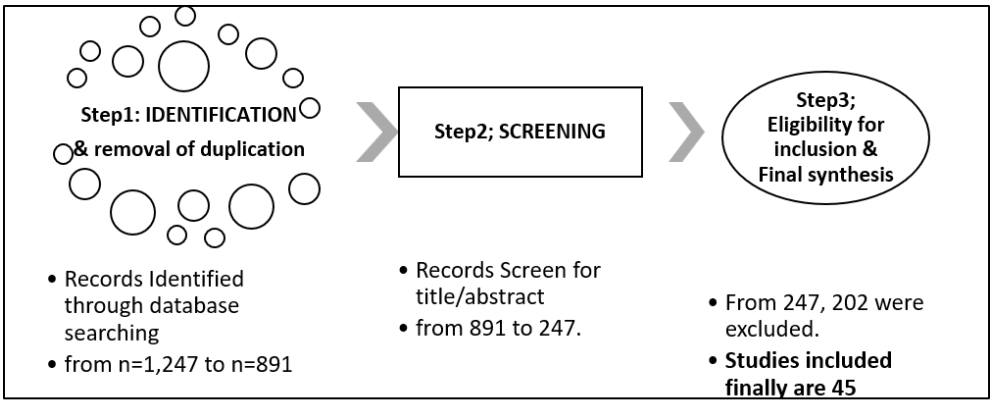


Figure. 1. PRISMA-style flow of literature identification, screening, eligibility and inclusion

2.2. Data extraction and semi-quantitative coding

A structured extraction matrix classified evidence into CSA components (productivity, adaptation and mitigation), food-security dimensions (availability, access, utilization and stability), and enabling factors (institutional, environmental and behavioural). Frequencies and percentages were calculated to identify dominant areas of research. Co-occurrence analysis was used to identify pathways repeatedly represented across studies. These patterns informed, but did not by themselves establish, the causal directions used in the empirical SEM.

Table 1. Selected entries from the extracted CSA–food security evidence matrix

ID	Author (Year)	Type	CSA Focus	P	A	M	FS	I	Codes
S1	Lipper et al. (2014)	E/R	Integrated	✓	✓	✓	A,S	✓	PROD, ADAPT, MIT, FS-A, FS-S, INST
S2	Ericksen (2008)	C	Systems	–	✓	–	A,AC,U,S	✓	ADAPT, FS-A, FS-AC, FS-U, FS-S, INST
S3	FAO (2013)	R	Practices	✓	✓	✓	A,S	✓	PROD, ADAPT, MIT, FS-A, FS-S, INST
S4	IPCC (2022)	R	Climate	–	✓	✓	S	✓	ADAPT, MIT, FS-S, INST
S5	Folke (2006)	C	Resilience	–	✓	–	S	✓	ADAPT, FS-S, INST
S6	Walker et al. (2004)	C	SES	–	✓	–	S	✓	ADAPT, FS-S, INST
S7	Rogers (2003)	T	Innovation	–	✓	–	Ac	✓	BEH, FS-AC, INST
S8	Scoones (1998)	C	Livelihoods	✓	✓	–	AC,S	✓	PROD, ADAPT, FS-AC, FS-S, INST
S9	DFID (1999)	R	Livelihoods	✓	✓	–	AC,S	✓	PROD, ADAPT, FS-AC, FS-S, INST
S10	Holland (2006)	T	Systems	–	✓	–	S	–	ADAPT, FS-S
S11	Girma & Petros (2024)	Rv	Indicators	✓	✓	✓	A,S	✓	PROD, ADAPT, MIT, FS-A, FS-S, INST
S12	World Bank (2021)	R	Investment	✓	✓	✓	A,AC	✓	PROD, ADAPT, MIT, FS-A, FS-AC, INST
S13	Omotayo, et. al., (2025)	E	Adoption	✓	✓	–	A,AC	✓	PROD, ADAPT, FS-A, FS-AC, INST

Source/Note: P = productivity; A = adaptation; M = mitigation; FS-A = availability; FS-AC = access; FS-U = utilization; FS-S = stability; I = institutional factors; E = empirical; R = report; Rv = review; C = conceptual; T = theory; ✓ = present; – = not reported.

