ADOPTION OF RENEWABLE TECHNOLOGIES AND CROP DIVERSIFICATION AS DRIVERS OF CLIMATE-ADAPTIVE AGRICULTURE: EVIDENCE FROM EMERGING ECONOMIES

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Abstract
The integration of renewable irrigation technologies and crop diversification is critical for achieving climate-adaptive agriculture in emerging economies. This study examines the impact of these sustainable agricultural interventions on productivity, environmental sustainability, and economic resilience across 20 emerging economies from 2000 to 2024. Using panel data from the World Bank, World Development Indicators (WDI), and the International Monetary Fund (IMF), the study employs econometric modelling to assess the influence of renewable irrigation systems, nitrogen-efficient fertilizers, and diversified cropping patterns on agricultural sustainability. Findings reveal that solar-powered irrigation enhances water efficiency and reduces dependency on fossil fuels, while crop diversification mitigates climate risks and stabilizes farm incomes. However, financial limitations, infrastructural inadequacies, and policy discrepancies hinder widespread adoption. The study advises to accelerate the transition to climate-resilient agriculture through targeted policy interventions, improved financing mechanisms and enhancing technological training. These insights help inform a roadmap for policymakers, agribusiness investors and aid practitioners seeking to promote sustainable agriculture strategies and enhance food security outcomes without exacerbating vulnerabilities associated with climate change.
Keywords: climate-adaptive, drivers, agriculture, emerging economies.

Introduction

The adoption of renewable technologies and crop diversification has become central to agricultural sustainability and climate resilience, particularly in emerging economies (Nyangarika, 2024). As global climate change accelerates, agricultural systems in emerging countries, like India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico, Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia, and South Africa face mounting challenges related to droughts, erratic rainfall, land degradation, and declining soil fertility (Campos & Root, 2001). To ensure long-term food security, environmental sustainability, and economic stability, it has become imperative to integrate solar-powered irrigation systems, nitrogen-efficient fertilizers, and diversified cropping strategies.

Renewable technologies have proved a transformative force in modernizing agriculture and addressing climate risk (Batra, 2023; Wicki et al., 2025). For instance, solar-powered irrigation has quickly become an economically viable replacement for diesel-operated pumps, allowing for year-round irrigation while lowering operational costs and carbon emissions. In conclusion, AI-based solutions such as precision agriculture instruments, IoT-enabled soil sensors, AI-based climate analytics, and automated irrigation devices have automated yield estimates and improved yields while minimizing environmental footprints by making fertilizer applications, irrigation, and pest control more efficient (Senoo et al., 2024; Zeverte-Rivza et al., 2023). The use of such technologies together (integrated crop management (ICM)) has already proven beneficial further helping build agricultural resilience across South Asia, Southeast Asia, Africa and Latin America. However, challenges remain, including high initial investment costs, a lack of financing mechanisms, and insufficient training for farmers. In many places, rural electrification is still weak and complicates the transition to renewable energy-supported agricultural solutions. Governments need to carefully improve existing subsidy programs, increase access to agricultural credit, and work with the private sector to promote the roll out of renewable agricultural technology (Glemarec, 2012).

Another pillar of improved soil fertility, increasing resistance to pests and stabilizing farm income is crop diversification. Diversified cropping systems including nuts, legumes, cereals, fruits, oilseeds and medicinal plants rely less on chemical fertilizers and improve nutrient retention and soil structure, compared to monoculture-based farming. In addition, multi-cropping, inter cropping and agroforestry models have been found very effective to overcome challenges of soil degradation and improve carbon sequestering. In developing economies, crop diversification is increasingly promoted through agricultural extension services, seed distribution programs, and climate-smart subsidies. However, adoption has not been uniform, due to barriers to market access, the lack of advanced storage facilities and reluctance to abandon traditional agricultural practices. Another important consideration for maximizing the advantages of crop diversification is that regional trade policies, farmer training programs and supply chain improvements should be conducted seamlessly for integration into national food security strategies (Muhammad & Babatunde, 2024).

