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ORIGINAL

Enhancing Agricultural Resilience in Malawi: The Impact of Simple Irrigation Adoption and AI-Driven Solutions on Smallholder Farmers in Kamudidi

Fortalecimiento de la Resiliencia Agrícola en Malawi: El Impacto de la Adopción de Riego Simple y Soluciones Basadas en Inteligencia Artificial para Pequeños Agricultores en Kamudidi

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ABSTRACT

Agriculture is the backbone of Malawi's economy, yet smallholder farmers face significant challenges due to erratic rainfall, water scarcity, and inefficient irrigation practices. This study examines the impact of simple irrigation adoption on maize productivity and household income among smallholder farmers in Kamudidi, Malawi. Using Propensity Score Matching (PSM), we compare farmers who adopt simple irrigation with those who rely on traditional rain-fed agriculture. The results show that irrigation adapters produce, on average, 244,21 more kilograms of maize and experience a 6562,79 Malawian Kwacha increase in household total expenditure compared to non-adopters. These findings underscore the role of irrigation in improving food security and economic stability. Furthermore, the study explores the potential of Artificial Intelligence (AI) to optimize irrigation practices through predictive analytics, weather forecasting, and smart water management. While AI-driven solutions can enhance decision-making and resource allocation, challenges such as limited digital literacy, infrastructure constraints, and financial barriers hinder widespread adoption. The study highlights the need for targeted policies, including access to affordable credit, farmer training programs, and investment in digital infrastructure, to facilitate both irrigation and AI adoption. Overall, the research provides valuable insights into how simple irrigation and AI-driven solutions can enhance agricultural resilience. Policymakers and development agencies should prioritize interventions that improve irrigation access and integrate AI to support smallholder farmers, ultimately fostering sustainable agricultural growth and rural development in Malawi.

Keywords: Smallholder Farmers; Simple Irrigation; Maize Productivity; Household Income; Artificial Intelligence; Agricultural Resilience.

RESUMEN

La agricultura es la columna vertebral de la economía de Malawi; sin embargo, los pequeños agricultores enfrentan desafíos significativos debido a las lluvias erráticas, la escasez de agua y las prácticas de riego ineficientes. Este estudio examina el impacto de la adopción de riego simple en la productividad del maíz y los ingresos familiares entre los pequeños agricultores de Kamudidi, Malawi. Utilizando el método de Emparejamiento por Puntaje de Propensión (PSM), comparamos a los agricultores que adoptan riego simple con aquellos que dependen de la agricultura tradicional de secano. Los resultados muestran que los adoptantes de riego producen, en promedio, 244,21 unidades más de maíz y experimentan un aumento de 6562,79 en el gasto total del hogar en comparación con los no adoptantes. Estos hallazgos subrayan el papel del riego en la mejora de la seguridad alimentaria y la estabilidad económica. Además, el estudio explora el potencial de la Inteligencia Artificial (IA) para optimizar las prácticas de riego mediante análisis predictivos, pronósticos climáticos y gestión inteligente del agua. Si bien las soluciones basadas en IA pueden mejorar la toma de decisiones y la asignación de recursos, desafíos como la baja alfabetización digital, las limitaciones de infraestructura y las barreras financieras dificultan su adopción generalizada. El estudio destaca la necesidad de políticas específicas, como el acceso a créditos asequibles, programas de capacitación para agricultores e inversión en infraestructura digital, para facilitar la adopción tanto del riego como de la IA. En general, la investigación proporciona información valiosa sobre cómo el riego simple y las soluciones basadas en IA pueden fortalecer la resiliencia agrícola. Los formuladores de políticas y las agencias de desarrollo deberían priorizar intervenciones que mejoren el acceso al riego e integren la IA para apoyar a los pequeños agricultores, fomentando finalmente un crecimiento agrícola sostenible y el desarrollo rural en Malawi.

Palabras clave: Pequeños Agricultores; Riego Simple; Productividad De Maíz; Ingresos Familiares; Inteligencia Artificial; Resiliencia Agrícola.

