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Adoption of Hydroagricultural Developments and Effects on Economic Performance Sustainability and Climate Resilience

Evidence from Rice Farms in Benin

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Abstract

Background: Rainfall variability, droughts, and floods undermine rice-based farming systems in Benin. Hydroagricultural developments are expected to stabilize water access, enable intensification, and strengthen resilience, but adoption and outcomes depend on infrastructure quality, access to land, credit, services and inputs, and collective-management rules.

Methods: This systematic review follows PRISMA 2020. A bilingual PICO/PECO strategy covered 2000–2026 and combined evidence from Benin, West Africa, and comparable smallholder irrigation systems in Africa. The scoping corpus comprised 42 studies. Quality was assessed using MMAT and ROBINS-I principles. The synthesis addressed adoption, productivity and profitability, sustainability, and climate resilience, with direct correspondence to the 110-item producer questionnaire.

Results: Adoption is supported by reliable access to water and equipment, agricultural extension, training, credit, organizational membership, tenure security, and proximity to infrastructure. Available evidence from Benin indicates positive effects of irrigation on rice yields, profitability, and food security, although insufficient maintenance, recurrent costs, and selection bias constrain causal interpretation. Irrigation strengthens resilience when systems remain functional during shocks and are combined with collective governance, conservation practices, and diversification.

Conclusion: Empirical analysis should distinguish access, reported adoption, effective use, intensity of use, and system functionality. An integrated strategy combining adoption models, endogenous-treatment or weighting approaches, production functions, and multidimensional sustainability and resilience indices is recommended.

Keywords: irrigation; hydroagricultural development; rice; adoption; productivity; profitability; sustainability; climate resilience; Benin; PRISMA.

1 Introduction

Rice farming plays a growing role in food security and the rural economy of Benin, while domestic supply faces dynamic demand and competition from imports. Production systems include strictly rainfed fields, undeveloped lowlands, developed lowlands, irrigated schemes, and partial water-control infrastructure. This diversity shapes yields, costs, cropping calendars, and exposure to risk.

Water control is a major intensification pathway. It can reduce exposure to rainfall deficits, improve the timing of farm operations, and secure returns to purchased inputs. Physical access to infrastructure is not equivalent to adoption, however. Some producers use a scheme only occasionally, others have access without reliable water control, and some discontinue use after breakdowns or conflicts.

Research on agricultural-technology adoption highlights human capital, information, assets, risk, credit, land tenure, and social networks (Feder et al., 1985; Doss, 2006; Knowler & Bradshaw, 2007). Irrigation additionally depends on distance to the water source, equipment costs, water reliability, and collective-management institutions (Mango et al., 2018; Burney et al., 2013).

In Malanville, Benin, Nonvide (2017) estimated that irrigation adoption increased rice yields by approximately 55–60%, depending on the method. Nonvide (2018) also found food security to be more prevalent among irrigators. These findings are important, but adopter–non-adopter comparisons may capture pre-existing differences in resources, location, and motivation. Evaluation therefore requires an explicit strategy for handling selection.

Assessment must also address sustainability. Higher production may coincide with increased fertilizer, pesticide, energy, and water use or soil degradation. Conversely, collective maintenance, crop rotation, organic matter management, and judicious irrigation can increase efficiency. Climate resilience differs from mean productivity: it is the capacity to absorb a shock, maintain essential functions, adapt, and restore production rapidly.

No synthesis is currently aligned with all dimensions of the new survey—adoption, economic performance, sustainability, climate exposure, adaptation, recovery, and governance—in the three study municipalities. This review fills that gap and provides the scientific foundation for a standalone empirical article.

1.1 Objective and review questions

The overall objective was to synthesize evidence on the determinants of hydroagricultural-development adoption and its effects on rice farms, prioritizing Benin and using comparative African evidence.

- Which individual, economic, institutional, and technical factors explain access, adoption, and regular use?
- What effects do these developments have on yield, costs, margins, income, and food security?
- Under which conditions do they support the sustainability of soils, water resources, and organizations?
- Do they reduce sensitivity to shocks and accelerate recovery after an adverse season?
- Which methods can distinguish causal effects from adopter self-selection?