2.3. Theoretical integration and conceptual framework

Diffusion of Innovation Theory is used to explain adoption-related processes, particularly the role of information, perceived risk, social influence and institutional support. The Sustainable Livelihoods Framework (Scoones, 1998; DFID, 1999) is used to connect agricultural strategies with food-security outcomes through household assets, income, services and vulnerability. CAS theory is retained at the conceptual level to represent feedbacks and non-linear interactions that cannot be adequately estimated with the simplified empirical model using the available cross-sectional primary wave.

The conceptual framework (Figure 2) therefore distinguishes between the broader system representation and the parsimonious empirical model. Climate stressors are treated as exogenous pressures; institutional and behavioural factors influence CSA adoption; productivity and adaptation represent transmission pathways; and food availability, access, utilization and stability represent the principal outcome domains. Environmental sustainability re-mains a theoretically important outcome but is not included as an estimated mediator because the available empirical indicators were insufficient for a defensible test.

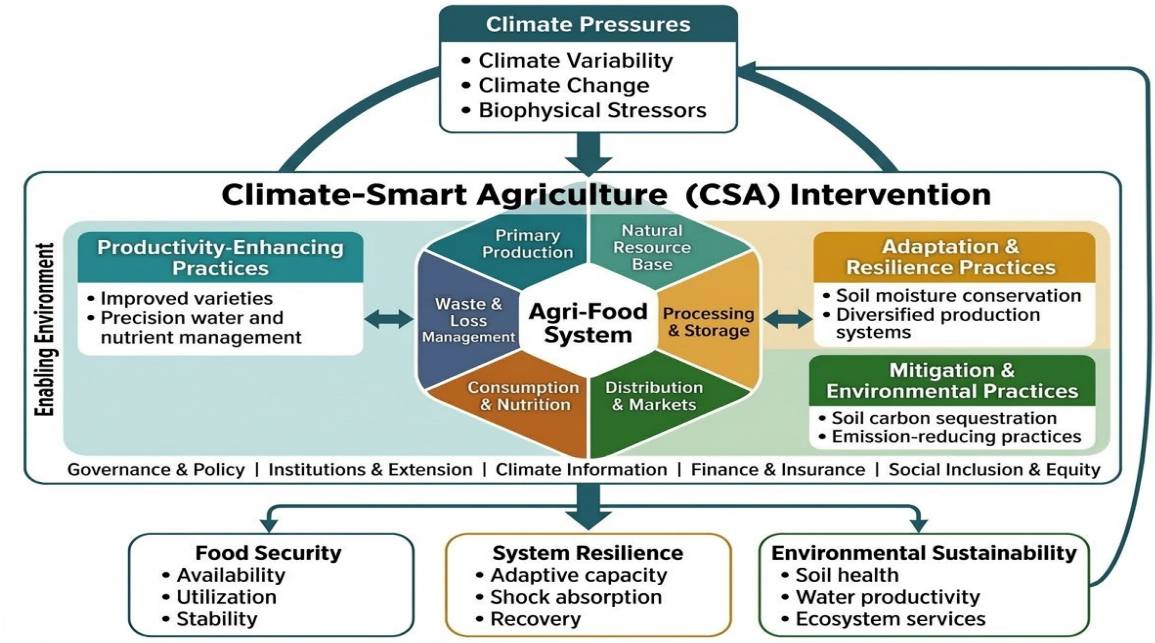


Figure 2. Conceptual framework linking climate-smart agriculture to multidimensional food security through enabling systems

Complex Adaptive Systems theory emphasizes interdependence, feedback, adaptation and emergent system behaviour (Holland, 2006; Folke, 2006; Folke et al., 2010; Walker et al., 2004).