INTRODUCTION

Agriculture is the backbone of Malawi's economy, with smallholder farmers playing a critical role in food production and rural livelihoods. However, limited access to reliable water sources, erratic rainfall, and inefficient irrigation methods poses significant challenges to agricultural productivity. To address these issues, simple irrigation techniques, combined with Artificial Intelligence (AI)-driven insights, offer a promising solution for optimizing water use and enhancing yields. This research investigates the impact of adopting simple irrigation systems among smallholder farmers in Kamudidi, Malawi, focusing on how AI can enhance decision-making, resource allocation, and productivity.[1,2,3]

Despite the potential benefits of simple irrigation, adoption rates remain low among smallholder farmers. Many farmers still rely on traditional rain-fed agriculture, making them highly vulnerable to climate variability and prolonged droughts. This study examines the key factors influencing the adoption of small-scale irrigation, including financial constraints, access to information, land tenure security, and technical knowledge. Understanding these factors can help policymakers and development agencies design targeted interventions to promote irrigation adoption and improve agricultural resilience.[4,5,6]

A crucial gap in existing research is the comparative analysis of household expenditure and maize production between farmers who adopt simple irrigation and those who do not. While some studies highlight the benefits of irrigation in general, limited research focuses on smallholder farmers in Kamudidi and how irrigation adoption directly influences household income, food security, and economic stability. This study seeks to fill this gap by assessing whether simple irrigation adopters experience higher maize yields and lower household food expenditures compared to non-adopters.[7,8,9,10]

This study explores AI's role in supporting smallholder farmers through predictive analytics, weather forecasting, and smart irrigation management, enabling data-driven decisions on water usage, crop selection, and pest control to enhance efficiency and reduce losses. However, challenges such as digital literacy, infrastructure limitations, and affordability must be addressed for widespread adoption.[6,11,12] By analyzing household expenditure, maize production, and irrigation adoption factors, the research provides insights for policymakers, researchers, and agricultural stakeholders to develop strategies that enhance irrigation adoption, improve food security, and promote sustainable farming in Kamudidi and similar rural areas.

Literature Review

Agriculture is the backbone of Malawi's economy, with smallholder farmers contributing significantly to food production and rural livelihoods. However, these farmers face persistent challenges, including erratic rainfall, water scarcity, and inefficient irrigation practices, which hinder productivity and exacerbate food insecurity. Traditional rain-fed agriculture, which dominates the sector, leaves farmers highly vulnerable to climate variability and prolonged droughts. In response, simple irrigation techniques have emerged as a viable solution to improve water access and crop yields. Studies have shown that small-scale irrigation can enhance agricultural productivity, reduce poverty, and increase resilience to climate shocks. Despite these benefits, adoption rates remain low due to financial constraints, lack of technical knowledge, and limited access to information.

Recent advancements in Artificial Intelligence (AI) offer new opportunities to address these challenges.[13,14,15] AI-driven solutions, such as predictive analytics, smart irrigation systems, and remote sensing, can optimize water use, improve crop management, and provide real-time decision-making support. For instance, AI-powered weather forecasting can help farmers anticipate droughts and plan irrigation schedules more effectively, while IoT sensors can monitor soil moisture and crop health in real-time. These technologies have the potential to bridge the gap between resource-constrained smallholder farmers and modern agricultural practices, enabling them to achieve higher yields and greater economic stability.

However, the adoption of AI in agriculture faces significant barriers, particularly in low-resource settings like Kamudidi, Malawi. Limited digital literacy, inadequate infrastructure, and high costs hinder the widespread use of AI-driven solutions. Additionally, there is a lack of localized AI models tailored to the specific agroecological conditions of smallholder farmers.[14,16,17,18] Addressing these challenges requires a multi-faceted approach, including investments in digital infrastructure, farmer training programs, and policy support to make AI technologies more accessible and affordable. This study builds on existing research by exploring the impact of simple irrigation adoption and AI-driven solutions on smallholder farmers in Kamudidi. It seeks to fill a critical gap in the literature by examining how these technologies can enhance agricultural resilience, improve food security, and promote sustainable farming practices in a region characterized by high climate vulnerability and limited resources (table 1).

Table 1. Existing Simple Irrigation Practices and Crops Among Smallholder Farmers in Malawi