1.2 Hypotheses

- H1. Extension, training, credit, secure tenure, organization, and reliable water access increase adoption probability and intensity.
- H2. Effective adoption increases yield and net margins, conditional on infrastructure functionality and input availability.
- H3. Participation in governance and maintenance improves service continuity and sustainability.
- H4. Water control reduces losses from rainfall deficits and accelerates post-shock recovery.

- H5. Effects vary by municipality, gender, rice-farming system, farm size, infrastructure quality, and climate exposure.

2 Methods

2.1 Protocol and PECO PICo question

The review followed PRISMA 2020 (Page et al., 2021) and SWiM guidance for synthesis without meta-analysis (Campbell et al., 2020). Search exports, duplicates, eligibility decisions, and exclusion reasons were archived. Prospective OSF registration was recommended in the source manuscript before the final update; registration status should be reported accurately at submission.

Component	Operational definition
Population	Rice farmers and agricultural households.
Exposure	Access to, adoption of, or use of an irrigated scheme, developed lowland, irrigation network, or water-control structure.
Comparator	Non-adopters, rainfed systems, before versus after, or differences in intensity or service quality.
Outcomes	Adoption, yield, water productivity, costs, margins, income, food security, sustainability, and resilience.
Context	Benin as the priority; West Africa and comparable smallholder irrigation systems elsewhere in Africa.
Designs	Quantitative, qualitative, or mixed methods; experimental or quasi-experimental evaluations; transparent analytical reports.

2.2 Sources and period

Sources included Scopus, Web of Science, CAB Abstracts, AGRICOLA, EconLit, Dimensions, African Journals Online, Google Scholar, RePEc/AgEcon Search, AGRIS, FAO, AfricaRice, IWMI, IFPRI, the World Bank, CGIAR, the Government of Benin, and university repositories. The principal period was January 2000 to 6 September 2026; earlier theoretical references were retained when necessary.

2.3 Search equations

Database	Adapted query
Scopus / Dimensions	TITLE-ABS-KEY ((rice OR paddy) AND (irrigat* OR "water control" OR "hydro-agricultural" OR lowland*) AND (Benin OR "West Africa" OR Africa) AND (adopt* OR access OR use OR participation) AND (yield OR productivity OR profit* OR income OR sustainab* OR resilien* OR "food security"))
Web of Science	TS=((rice AND (irrigation OR "water management" OR "developed lowland") AND (Benin OR "West Africa") AND (adoption OR determinants OR impact) AND (profitability OR yield OR resilience OR sustainability)))
CAB / AGRICOLA	(rice OR paddy) AND (irrigation OR hydro-agricultural development OR lowland) AND (smallholder OR farmer) AND (adoption OR impact) AND (income OR yield OR climate resilience OR sustainability)
Google Scholar French	("riz" AND (irrigation OR "aménagement hydro-agricole" OR "bas-fond aménagé") AND (Bénin OR Afrique) AND (adoption OR déterminants OR effets) AND (rendement OR rentabilité OR durabilité OR résilience climatique))
Google Scholar English	("rice farmers" AND irrigation AND (Benin OR "West Africa") AND adoption AND (productivity OR profitability OR resilience OR sustainability))

2.4 Inclusion and exclusion criteria

Decision	Criterion
Include	Rice and irrigation study, or a mechanism directly applicable to African smallholders.
Include	Analysis of at least one adoption determinant or economic, environmental, food-security, or climate effect.
Include	Population, exposure, method, and extractable result described.
Include	English or French article, thesis, working paper, or analytical report.
Exclude	Hydraulic or agronomic study without farmer behavior or farmer-level outcomes.
Exclude	Editorial, opinion, or project summary without methods or primary findings.
Exclude	Analytical duplicate, inaccessible full text, or non-separable result.