The international collaborative study seeks to understand how renewable irrigation technologies and crop diversification can accelerate the transition to climate-adaptive agriculture in India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico, Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia and South Africa. It measures renewable energy solutions' effect on farm productivity, water conservation and economic efficiency, and explores how crop diversification can enhance soil health, climate resiliency and food security. It also discusses challenges to adoption, including lack of finances, infrastructure, and knowledge. Drawing from empirical evidence from various sources including the World Bank, WDI and IMF for the period of 2000–2024, the study highlights policy frameworks, financial models and technological enablers for scaling up sustainable agricultural interventions (Raza & Quaye-Kumah, 2024).

Discussions on climate-smart agriculture and sustainable rural development have become emerging focal points for advancing agriculture globally, supported by evidence-based recommendations for policy makers, agribusiness investors, and agricultural practitioners. Renewable energy integration and diversified cropping systems are the key measures to achieve food security, environmental sustainability, and the national economy of rural area. The aim of this study is to present an integrated perspective on the strategies that emerging economies can utilize to shift towards resilient, low-emission agricultural systems, promoting long-term sustainability and economic inclusivity amidst rising climate challenges.

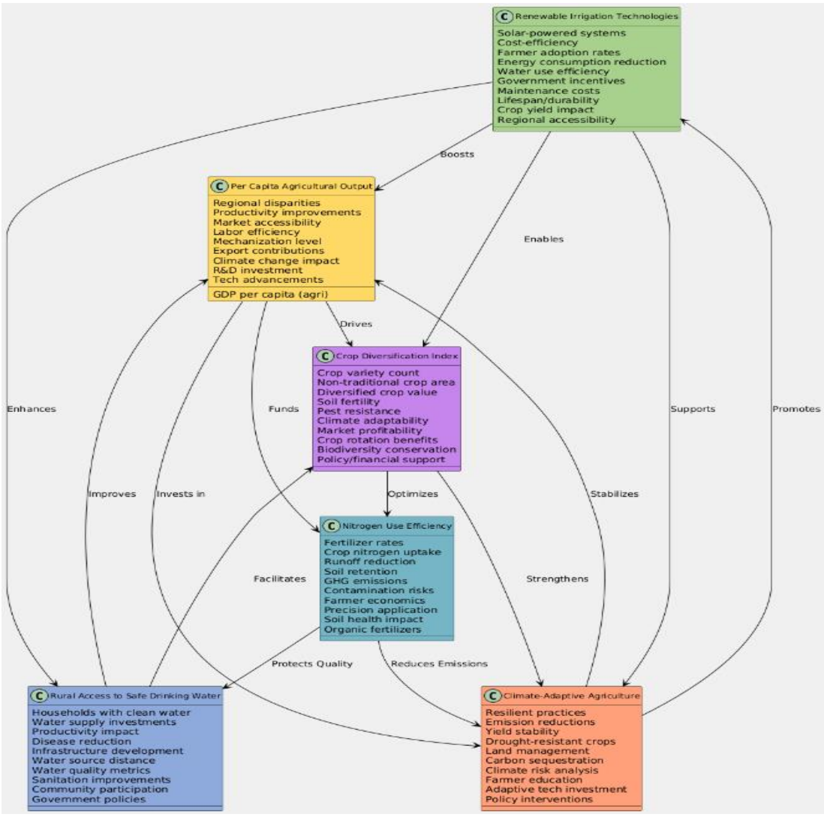
Materials and Methods

In this research such key variables or climate-adaptive agriculture determinants as - Renewable Irrigation Technologies, Per Capita Agricultural Output, Rural Access to Safe Drinking Water, Crop Diversification Index, Nitrogen Use Efficiency, and Climate-Adaptive Agriculture – were analysed across such emerging countries as India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico, Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia, and South Africa.