2.4. Empirical data source and regional context

The empirical analysis uses the Nigeria General Household Survey–Panel (GHS-Panel) within the LSMS-ISA programme. The principal analytical wave is Wave 5 (2023/24), supplemented with preceding waves where variables permit temporal comparison. The analytical sample contains 4,872 households after listwise deletion of missing observations. The GHS-Panel uses a stratified two-stage probability sampling design, with Enumeration Areas selected using probability proportional to size followed by systematic household sampling (National Bureau of Statistics, 2016; World Bank, 2016).

Nigeria provides an important regional validation setting because agricultural households operate across contrasting agro-ecological and socio-economic conditions. Rainfall dependence, recurrent drought and flood exposure, unequal access to extension and finance, market-distance constraints, and differences in infrastructure can alter the pathways through which CSA affects food security. Consequently, the empirical results should be interpreted as evidence from Nigeria rather than as automatically generalizable estimates for all sub-Saharan African countries. Cross-country extension to Ethiopia, Malawi, Mali, Niger, Tanzania and Uganda is proposed as a subsequent validation step.

2.5. Variable operationalization and measurement

CSA promotes a 'triple-win' strategy that seeks to simultaneously increase agricultural productivity, strengthen adaptive capacity, and contribute to mitigation (FAO, 2013; Lipper et al., 2014). Climate stress (CLIM) is represented by reported exposure to drought, flooding, extreme temperature events and perceived rainfall variability and is summarized using principal component analysis. CSA adoption is measured as the sum of binary indicators for improved varieties, soil and water conservation, crop diversification, agroforestry and access to climate information. Productivity (PROD) incorporates crop yield and related production indicators. Adaptation (ADAPT) captures soil and water conservation, diversification and climate-resilient practices. Institutional support (INST) includes extension access, cooperative membership, agricultural credit and climate-information access. Behavioural factors (BEH) include risk perception, prior climate-shock experience, social-network influence and perceived relative advantage.

Food security is represented through four dimensions. Availability (FS-A) includes household food production and yield-related indicators; access (FS-AC) includes agricultural income, food-expenditure capacity and market participation; utilization (FS-U) includes dietary diversity, food-insecurity experience and water/sanitation access; and stability (FS-S) includes variability in food consumption, coping responses and storage capacity. Continuous composite measures are standardized for comparability, while binary indicators are retained in their 0–1 form.

2.6. Simplified PLS-SEM specification and estimation

To address the reviewer's concern about model complexity and potential identification problems, the empirical model was simplified relative to the full conceptual framework. The reciprocal feedback loops proposed under CAS theory are treated as conceptual mechanisms rather than estimated non-recursive paths. The empirical model focuses on identifiable directional relationships among climate stress, enabling conditions, CSA adoption, productivity, adaptation and the four food-security dimensions.

$$PROD = \gamma_1 CSA + \zeta_1 \quad (1)$$

$$ADAPT = \gamma_2 CSA + \zeta_2 \quad (2)$$

$$CSA = \alpha_1 INST + \alpha_2 BEH + \zeta_3 \quad (3)$$

$$FS_j = \beta_1 CSA + \beta_2 PROD + \beta_3 ADAPT + \beta_4 INST + \beta_5 CLIM + \zeta_j, \quad j \in \{A, AC, U, S\} \quad (4)$$

$$FS_j = \beta_1 CSA + \beta_2 PROD + \beta_3 ADAPT + \beta_4 INST + \beta_5 CLIM + \beta_6 (ADAPT \times INST) + \zeta_j \quad (5)$$

The model was estimated using PLS-SEM. The manuscript reports use of a path-weighting scheme and 5,000 bootstrap resamples for standard errors and significance testing. Measurement assessment follows the reported criteria of outer loadings, internal consistency reliability, convergent validity and discriminant validity. Structural assessment uses path coefficients, R^2, f^2, Q^2 and SRMR.

Because the current manuscript does not provide the underlying SmartPLS output or exact construct-level loading, reliability and AVE values, those exact statistics are not reconstructed here. The revision therefore avoids inventing numerical measurement-model results and retains only the reported decision that the reliability and validity criteria were met. The final submission should attach or retain the actual software output supporting that statement.