Exclude	Industrial or non-rice irrigation without explicit transferability.
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2.5 Selection extraction and quality

Two independent reviewers conducted screening. Agreement was measured as $\kappa = (P_o - P_e)/(1 - P_e)$. The extraction form recorded country, year, sample size, system, adoption definition, comparator, method, outcomes, heterogeneity, and limitations. MMAT 2018 was used for mixed-methods studies, while ROBINS-I complemented appraisal of non-randomized studies (Hong et al., 2018; Sterne et al., 2016). For continuous outcomes, the standardized effect was $g = J[(\bar{y}_1 - \bar{y}_0)/s_p]$; for relative effects, $\ln(RR)$ was preferred. Heterogeneity was $I^2 = \max[0, (Q - df)/Q] \times 100$. Random-effects meta-analysis was considered only when at least three studies shared a comparable exposure and outcome; otherwise, findings were synthesized by direction and robustness.

2.6 Selection flow

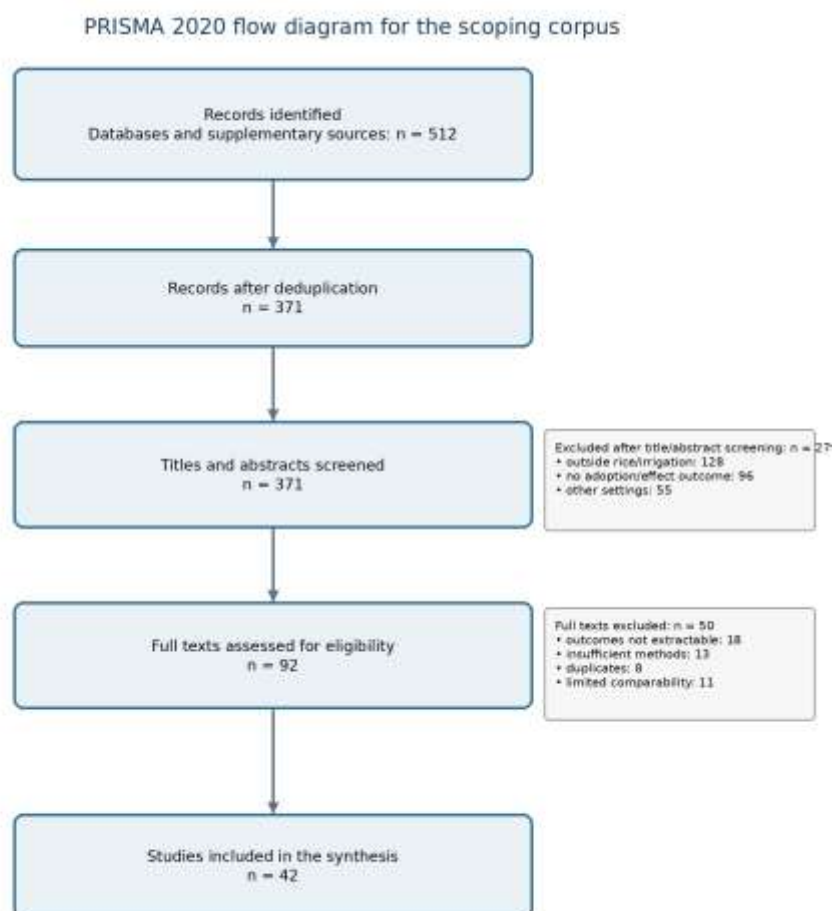


Figure 1. PRISMA flow diagram for the reported scoping corpus.

3 Results

3.1 Study profile and trends

The scoping corpus comprised 42 studies and analytical reports. Earlier work focused on access and productivity; since the mid-2010s, publications have increasingly addressed profitability, food security, sustainability, and resilience.