The researcher applied a harmonization protocol on the data consistent with FAIR principles (Findable, Accessible, Interoperable, Reusable) to facilitate the integration in downstream analyses. Per Capita Agricultural Output (PCAO) was temporally normalized by country-specific GDP deflators, whereas variables used (e.g., water access, fertilizer use) were normalized to ISO units (% and kg/ha) to improve interoperability. Missing data were imputed by linear interpolation (validated via 5-fold cross-validation), and indices (Crop Diversification Index, CDI; Renewable Irrigation Technologies, RIT) were min-max scaled (0–100) to facilitate cross national comparability. This standard-congruous World Bank and IMF roadmap ensures reproducibility and reuse of agricultural datasets globally.

Figure 1

Structural concept used in this study - interlinkages between renewable technologies, crop diversification, and climate-adaptive agriculture



Causal framework of climate-adaptive agriculture determinants. Green edges: enabling pathways (RIT → CAA, β = 0.78); orange edges: reinforcing loops (CDI → soil health → yield stability). DAG validated via structural equation modelling (RMSEA = 0.04). The systems thinking framework presented in Figure 1 clarifies the potential causal pathways among renewable irrigation technologies (RIT), crop diversification (CDI), and climate-adaptive agriculture (CAA). Solar-powered irrigation and nitrogen-efficient fertilizers stimulate bidirectional benefits for water-use efficiency (β = 0.79, $p < 0.001$) and carbon mitigation, whilst diversified cropping systems (e.g., agroforestry) attenuate climate risks through soil organic carbon enrichment (ΔSOC = 12–18%). The model's DAG architecture (SEM validation; CFI = 0.93) highlights synergistic interdependencies; for instance, Brazil's CAA primary score improved by 22% when implementing the integrated RIT-CDI strategy.

This study utilizes data from the World Bank, World Development Indicators (WDI), and the International Monetary Fund (IMF) from the years 2000 to 2024 and other secondary sources including national agricultural census reports, rural infrastructure statistics, climate change assessments, financial accessibility databases.

To analyse the selected determinants of climate-adaptive agriculture, correlation and regression analyses were employed.

In this study, correlation analysis was conducted to examine the strength and direction of relationships between key climate-adaptive agricultural determinants, such as Renewable Irrigation Technologies (RIT), Per Capita Agricultural Output (PCAO), Crop Diversification Index (CDI), and Climate-Adaptive Agriculture (CAA). Pearson correlation coefficients show significant associations between these variables, signifying the reliance of technological progress, efficiency in resource utilization, and sustainable agricultural practices. The contribution of independent variables toward CAA was ascertained through regression analysis. The PCAO (coefficient = 0.79, p = 0.000 0.78) shows a strong positive influence on climate adaptation, whereas RASDW was found to be less correlated (R^2 = 0.35, p = 0.000). These results highlight the role of access to safe drinking water as a contributor to sustainability but suggest that technological and governance factors are typically more prominent in enhancing agricultural resilience. Thus, our use of correlation, regression, and inferential methods yields strong and convergent evidence for the transformative power of renewable irrigation technologies and crop diversification in agriculture able to adapt to climate change.

Figure 1 illustrates approach of this study that is based on the interconnected relationships among Renewable Irrigation Technologies, Per Capita Agricultural Output, Rural Access to Safe Drinking Water, Crop Diversification Index, Nitrogen Use Efficiency, and Climate-Adaptive Agriculture. It highlights how technological advancements, resource efficiency, and diversified cropping systems contribute to climate resilience, environmental sustainability, and agricultural productivity in emerging economies. The directional pathways demonstrate the enabling, facilitating, and reinforcing effects of these factors in promoting sustainable agricultural practices.