Category	Specific Crops/Irrigation Methods	Primary Use/Description	Importance/Advantages
Staple Crops	Maize, Cassava, Sweet Potatoes	Food security, household consumption	Maize provides the bulk of dietary calories.
Cash Crops	Tobacco, Cotton, Tea, Sugarcane	Income generation, export	Tobacco is Malawi's largest export crop, contributing significantly to GDP.
Legumes	Beans, Groundnuts, Soybeans, Cowpeas	Food security, soil fertility	Vital for protein intake and improving soil nitrogen levels.
Vegetables	Tomatoes, Onions, Cabbage, Leafy Greens	Household consumption, local markets	Provide essential nutrients and additional income for farmers.
Fruits	Bananas, Mangoes, Citrus, Papayas	Household consumption, local markets	Important for nutrition and diversifying income sources.
Tubers and Roots	Irish Potatoes, Yams, Taro	Food security, household consumption	Drought-resistant and provide food during lean seasons.
Cereals	Rice, Sorghum, Millet	Food security, alternative staples	Suitable for areas where maize production is less viable.
Watering Cans	Manual irrigation using watering cans filled from wells, rivers, or boreholes	Low-cost, easy to use, and widely available	Labor-intensive, inefficient for large farms, and time-consuming.
Treadle Pumps	Foot-operated pumps used to lift water from shallow wells, streams, or rivers for irrigation	Affordable, increases water accessibility, and does not require fuel	Physically demanding, limited to areas with water sources, and requires maintenance.
Bucket Irrigation	Water drawn manually from wells or streams and applied directly to crops using buckets	Simple, low-cost, and accessible to all farmers	Very labor-intensive, not efficient for larger plots, and high water loss.
Drip Irrigation	Pipes with small holes deliver water directly to plant roots, minimizing waste	Efficient water use, reduces soil erosion, and enhances crop yield	High initial setup cost, requires technical knowledge, and may need maintenance.
Furrow Irrigation	Water directed through small trenches between crop rows	Simple, effective for row crops, and requires minimal equipment	High water usage, potential soil erosion, and uneven water distribution.
Gravity-Fed Systems	Water channeled from higher elevation sources to lower agricultural fields through pipes or ditches	Energy-efficient, no need for fuel or electricity, and suitable for hilly areas	Limited to areas with suitable topography, risk of water loss, and maintenance required.
Solar-Powered Pumps	Pumps powered by solar panels lift water from boreholes, rivers, or reservoirs for irrigation	Sustainable, reduces reliance on fuel, and efficient for water lifting	High initial investment, requires technical expertise, and dependent on sunlight availability.

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METHOD

Research Design

This study employs a mixed-methods approach, integrating quantitative and qualitative techniques to assess the impact of simple irrigation adoption on maize productivity and household income among smallholder farmers in Kamudidi, Malawi. A quasi-experimental design is utilized, applying Propensity Score Matching (PSM) to mitigate selection bias when comparing irrigation adopters (treatment group) with non-adopters (control group). Logistic regression is employed to identify factors influencing irrigation adoption. Additionally, qualitative methods such as Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) are incorporated to gain deeper insights into farmers' experiences, perceptions, and challenges regarding irrigation adoption.

Data Processing

The data processing phase involves cleaning, coding, and organizing both primary and secondary data sources. Household survey responses are checked for consistency, and missing values are addressed using imputation techniques where necessary. The qualitative data from FGDs and KIIs are transcribed, coded thematically, and categorized for analysis. Climate and agricultural reports are digitized and structured for integration into the overall dataset. The processed data is then standardized to facilitate statistical analysis.

Statistical Analysis

Quantitative data analysis includes descriptive statistics, impact evaluation, and regression modeling. Descriptive statistics summarize key variables, with measures such as mean and standard deviation, while data visualization (histograms and boxplots) provides comparative insights. PSM is used to estimate the Average Treatment Effect on the Treated (ATT), ensuring a balanced comparison between adopters and non-adopters. Logistic regression identifies determinants of irrigation adoption, and hypothesis testing is conducted to validate findings. Qualitative data undergoes thematic analysis to extract key themes related to farmer experiences, challenges, and policy recommendations.

Ethics

Ethical considerations are upheld throughout the study. Informed consent is obtained from all participants, ensuring they are aware of the study's purpose and their right to withdraw at any time. Confidentiality and anonymity of respondents are maintained by using coded identifiers. Ethical clearance is sought from relevant institutional review boards, and data collection follows protocols that respect local customs and norms. The study prioritizes transparency, ensuring that findings are shared with stakeholders, including farmers and policymakers, to foster informed decision-making in agricultural practices.

RESULTS

Impacts of Simple Irrigation Smallholder Farmers' Households

The Propensity Score Matching (PSM) analysis estimated the impact of adopting simple irrigation on crop productivity and household income, using total household expenditure as a proxy for financial well-being. By matching farmers who adopted simple irrigation (treatment group) with those who did not (control group) based on similar socio-economic and farm characteristics, we ensured that the comparisons were made between farmers with comparable backgrounds. After matching, the average outcomes between the two groups were assessed to measure the effect of irrigation adoption.

The results indicate that farmers who adopted simple irrigation produced, on average, 244,21 more kilograms of maize than their matched non-adopter counterparts. This suggests that simple irrigation significantly enhances maize yields, likely due to improved water availability during critical growth periods. Farmers without irrigation may experience lower productivity due to reliance on unpredictable rainfall patterns, while irrigation adopters benefit from a consistent moisture supply, reducing the risk of drought stress. Additionally, irrigation allows for more efficient use of inputs such as fertilizers and improved seeds, further boosting production.[18,19,20,21] Some farmers may also cultivate multiple cropping cycles per year, leading to increased overall output.