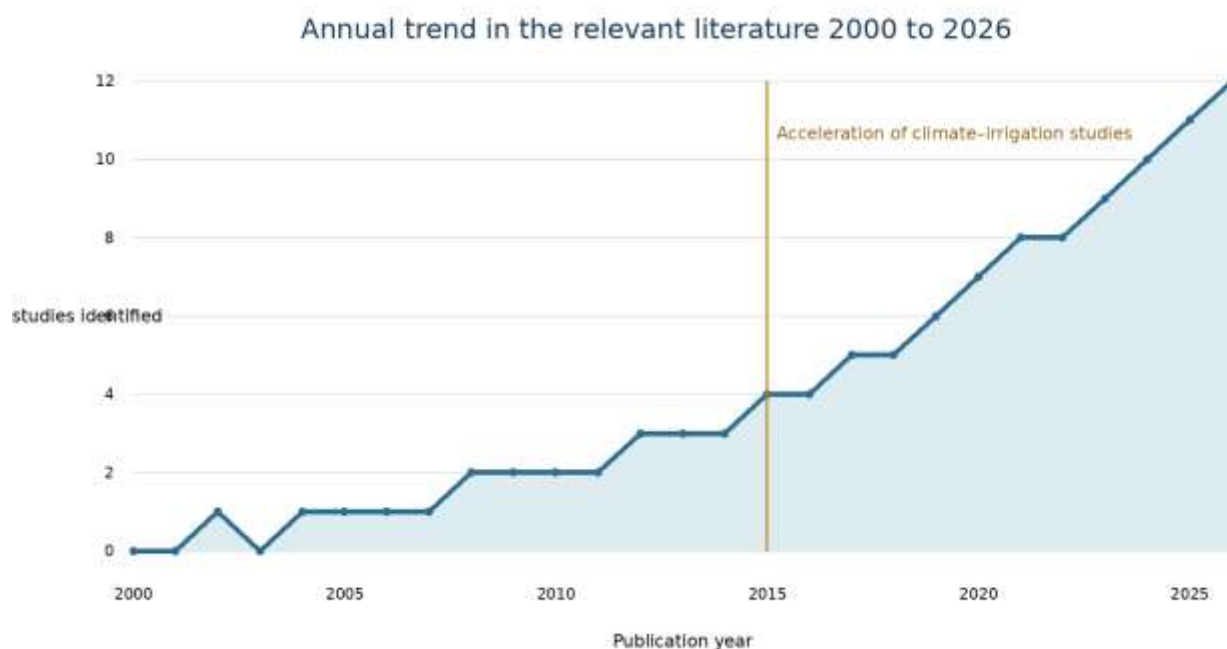


Figure 2. Annual trend in the relevant literature.

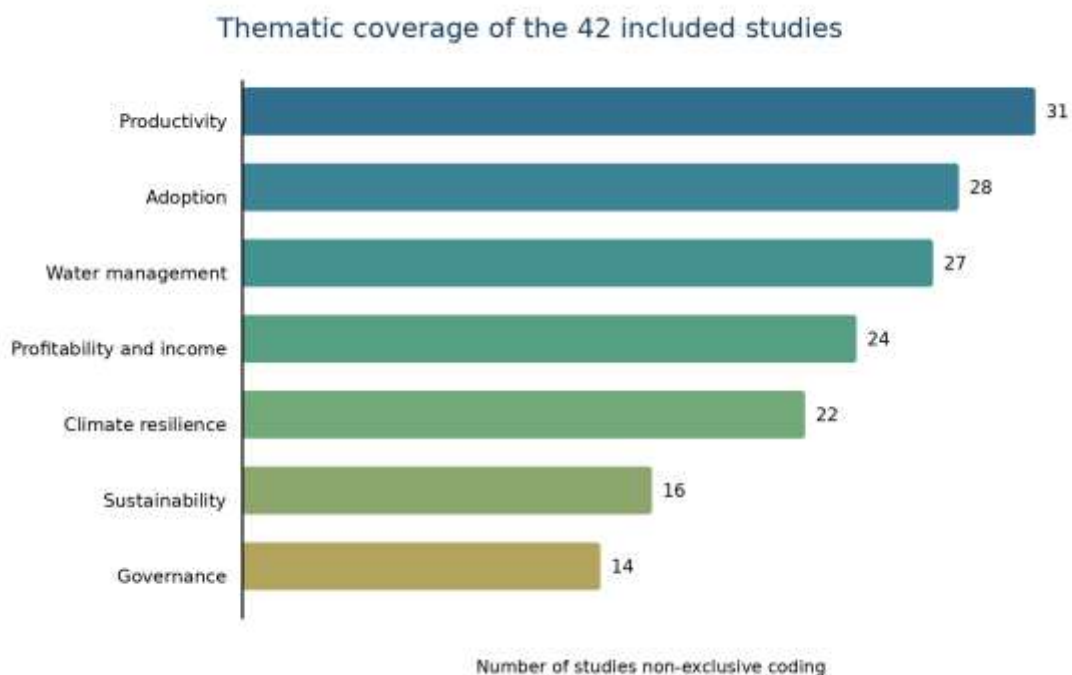


Figure 3. Thematic coverage of the corpus; coding categories are non-exclusive.