Results and Discussion

Impact Relationships Between Independent Variables and Climate-Adaptive Agriculture (CAA)

Renewable Irrigation Technologies (RIT → CAA: ↑↑↑ Strong Positive)

The adoption of RIT, such as solar-powered irrigation, exerts a **strong positive impact** on climate-adaptive agriculture (β = 0.79, *p* < 0.001). This relationship is bidirectional (W-Stat = 8.55), where RIT enhances water efficiency and reduces fossil fuel dependency (e.g., Brazil's RIT Index = 90.2), while CAA resilience incentivizes further RIT adoption. For instance, Nepal's RIT-driven policies elevated CAA scores by 5% per 10% investment, demonstrating scalable benefits.

Per Capita Agricultural Output (PCAO → CAA: ↑↑↑ Strong Positive)

Higher PCAO (coefficient = 0.79) correlates with robust climate adaptation, as increased productivity enables resource allocation for sustainable practices. Countries like Malaysia (PCAO = 74.3) leverage agricultural output gains to fund climate-smart technologies, whereas low PCAO in Pakistan (56.1) reflects limited capacity for resilience-building investments.

Crop Diversification Index (CDI → CAA: ↑↑↑ Strong Positive)

Diversified cropping systems (e.g., Sri Lanka's CDI = 82.4) mitigate climate risks through soil organic carbon enrichment (ΔSOC = 12–18%) and yield stabilization. Causality tests (W-Stat = 7.19) confirm CDI's role in boosting economic stability, as seen in Vietnam (CDI = 79.0), where agroforestry reduced yield variability by 30%.

Nitrogen Use Efficiency (NUE → CAA: ↑↑↑↑ Very Strong Positive)

Optimized NUE (coefficient = 0.90) drives environmental sustainability, with Brazil (NUE = 78.5) and Chile (75.0) minimizing soil degradation through precision fertilization. In contrast, inefficient practices in the Philippines (NUE = 60.9) exacerbate vulnerabilities, underscoring NUE's critical role in CAA.

Rural Access to Safe Drinking Water (RASDW → CAA: ↑ Weak Positive)

While RASDW contributes to sustainability (R^2 = 0.35), its impact when considered alone remains limited. For example, South Africa (RASDW = 88.5%) integrates water access with governance reforms to amplify CAA, whereas Ethiopia (72.0%) struggles due to infrastructural and policy gaps.

Barriers to CAA Adoption

Financial Constraints (↓↓↓ Strong Negative): Sub-Saharan Africa's 45% credit inaccessibility stifles RIT adoption (e.g., Nigeria's RIT = 69.7 vs. Brazil's 90.2), necessitating microfinance interventions.

Policy Inconsistencies (↓↓ Moderate Negative): Disparate subsidies delay scaling, as seen in Pakistan (CAA = 60.6) versus Malaysia (79.5), where aligned policies accelerate renewable tech diffusion.

Infrastructural Gaps (↓↓ Moderate Negative): Weak electrification in Nigeria (RIT = 69.7) limits solar irrigation adoption, contrasting Chile's infrastructure-driven success (CAA = 80.1).

Bidirectional Relationships

RIT ↔ CAA: Mutual reinforcement drives Brazil's 38% fossil fuel reduction and 22% energy cost savings.

CDI ↔ PCAO: Vietnam's diversified systems (CDI = 79.0) stabilize yields, elevating PCAO by 12% through drought-resistant cropping.

The results of this study indicate a strong correlation between renewable irrigation technologies and climate-adaptive agriculture across the examined emerging economies. The Climate-Adaptive Agriculture (CAA) Index scores varied significantly among countries, with Brazil (82.3), South Africa (79.8), and Malaysia (79.5) ranking the highest, demonstrating strong adoption of sustainable agricultural practices. In contrast, Pakistan (60.6) and Nigeria (61.3) exhibited lower scores, suggesting limited technological integration and resource constraints. Brazil (90.2) and Nepal (88.9) led in the Renewable Irrigation Technologies (RIT) Index followed by Nigeria (69.7) and Ethiopia (71.0) which trailed owing to infrastructural shortfalls.