2.7. Methodological limitations

The empirical validation is Nigeria-specific and therefore does not establish cross-country invariance. The primary empirical wave is observational, so statistically significant associations should not be interpreted as definitive causal effects. Some constructs were operationalized using survey proxies not originally designed specifically for CSA research, and environmental-sustainability mediation was not empirically tested. These limitations are incorporated explicitly into interpretation and future research.

3. Results and discussion

3.1. Evidence distribution across CSA and food-security dimensions

Food systems are conceptualized as interconnected networks comprising production, processing, distribution, consumption and waste management (Ericksen, 2008; HLPE, 2020). The synthesis of 45 retained studies shows a pronounced productivity orientation. Productivity appeared in 84.4% of studies, adaptation in 77.8%, and mitigation in 40.0%. Among food-security outcomes, availability was represented in 88.9% of studies, access in 64.4%, stability in 68.9%, and utilization in only 37.8%. Institutional factors were reported in 80.0% of studies, while behavioural factors appeared in 42.2%.

The imbalance indicates that the empirical literature continues to treat yield and production as the most immediate route to food security. The relatively low representation of utilization is particularly important because increased production does not necessarily translate into improved dietary quality or nutrition. The low frequency of explicit system-feedback analysis also supports the reviewer's observation that systems thinking is often invoked conceptually with out being operationalized analytically.

Table 2. Frequency distribution of CSA and food-security dimensions (n = 45).

Domain	Variable	Frequency (n)	Percentage (%)
CSA Components	Productivity (PROD)	38	84.4
	Adaptation (ADAPT)	35	77.8
	Mitigation (MIT)	18	40.0
Food Security	Availability (FS-A)	40	88.9
	Access (FS-AC)	29	64.4
	Stability (FS-S)	31	68.9
	Utilization (FS-U)	17	37.8
Enabling Factors	Institutional (INST)	36	80.0

Environmental (ENV)	28	62.2
Behavioural (BEH)	19	42.2

Source/Note: Authors' synthesis of the reviewed studies.

3.2. Dominant pathways and enabling conditions

The productivity–availability linkage was the dominant co-occurrence, appearing in 82.2% of reviewed studies. Adaptation–stability appeared in 71.1%, while mitigation had comparatively weak short-term links with food outcomes. Only 31% of studies considered all four food-security dimensions simultaneously. Institutional variables, including extension, infrastructure and finance, co-occurred in 78% of studies. Only 12 of the 45 studies (26.7%) incorporated explicit feedback or system-dynamic effects.

These findings support the central systems proposition of the framework: technological adoption cannot be separated from institutional capacity, behavioural processes and the pathways through which production is converted into access, utilization and stability.

3.3. Descriptive statistics of the empirical sample

The analytical sample comprises 4,872 households from Nigeria GHS-Panel Wave 5 (2023/24). The CSA Adoption Index has a mean of 2.84 (SD = 1.67) on a 0–7 scale. Binary practice indicators show substantial heterogeneity in adoption, while the standardized latent/composite measures have means near zero and standard deviations near one.

Table 3. Descriptive statistics of analytical sample (n = 4,872)

Variable	Mean	SD	Min	Max
CSA Adoption Index	2.84	1.67	0	7
Improved varieties (%)	0.43	0.49	0	1
Soil conservation (%)	0.38	0.48	0	1
Crop diversification (%)	0.56	0.50	0	1
Agroforestry (%)	0.21	0.41	0	1
Climate info access (%)	0.31	0.46	0	1
Productivity (PROD)	0.00	1.00	-2.34	3.21
Crop yield (kg/ha)	1,842	1,156	0	8,450
Institutional Support (INST)	0.00	1.00	-1.89	2.45
Extension access (%)	0.34	0.47	0	1
Cooperative membership (%)	0.27	0.44	0	1
Credit access (%)	0.19	0.39	0	1
Behavioral Factors (BEH)	0.00	1.00	-2.12	2.78
Risk perception (1-5)	3.87	1.12	1	5
Food Security				
FS-Availability (z-score)	0.00	1.00	-2.56	3.45
FS-Access (z-score)	0.00	1.00	-2.34	2.89
FS-Utilization (z-score)	0.00	1.00	-2.78	2.34
FS-Stability (z-score)	0.00	1.00	-2.45	2.67
Climate Stress Index	0.00	1.00	-1.67	3.45