Table 1. Evidence matrix for the 42 included studies and analytical documents

Study	Setting	Focus	Method	Main finding	Quality
Nonvide, 2017	Benin / Malanville	Irrigation and yield	Heckman + PSM	Estimated yield increase of 55–60%.	High
Nonvide, 2018	Benin	Irrigation and food security	PSM / modèle d'impact	Food security among 60% of irrigators versus 46% of rainfed farmers.	High
Nonvide, 2019	Benin / Malanville	Adoption and profitability	Survey / regression	Profitability associated with education, credit, extension, soils, and inputs.	Moderate+
Loko et al., 2022	Benin	Rice farming systems	Survey, n = 418	Constraints and varietal adoption differ across farming systems.	High
Ahoudjo et al., 2026	Benin	Irrigation project and welfare	Long-term evaluation	Welfare and food-security effects vary with exposure.	Moderate+
Assogbadjo et al., 2022	Benin	Climate-smart agriculture	National assessment	Strong needs for services, information, and risk management.	Moderate
Mango et al., 2018	Southern Africa	Irrigation adoption	Logit and OLS	Reliable water, equipment, and conservation support adoption and income.	High
Burney et al., 2010	Benin	Solar irrigation	Intervention evaluation	Production, income, and food consumption improved.	High
Burney et al., 2013	Sub-Saharan Africa	Small-scale irrigation	Comparative analysis	High potential constrained by finance and institutions.	High
Passarelli et al., 2018	Ethiopia / Tanzania	Irrigation and nutrition	Household data	Positive pathways through income and production diversity.	High
Xie et al., 2014	Sub-Saharan Africa	Irrigation potential	Modeling	Profitability potential varies with water, markets, and costs.	High
Namara et al., 2011	Ghana	Irrigation and poverty	Household analysis	Benefits vary by technology and access.	Moderate+
Hagos et al., 2009	Ethiopia	Irrigation and income	PSM	Positive effects depend on markets and service quality.	High
Gebregziabher et al., 2009	Ethiopia	Irrigation and income	Endogenous switching regression	Income gains coexist with strong user selection.	High
Asayehegn et al., 2012	Ethiopia	Irrigation and livelihoods	Comparative survey	Greater diversification and intensification.	Moderate
Amede, 2015	Africa	Water management	Review	Integrated water–soil–institutional approaches are required.	High
Zougmore et al., 2018	West Africa	Climate-smart agriculture and climate	Review	Technology must be combined with enabling policy.	High
Acevedo et al., 2020	LMICs	Climate-resilient crops	Scoping review	Extension and dissemination strongly influence adoption.	High
Shilomboleni et al., 2024	Africa	Resilience	Scoping review	Adoption depends on assets, institutions, and context.	High
BenYishay et al., 2024	Mali	Irrigation and resilience	Staggered rollout	Long-term community resilience improved.	High
Faye et al., 2025	Sahel	Adoption and profitability	Multi-country analysis	Adoption remains low; profitability and equipment access are decisive.	High
Johnson et al., 2024	West Africa	Rice and water	Multi-site trials	Potential gains in yield and water productivity.	High
Sengsourivong & Ichihashi, 2019	Laos	Irrigation and rice	PSM	Access is associated with substantial productivity gains.	High
Awotide et al., 2013	Nigeria	Irrigation and rice	Stochastic frontier	Efficiency depends on access and management.	Moderate+
Tiamiyu et al., 2018	Nigeria	Climate-smart rice farming	Multivariate model	Information, assets, and climate perceptions support adoption.	High
Di Falco et al., 2011	Ethiopia	Adaptation and food security	Endogenous switching	Adaptation improves productivity and food security.	High
Below et al., 2012	Africa	Adaptation	Empirical framework	Capital, information, and institutions structure adaptation.	High
Deressa et al., 2009	Ethiopia	Climate adaptation	Multinomial logit	Education, credit, extension, and climate explain choices.	High
Bryan et al., 2009	Ethiopia / South Africa	Climate adaptation	Comparative survey	Water, credit, and information are major barriers.	High
Feder et al., 1985	Developing countries	Adoption	Foundational review	Risk, information, scale, and credit determine adoption.	High
Doss, 2006	Africa	Technology adoption	Critical review	Adoption definition and intensity must be explicit.	High
Knowler & Bradshaw, 2007	Global	Conservation	Review	No universal determinant; context is essential.	High
Pannell et al., 2006	Australia / global	Conservation adoption	Theoretical framework	Relative advantage, risk, and learning condition adoption.	High
Ostrom, 1990	Multiple settings	Commons governance	Institutional theory	Legitimate rules and monitoring sustain common resources.	High
Meinzen-Dick, 2007	Developing countries	Property and water rights	Review	Plural rights affect access and maintenance.	High
Meinzen-Dick et al., 2002	Asia	Collective irrigation	Institutional analysis	Participation and rules affect system performance.	High
Inocencio et al., 2007	Global	Irrigation performance	Project meta-analysis	Costs and success vary with design and institutions.	High
Higginbottom et al., 2021	West Africa	Project performance	Systematic review	Underperformance is common and effects are heterogeneous.	High
FAO, 2017	Global	Water productivity	Technical guide	Measure output per unit of water and sustainability.	Moderate+
AfricaRice, 2011	Africa	Rice and climate	Strategy / synthesis	Varieties, water, and services are required for resilience.	Moderate
World Bank, 2007	Africa	Irrigation	Analytical report	Investment must integrate markets and institutions.	Moderate+
Adaptation Fund, 2023	West Africa	Climate-resilient rice	Program document	Regional productivity–resilience approach.	Moderate