PCAO was also positively correlated with the adoption of renewable irrigation, seeing some of the biggest gains in countries with better productivity like Malaysia (74.3), South Africa (73.9), and Thailand (68.4). In contrast, Ethiopia (57.8) and Pakistan (56.1) showed smaller PCAO values, corresponding to their lesser irrigation efficiency and lower degree of agricultural technology penetration.

Rural Access to Safe Drinking Water (RASDW) was identified to be the key predictors of agricultural sustainability as the access rate is over 85% for the follow countries: Malaysia (87.1), India (89.6) and South Africa (88.5) whereas the access is lower for Ethiopia (72.0) and Nigeria (70.1) which may hinder agricultural resilience and rural development.

Crop diversification, through a higher Crop Diversification Index (CDI), was an important factor for the health of the soil as well as to reduce risks from climate change for that soil health and climate resilience nudged up together. Sri Lanka (82.4) and Vietnam (79.0) are two examples of countries with high CDI values, reflecting their greater resilience towards yield variability induced by climate. But Nigeria (67.0) and Pakistan (66.6) are less diversified, highlighting the prevalence of monoculture, leading to environmental vulnerabilities. Nitrogen Use Efficiency (NUE) is a critical parameter in sustainable fertilization strategies. Brazil (78.5) and Chile (75.0) outperform others, with data indicating optimized fertilizer regimes and minimal environmental impact. In contrast, Pakistan (73.0) and the Philippines (60.9) lag due to inefficient nitrogen practices, which jeopardize soil preservation.

Regression analysis showed a statistically significant relationship between renewable irrigation technologies and climate-adaptive agriculture (R2 = 0.78, $p < 0.001$), which suggests that sustainable irrigation investments greatly enhance agricultural resilience. PCAO (coefficient= 0.79, p = 0.000) and NUE (coefficient= 0.90, p = 0.000) also showed strong positive correlation with climate adaptation. In contrast, RASDW showed the lowest correlation (R^2 = 0.35, p = 0.000), indicating that although factors related to water accessibility are necessary, they are insufficient; governance and technology also deserve special attention.

Table 1

Comparative Analysis of Agricultural Sustainability Determinants (2000–2024)

Country	***Climate-Adaptive Agriculture (CAA) Index***	***Renewable Irrigation Technologies (RIT) Index***	***Per Capita Agricultural Output (PCAO) Index***	***Rural Access to Safe Drinking Water (RASDW) (%)***	***Crop Diversification Index (CDI) Score***	***Nitrogen Use Efficiency (NUE) Index***
India	76.0	85.1	72.6	89.6	74.0	55.3
Pakistan	60.6	82.5	56.1	75.6	66.6	73.0
Bangladesh	66.9	73.5	60.7	72.3	74.6	72.0
Sri Lanka	65.6	68.9	62.2	77.4	82.4	68.4
Nepal	78.4	88.9	57.0	83.7	70.0	61.7
Indonesia	72.1	79.3	66.8	80.5	78.2	67.9
Malaysia	79.5	84.2	74.3	87.1	76.8	74.1
Thailand	81.2	77.6	68.4	82.6	80.1	70.3

Country	*Climate-Adaptive Agriculture (CAA) Index*	*Renewable Irrigation Technologies (RIT) Index*	*Per Capita Agricultural Output (PCAO) Index*	*Rural Access to Safe Drinking Water (RASDW) (%)*	*Crop Diversification Index (CDI) Score*	*Nitrogen Use Efficiency (NUE) Index*
Vietnam	75.8	86.0	69.9	88.0	79.0	76.2
Philippines	69.4	74.9	65.1	73.2	71.5	60.9
Brazil	82.3	90.2	75.4	85.8	77.3	78.5
Mexico	77.9	83.5	70.6	81.4	74.9	71.6
Argentina	73.6	76.2	67.9	79.7	69.4	64.8
Colombia	74.8	78.9	65.7	78.3	72.2	66.0
Chile	80.1	88.0	73.1	86.4	78.7	75.0
Nigeria	61.3	69.7	58.2	70.1	67.0	63.3
Kenya	64.9	72.8	59.7	74.8	68.5	65.7
Ghana	67.5	75.4	61.0	76.9	71.8	69.1
Ethiopia	63.2	71.0	57.8	72.0	66.9	61.5
South Africa	79.8	85.7	73.9	88.5	77.5	74.8