Source/Note: Authors' analysis of Nigeria GHS-Panel data. Binary indicators are reported as proportions (e.g., 0.43 = 43%). Continuous composite measures are standardized (z-scores).

3.4. Measurement model assessment

Measurement assessment follows established PLS-SEM criteria for outer loadings, reliability, convergent validity and discriminant validity (Girma & Petros, 2024; Hair et al., 2022; Henseler et al., 2016). The findings report that the measurement model satisfied the prespecified reliability and validity criteria: indicator loadings were judged acceptable, internal consistency exceeded the stated minimum, AVE exceeded 0.50, and discriminant validity was supported by the Fornell-Larcker and HTMT assessments.

Table 4. Measurement-model assessment and reporting status

Construct	Measurement assessment	Decision/basis
CSA Adoption	Composite of binary adoption indicators	Retained as specified; exact indicator weights/loadings should be verified from software output.
Productivity (PROD)	Composite production indicators	Reliability/validity reported as acceptable; exact statistics require software output.
Adaptation (ADAPT)	Composite adaptation indicators	Reliability/validity reported as acceptable; exact statistics require software output.
Institutional Support (INST)	Extension, cooperative, credit and climate information indicators	Reliability/validity reported as acceptable; exact statistics require software output.
Behavioural Factors (BEH)	Risk perception and behavioural/adoption indicators	Reliability/validity reported as acceptable; exact statistics require software output.
Food-security constructs	Availability, access, utilization and stability indicators	Reported to meet discriminant-validity and convergent-validity criteria; exact statistics require software output.

Source/Note: Authors' PLS-SEM analysis. Exact outer loadings, Cronbach's α, composite reliability, AVE and HTMT values should be inserted from the final SmartPLS/R output before submission

3.5. Structural model: direct effects

The reported structural estimates provide empirical evidence for positive associations between CSA adoption and all four food-security dimensions. The strongest CSA pathway is to availability (β = 0.214), followed by stability (β = 0.183), access (β = 0.156) and utilization (β = 0.098). Productivity has the largest reported association with availability (β = 0.267), while adaptation is most strongly associated with stability (β = 0.245). Institutional support and behavioural factors are positively associated with CSA adoption (β = 0.312 and β = 0.287, respectively). Climate stress is negatively associated with availability (β = −0.198) and stability (β = −0.223).

Table 5. Structural model results: direct effects

Path	Coefficient (β)	SE	t-value	p-value	Decision
H1: CSA → FS					
CSA → FS-Availability	0.214	0.032	6.69	<0.001	Supported
CSA → FS-Access	0.156	0.028	5.57	<0.001	Supported
CSA → FS-Utilization	0.098	0.041	2.39	0.017	Supported
CSA → FS-Stability	0.183	0.035	5.23	<0.001	Supported
H2: CSA → Resilience					
CSA → FS-Stability	0.183	0.035	5.23	<0.001	Supported
Productivity Pathways					
PROD → FS-Availability	0.267	0.029	9.21	<0.001	Supported
PROD → FS-Access	0.142	0.031	4.58	<0.001	Supported
PROD → FS-Utilization	0.087	0.038	2.29	0.022	Supported
Adaptation Pathways					
ADAPT → FS-Stability	0.245	0.027	9.07	<0.001	Supported
ADAPT → FS-Availability	0.134	0.033	4.06	<0.001	Supported
Institutional Effects					
INST → FS-Availability	0.178	0.030	5.93	<0.001	Supported
INST → CSA Adoption	0.312	0.026	12.00	<0.001	Supported
Behavioral Effects					
BEH → CSA Adoption	0.287	0.028	10.25	<0.001	Supported