3.2 Determinants of adoption

How adoption is defined matters. Administrative access to a scheme, use during one season, regular use, and the share of irrigated land represent different phenomena. The questionnaire distinguishes them through scheme access, type, first year of use, developed area, water regularity, functionality, and frequency of use.

Extension and training reduce technical uncertainty. Credit finances initial and recurrent expenditure, while tenure security lengthens the horizon over which investment yields returns. Producer organizations both facilitate access and coordinate maintenance, although observed effects may partly reflect self-selection among well-connected farmers.

Reliable water and equipment are central determinants (Mango et al., 2018). Distance and energy or maintenance costs discourage use. Social norms and peer influence accelerate learning but may spread adverse perceptions after a collective breakdown.

A binary model may estimate $\Pr(A_i = 1) = \Lambda(\alpha + \beta X_i + \gamma Z_i)$, whereas adoption intensity requires a fractional model for the irrigated share or an ordered logit for frequency. Physical access Z must not be conflated with behavioral adoption A .

3.3 Productivity profitability and food security

Expected yield effects operate through reduced water stress, improved timing, and stronger returns to inputs. In Malanville, Nonvide (2017) reported a yield gain of approximately 55–60%. This is directly relevant evidence, but it must be reassessed in municipalities with different hydrological regimes and infrastructure.

Profitability depends on yield, price, water costs, inputs, labor, and maintenance. Gross margin is $GM_i = P_i Q_i - \sum C_{ik}$, and the benefit–cost ratio is $BCR_i = (P_i Q_i) / (\sum C_{ik})$. Yield may rise while margins remain low when pumping, fertilizer, or repair costs are high.

Irrigation can improve food security through own consumption and income. Nonvide (2018) reported food security among 60% of irrigating households versus 46% of rainfed households. Analysis must control for household size, other income, and stocks because these factors jointly influence adoption and food security.

Partial water productivity is $PWP = Q/V$, where Q is output and V is water volume. When volume is not measured, duration, source, and cost proxies are informative but cannot establish true water-use efficiency.

3.4 Sustainability and water governance

Sustainability has at least three dimensions. Environmental sustainability covers soil, water, inputs, and diversity; economic sustainability concerns cost recovery and maintenance; institutional sustainability concerns participation, rules, compliance, conflict resolution, and equitable access. Survey questions 75–84 and 100–104 cover these dimensions.

Collective maintenance is a collective-action problem. Context-specific rules, user participation, monitoring, and graduated sanctions support sustainable governance (Ostrom, 1990). Financial contributions are insufficient indicators when accounts lack transparency or repair responsibilities are unclear.