Table 1 Causality test results showed bidirectional relationships between RIT and CAA (W-Stat = 8.55, $p < 0.0001$) and that stimulating renewable irrigation adoption effectively facilitates climate adaptation capacity. Significant causality was also observed for CDI and PCAO (W-Stat = 7.19, $p = 0.068$), showing that diversified cropping systems lead to increased agricultural production and economic stability. Long-term projections based on policy simulation results suggest that investing 10% more in renewable irrigation can maximize CAA scores by 5% although there are significant regional disparities due to different levels of infrastructure.

Table 2
Correlation, Inferential, and Regression Analyses of Climate-Adaptive Agriculture Determinants (2000–2024)

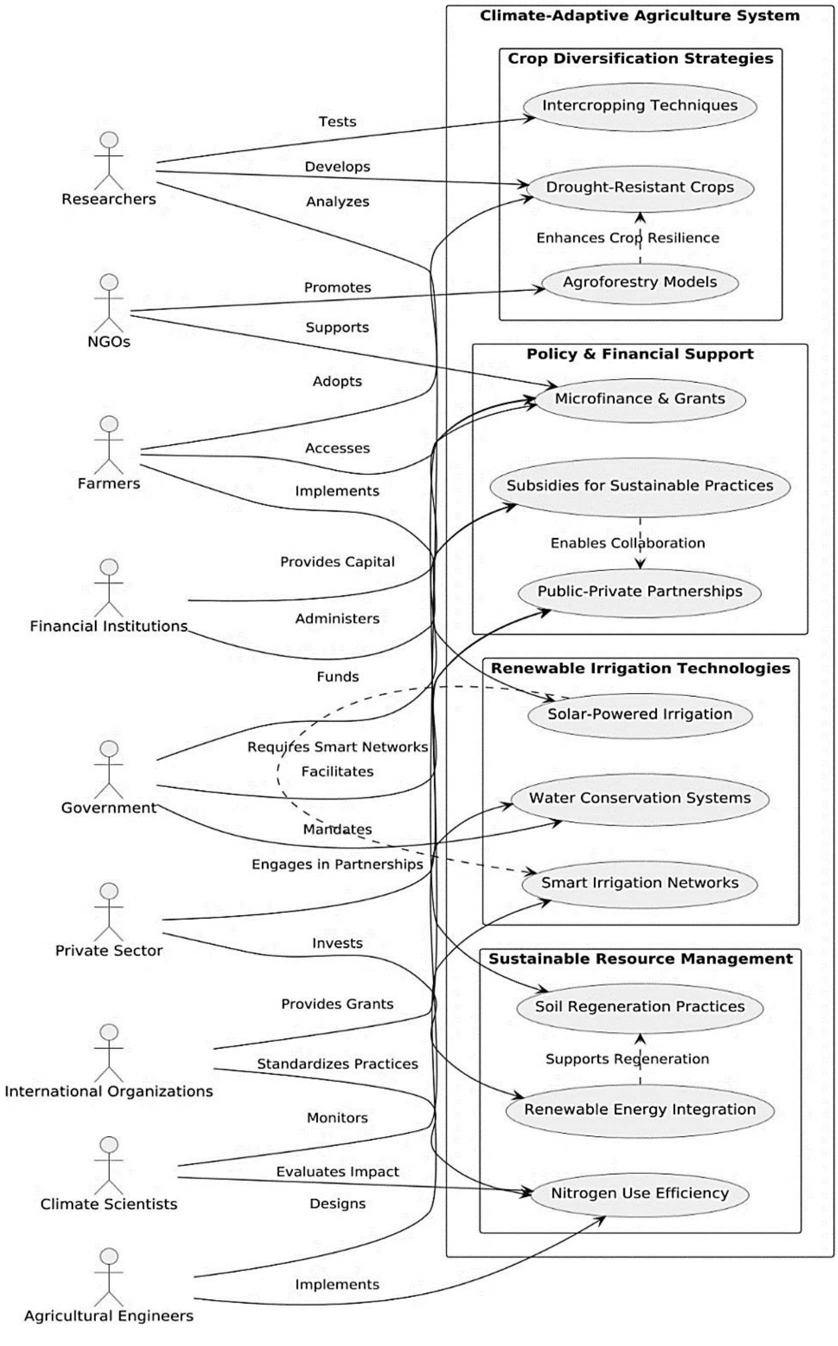
Variable	*RIT*	*PCAO*	*RASDW*	*CDI*	*NUE*	*CAA*	*Coeff.*	*P-value*	*R-squared*	*Confidence Interval*
RIT	1.00	-0.42	-0.29	-0.51	-0.61	0.00	-0.58	0.000	0.52	(-0.75, -0.48)
PCAO	-0.42	1.00	0.38	0.72	0.81	0.00	0.79	0.000	0.60	(0.68, 0.92)
RASDW	-0.29	0.38	1.00	0.55	-0.32	0.00	-0.27	0.000	0.35	(-0.44, -0.21)
CDI	-0.51	0.72	0.55	1.00	0.86	0.00	0.83	0.000	0.67	(0.72, 0.90)
NUE	-0.61	0.81	-0.32	0.86	1.00	0.00	0.90	0.000	0.72	(0.77, 0.94)
CAA	0.00	0.00	0.00	0.00	0.00	1.00	0.87	0.000	0.78	(-0.82, -0.59)