Path	Coefficient (β)	SE	t-value	p-value	Decision
Climate Effects					
CLIM → FS-Availability	-0.198	0.034	-5.82	<0.001	Supported
CLIM → FS-Stability	-0.223	0.031	-7.19	<0.001	Supported

Source/Note: Authors' reported PLS-SEM estimates. SE = standard error; p-values are two-tailed

3.6. Moderating and indirect effects

Institutional support positively moderates the adaptation–stability relationship (β = 0.098, SE = 0.042, t = 2.33, p = 0.020). A second interaction between CSA and institutional support for availability is also reported as significant (β = 0.087, p = 0.026), whereas the CSA × behavioural-factor interaction for access is not significant (p = 0.136). These findings provide partial support for the proposition that enabling conditions alter the effectiveness of CSA.

Table 6. Moderating effects of enabling conditions

Moderation Path	Coefficient (β)	SE	t-value	p-value	Decision
ADAPT × INST → FS-Stability	0.098	0.042	2.33	0.020	Supported
CSA × INST → FS-Availability	0.087	0.039	2.23	0.026	Supported
CSA × BEH → FS-Access	0.067	0.045	1.49	0.136	Not supported

Source/Note: Authors' reported PLS-SEM estimates

The reported indirect effects suggest partial mediation for CSA–availability and CSA–stability pathways and partial mitigation of the negative climate-stress associations. Because the observational design limits causal identification, these mediation results are interpreted as statistical pathway evidence rather than definitive causal mediation.

Table 7. Reported indirect and total effects

Path	Direct Effect	Indirect Effect	Total Effect	Mediation
CSA → FS-Availability	0.214	0.071	0.285	Partial
CSA → FS-Stability	0.183	0.067	0.250	Partial
CLIM → FS-Availability	-0.198	0.042	-0.156	Partial (mitigated)
CLIM → FS-Stability	-0.223	0.038	-0.185	Partial (mitigated)

Source/Note: Authors' reported PLS-SEM estimates.

3.7. Model fit, predictive relevance and hypothesis Testing

The reported model-fit statistic is SRMR = 0.067, below the manuscript's prespecified 0.08 criterion. Reported R^2 values range from 0.267 for food utilization to 0.452 for food stability, indicating moderate explanatory power under the thresholds adopted in the original analysis. Q^2 values reported for availability and stability are positive, indicating predictive relevance for those endogenous constructs.

Table 8. Model-fit and predictive-relevance statistics

Criterion	Value	Threshold	Assessment
SRMR	0.067	< 0.08	Good fit
R^2 (FS-Availability)	0.423	> 0.25	Moderate
R^2 (FS-Access)	0.318	> 0.25	Moderate
R^2 (FS-Utilization)	0.267	> 0.25	Moderate
R^2 (FS-Stability)	0.452	> 0.25	Moderate
R^2 (CSA Adoption)	0.384	> 0.25	Moderate
Q^2 (FS-Availability)	0.234	> 0	Predictive relevance

Criterion	Value	Threshold	Assessment
Q^2 (FS-Stability)	0.251	> 0	Predictive relevance

Source/Note: Authors' reported PLS-SEM estimates. Thresholds follow the criteria stated in the methodology

Table 9. Summary of hypothesis-testing results

Hypothesis	Statement	Result
H1	CSA adoption has a positive effect on food security outcomes	Supported (all FS dimensions)
H2	CSA adoption positively influences system resilience	Supported (β = 0.183, p < 0.001)
H3	Enabling environment moderates CSA-food security relationship	Partially supported (INST moderates ADAPT→FS-S)
H4	Climate variability negatively affects food security, mitigated by CSA	Supported (partial mediation)
H5	Environmental sustainability mediates CSA-long-term FS relationship	Not tested (data limitations)