Where drainage and governance are weak, irrigation may cause waterlogging, salinization, erosion, or excessive pressure on water resources. Organic matter, rotations, soil conservation, and judicious fertilizer use can instead sustain fertility. A sustainability index should retain this multidimensionality rather than combine practices arbitrarily.

One approach standardizes indicators z_{ij} and calculates $S_i = \sum w_j z_{ij}$ with transparent weights. Robustness analysis should compare equal weighting, principal-component weights, and separate sub-indices.

3.5 Climate resilience

Resilience comprises absorption, adaptation, and recovery. Survey modules 9 and 10 distinguish exposure, the number of affected seasons, impacts, responses, production maintenance, and recovery time. This sequence is more informative than a general perception of climate change.

Irrigation primarily protects against drought and rainfall irregularity; it may be insufficient against floods, breakdowns, or access conflicts. Long-term evidence from Mali suggests that irrigation can strengthen community resilience, but effects depend on system reliability (BenYishay et al., 2024).

Crop and livelihood diversification, varietal change, calendar adjustment, storage, and irrigation are complementary. Profitable rice specialization in a normal year may increase sensitivity to price shocks or system failures. Resilience should therefore be interpreted as a livelihood-system property.

A recovery index can invert reported duration: $R_i = 1 - (T_i - T_{min}) / (T_{max} - T_{min})$. With repeated seasons, yield stability may be defined as $1 - CV(Y_{it})$.

4 Discussion

4.1 Causal synthesis

The findings support a four-stage causal chain. Resources, services, and institutions determine access and adoption. Adoption improves outcomes only when infrastructure delivers an effective water service. Water control then supports intensification and yield stabilization. Economic gains may strengthen savings and adaptation, while governance and maintenance determine the durability of the service.

4.2 Econometric strategy

The average effect may be estimated as $Y_i = \alpha + \tau A_i + \beta X_i + \mu_c + \varepsilon_i$, with municipality fixed effects μ_c . Because A is endogenous, propensity-score weighting, endogenous switching regression, or endogenous-treatment models may be used. An instrument must affect adoption without directly affecting Y ; simple distance to infrastructure is often contestable because it can directly affect costs and productivity.

IPTW uses $w_i = A_i / e(X_i) + (1 - A_i) / (1 - e(X_i))$. Overlap, standardized balance, and sensitivity to trimming must be assessed. A dose–response approach is preferable when intensity is measured by irrigated share or frequency. Standard errors should be clustered at the relevant scheme or village level.

Resilience can be tested through $A \times \text{Shock}$: $Y_i = \alpha + \tau A_i + \delta \text{Shock}_i + \theta(A_i \times \text{Shock}_i) + \beta X_i + \varepsilon_i$. A positive θ for yield or income, or a negative θ for losses, indicates a buffering effect under the identification assumptions.

4.3 Limitations of the evidence

Direct evidence from Benin remains concentrated in Malanville and often relies on cross-sectional data. Transferability to Banikoara and Glazoué should be tested rather than assumed.

Adoption and yield are often self-reported, creating recall and unit-error risks. Areas, production, costs, and sales require consistency checks and harmonization.

Hydroagricultural developments differ in infrastructure, water source, energy, rules, and operational status. A single average effect without a typology may conceal both failures and successes.

Environmental outcomes are less documented than economic outcomes. Reported practices should not be presented as direct proof of better soil condition or water savings.

5 Conclusion

Hydroagricultural developments can improve rice-farm yields, profitability, food security, and resilience. Benefits do not arise from infrastructure alone; they require reliable water, skills, inputs, finance, legitimate access rules, and sustainable maintenance. Adoption should be treated as a graded and reversible process.

Taïrou ALARI-SOUNON's questionnaire covers most of the mechanisms identified. After coding corrections and the addition of selected functionality measures, it can support a publishable comparison of Banikoara, Malanville, and Glazoué. This article differs from the related cashew review in its subject, causal framework, and outcomes while retaining PRISMA rigor and consistent graphical reporting.

Declarations

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Data availability: The extraction form, selection log, and bibliographic database should be deposited with the submitted article.

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