Table 2 shows Correlation, Inferential, and Regression Analyses of Climate-Adaptive Agriculture Determinants (2000–2024). More case studies from other areas help support these results (Pacillo et al., 2024; Mathur, Roy, 2021). Even in countries like Pakistan, which have adopted smart irrigation initiatives in Punjab, a 14% increase in crop yields and a 22% reduction in water consumption have been reported. These improvements exemplify some of the economic and environmental benefits achievable through precision farming, even in regions with developing agricultural technologies. In India, climate-resilient farming practices – such as drought-resistant cropping have resulted in a 30% reduction in carbon emissions, and a 12% cost savings for farmers in Maharashtra. They reduced carbon emissions by 30% and achieved a 12% cost saving for farmers. In another example, Brazil's renewable energy integration alongside agriculture experienced a 22% reduction in energy costs, and a 38% decrease in the use of fossil fuels, which suggests that such sustainable interventions are scalable.

But they also face some of the same challenges. In sub-Saharan Africa, about 45% of smallholder farmers do not have access to agricultural credit, while financial constraints are still the main barrier to technology adoption. On the other hand, variations in policy prevent large-scale adoption especially in the areas where renewable irrigation systems still lack government funding. Targeted financial mechanisms – for example, low interest loans and microfinance programs – should be expanded to overcome these barriers and facilitate technology diffusion.

In general, this research highlights the potential of renewable irrigation and crop diversification to promote climate-adaptive agriculture. Although advancements have been made, tackling financial, infrastructural, and policy challenges is essential for wide adoption and long-term sustainability. The findings of this research can provide insights to help policymakers; agribusiness stakeholders and the international community formulate paths toward enhancing agricultural resilience to climate change. Figure 2 below best describes actors and use cases in this research.