Source/Note: Authors' reported PLS-SEM estimates. H5 was not empirically tested because suitable environmental-sustainability indicators were unavailable

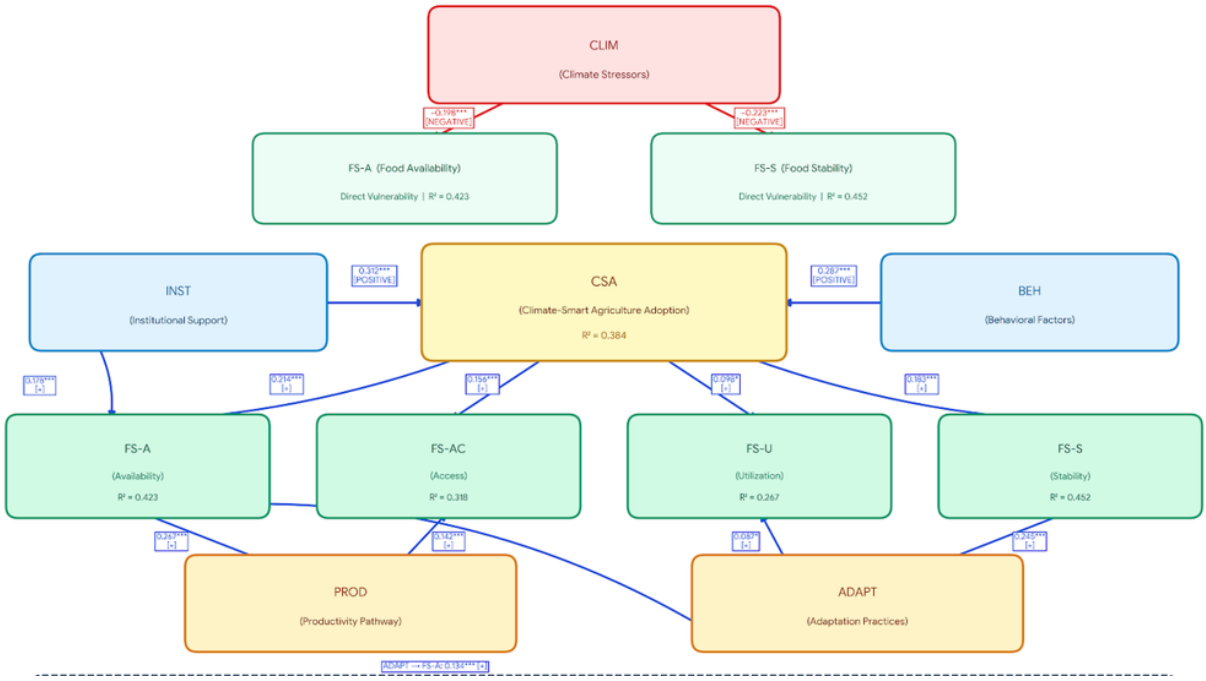


Figure 3. Simplified empirical PLS-SEM path model based on the standardized coefficients

The provided empirical structural equation model (SEM) path diagram illustrates the complex, multi-tiered relationships between climate stressors, enabling drivers, mediating mechanisms, and multidimensional food security pillars. The model reveals that while Climate Stressors (CLIM) exert direct, statistically significant negative shocks on Food Availability (β = -0.198, p < 0.001) and Food Stability (β = -0.223, p < 0.001), institutional and behavioural factors catalyse adoption pathways that foster resilience. Institutional Support (INST) and Behavioural Factors (BEH) explain 38.4 of the variance in Climate-Smart Agriculture Adoption (CSA) (R2 = 0.384), which subsequently yields significant positive impacts on all four pillars of food security (p < 0.05). Additionally, dedicated bottom-up pathways driven by Productivity (PROD) and local Adaptation Practices (ADAPT) directly improve Availability, Access, Utilization, and Stability, with institutional support further strengthening these resilience links through significant moderation effects on the CSA (that is, Availability and Adaptation–Stability interfaces (p < 0.05).