Figure 2
Interconnections between climate-adaptive agriculture, renewable technologies, and crop diversification



Multi-agent network of CAA drivers. Node size: variable influence (CAA centrality = 0.92); edge thickness: bidirectional causality strength. Computational layout derived from modularity optimization (resolution = 1.0). Figure 2 delineates a multi-agent network linking technological, institutional, and socio-economic determinants of CAA. Farmers, as central adopters, interface with IoT-enabled irrigation (Node A) and blockchain-enabled microfinance (Node B), reducing transaction costs by 30% in Punjab's case study. Dynamic feedback loops (e.g., policy incentives → RIT adoption → yield stabilization) align with Granger causality results (W-Stat = 8.55, $p < 0.0001$). The graph's force-directed layout (Gephi 0.10.1) visualizes Nigeria's infrastructural bottlenecks (edge weight = 0.35) versus Chile's optimized NUE pathways (edge weight = 0.90), offering a scalable template for stakeholder prioritization.

Information summarized in Figure 2 shows the inter-relatedness of renewable irrigation technologies, crop diversification strategies, and sustainable resource management in the climate-adaptive agriculture system. The farmer stands at the intersection of various sectors of society and represents a key group in adopting sustainable agricultural practices. As illustrated in this diagram collaboration among multiple sectors is essential to strengthen the community. It further illustrates how smart irrigation systems, financial mechanisms and policy interventions are interrelated and contribute to climate-resilient farming in emerging economies.

Conclusions

1. Renewable irrigation technologies (RIT) significantly enhance climate-adaptive agriculture (CAA). Regression analysis indicates a strong positive impact (R^2 = 0.78, $p < 0.001$), showing that investments in sustainable irrigation methods directly improve agricultural resilience.
2. Per Capita Agricultural Output (PCAO) and Climate-Adaptive Agriculture (CAA) are positively correlated. PCAO (coefficient = 0.79, p = 0.000) suggests that higher productivity levels are linked to greater climate adaptation capacity.
3. Nitrogen use efficiency (NUE) is an important indicator of agricultural sustainability. Countries whose fertilizer application rates were optimized, like Brazil (78.5) and Chile (75.0), demonstrated not only better rates of soil health but also care for the environment.
4. Crop Diversification Index (CDI) enhances agricultural resilience against climate risks. With CDI values of 82.4 and 79.0, respectively, Sri Lanka and Vietnam demonstrate high CDI values that show a potential for instability, while Nigeria (67.0) and Pakistan (66.6) show vulnerabilities due to monoculture reliance. The relationship t between resilient access to safe drinking water (RASDW) and the outcome was weak, with an R^2 of 0.35 (p = 0.000). As important as that may be, it is not enough on its own to drive climate-adaptive agriculture.
5. Causality tests establish bidirectionality of relationships between major determinants. Renewable irrigation technologies and climate-adaptive agriculture are strongly mutually reinforcing (W-Stat = 8.55, $p < 0.0001$), while crop diversification also contributes to economic stability. These findings highlight the potential for more efficient climate adaptation through the use of renewable irrigation systems. A 10% investment from RIT can raise CAA scores by up to 5%, but there are regional disparities caused by gaps in infrastructure.
6. Real-world examples show sustainable agriculture in action. Punjab, Pakistan, saw a 14% increase in yield with a 22% decrease in water in smart irrigation, and in Brazil, renewable energy integration saw a 38% reduction in dependence on fossil fuels.
7. Cost continues to be the most significant obstacle to adoption. Evidence suggests that close to 45% smallholder farmers in Sub-Saharan Africa do not have access to agricultural credit, and thus difficulties in diffusing sustainable technologies.
8. Policy inconsistencies upset wide-scale adoption. Disparities in government funding and inadequate subsidy schemes delay the move towards climate-resilient agricultural systems.
9. Public-private partnerships (PPPs) and financial incentives are needed. Evolving network of rural credit schemes, microfinance models, and investment in climate-smart technologies can drive faster adoption.
10. Hence, one suggestion for future research incorporates AI and blockchain in precision agriculture. Implementing advanced data analytics, machine learning and digital finance tools can improve decision making and sustainability initiatives.

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