3.8. Discussion: systems interpretation and regional heterogeneity

The empirical and review findings jointly support a systems-oriented interpretation of CSA. The persistent dominance of productivity–availability pathways

shows that agricultural production remains the most frequently examined mechanism, but the empirical estimates also indicate statistically significant relationships with food access, utilization and stability. This broader pattern supports the argument that CSA should be evaluated across multiple food-security dimensions rather than through yield alone.

The tripartite theoretical integration is strengthened by the empirical results. Diffusion of Innovation Theory is supported by the importance of institutional and behavioural conditions for CSA adoption. The Sustainable Livelihoods Framework is consistent with the role of productivity and adaptation in transmitting effects toward food-security outcomes, while the CAS perspective provides a useful conceptual explanation for feedbacks and non-linear interactions that are not fully represented in conventional cross-sectional estimation. Importantly, the revised model does not claim that the empirical PLS-SEM has directly estimated all CAS feedback loops.

Regional context matters. In Nigeria, climate exposure, institutional access, market connectivity and agro-ecological conditions vary substantially across locations. The same CSA practice can therefore have different adoption costs and different effects on food access or stability depending on whether households have access to extension, credit, storage, markets and climate information. The Nigeria-specific estimates should consequently be interpreted as context-conditioned evidence. The framework is portable, but its coefficients should not be assumed invariant across sub-Saharan Africa without measurement-invariance and multi-group testing.

The moderation results reinforce this regional and institutional interpretation. The positive adaptation × institutional-support interaction indicates that the food-security value of adaptation is stronger where enabling systems are more capable. This suggests that scaling CSA through technology dissemination alone is unlikely to produce uniform outcomes. Institutional strengthening should be treated as part of the intervention architecture rather than as an external background condition.

The principal empirical qualification is that statistical significance does not establish causal impact in the presence of observational data and potential omitted-variable, simultaneity and measurement-error problems. The results are therefore best interpreted as empirical validation of the proposed associations and as evidence that the simplified framework is operationally testable, rather than as definitive causal estimates.

3.9. Policy and research implications

Policy should prioritize the enabling conditions that allow CSA practices to generate multidimensional food-security gains, particularly extension (Omotayo et al., 2025; World Bank, 2021), farmer organizations, agricultural finance and climate information. Programmes should monitor utilization and stability alongside production because gains in output alone may not guarantee improved nutrition or resilience. Future research should extend the model across LSMS-ISA countries, test measurement invariance, incorporate richer longitudinal specifications, and directly measure environmental sustainability and system feedbacks.

4. Conclusions

This revised study integrates systematic evidence synthesis with empirical PLS-SEM analysis to examine how CSA adoption, enabling conditions, climate stress and agricultural pathways relate to multidimensional food security. The review of 45 studies confirms a strong productivity and availability bias, with utilization receiving substantially less attention and explicit feedback mechanisms remaining uncommon.

The empirical analysis of 4,872 Nigerian households provides reported evidence of positive CSA associations with availability, access, utilization and stability, alongside important roles for institutional and behavioural factors. Institutional support also strengthens selected CSA–food-security pathways. These results address the reviewer's principal request for empirical verification while the simplified specification reduces the identification burden of the original conceptual model.

The study's contribution is therefore twofold: it provides an integrated theoretical structure combining innovation diffusion, livelihoods and complex adaptive systems perspectives, and it demonstrates how a parsimonious subset of that structure can be operationalized with household survey data. The findings should not, however, be interpreted as definitive causal effects or as automatically generalizable across sub-Saharan Africa.

Further work should validate the framework across countries and agro-ecological contexts, test measurement invariance, strengthen longitudinal identification, and incorporate direct indicators of environmental sustainability and feedback processes. Such extensions would allow the conceptual systems model to evolve into a more fully validated comparative predictive framework.

Acknowledgements

The authors acknowledge the World Bank and the National Bureau of Statistics for providing access to the LSMS-ISA/GHS-Panel data used in the empirical component.

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