In terms of household income, the analysis found that irrigation adopters had, on average, 6562,79 Malawian Kwacha higher total expenditures compared to non-adopters. This implies that households using simple irrigation enjoy better financial well-being, as they can afford more goods and services. Increased maize production directly translates into higher household income, allowing families to spend more on essentials such as food, education, and healthcare.

Factors Affection Simple Irrigation Adoption

The logistic regression analysis presented in Table 2 examines the factors influencing smallholder farmers' adoption of simple irrigation practices in the study area. The model is statistically significant (Wald $chi^2(10) = 27,34$, $p = 0,0112$), explaining approximately 9,65 % of the variance in adoption behaviour (Pseudo R2 =

0,0965). The results reveal several key findings that have important implications for policy and practice. Age has a highly significant positive effect on the adoption of simple irrigation practices (p < 0,001, Coef. = 0,0857). Older farmers are more likely to adopt irrigation technologies, possibly due to their accumulated experience, financial stability, and greater exposure to agricultural innovations over time. This finding aligns with studies that highlight the role of experience in technology adoption. (8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24)

However, farming experience has a significant negative effect on adoption (p < 0,001, Coef. = -0,0871), which contrasts with expectations. This could indicate that more experienced farmers may be resistant to change or prefer traditional farming methods. Alternatively, they might perceive irrigation technologies as unnecessary if they have historically relied on rain-fed agriculture. This finding suggests a need for targeted extension services to address the scepticism of experienced farmers. Income has a marginally significant positive effect on adoption (p < 0,10, Coef. = 0,000035). Farmers with higher incomes are more likely to invest in irrigation technologies, as they have the financial resources to cover initial costs. This underscores the importance of affordability and access to credit in promoting irrigation adoption. Gender, on the other hand, is not statistically significant at the 5 % level, though it approaches significance at the 10 % level (p = 0,066).

This suggests that male and female farmers may have similar adoption rates, possibly due to gender-inclusive agricultural policies or programs in the study area. Education level does not significantly influence adoption (p = 0,187), which could be because formal education does not always translate into practical knowledge of irrigation technologies. Alternatively, farmers may rely more on experiential learning or community-based knowledge than formal education. Household size (p = 0,672) and farm size (p = 0,655) also do not significantly influence adoption. This could be because smallholder farmers, regardless of farm size, face similar constraints (e.g., access to water, credit, and technology). Access to climate information (p = 0,456) and extension services (p = 0,951) do not significantly affect adoption either. The non-significance of access to climate information may indicate that farmers do not perceive it as directly linked to irrigation decisions or that the information provided is not actionable. The non-significance of extension services could reflect inefficiencies in extension programs, such as inadequate training on irrigation technologies or poor dissemination of information.

These findings have several policy and practical implications. First, targeted interventions are needed for older and experienced farmers. While older farmers are more likely to adopt irrigation technologies, experienced farmers are less likely. Policymakers should design interventions that address these groups' specific needs and concerns (Table 2). For example, demonstration farms and peer-to-peer learning programs could help experienced farmers see the benefits of irrigation. Second, financial support mechanisms, such as subsidies, low-interest loans, or grants, are crucial to making irrigation technologies more accessible to low-income farmers.

Third, the non-significance of extension services suggests a need to improve their effectiveness. Extension programs should focus on practical, hands-on training and provide actionable information tailored to local conditions. Fourth, the non-significance of gender indicates that both men and women are equally likely to adopt irrigation technologies. Policymakers should continue to promote gender-inclusive programs to ensure equitable access to resources and training. Finally, while access to climate information is not significant, it remains a critical component of climate-smart agriculture. Efforts should be made to make climate information more relevant and actionable for farmers, linking it directly to irrigation decisions.

The study has several limitations. The low Pseudo R^2 value (9,65 %) indicates that other factors not included in the model (e.g., social networks, cultural beliefs, or access to water sources) may play a significant role in adoption behaviour. Additionally, the study relies on cross-sectional data, which limits the ability to establish causal relationships. Longitudinal studies are needed to better understand the dynamics of adoption over time. Finally, the results are specific to the study area and may not be generalizable to other regions with different socioeconomic, cultural, or environmental conditions.

Table 2. Factors affecting smallholder farmers' adoption of simple irrigation Logistic regression

Variable	Coef.	Robust Std. Err.	z	P>z	[95 % Conf. Interval]
Age	0,085697***	0,0222	3,8600	0,0000	[0,0422, 0,1292]
Gender	0,017260	0,4056	0,4400	0,0660	[-0,7776, 0,8122]
Marital_status	-0,178756	0,1399	-1,2800	0,2010	[-0,4530, 0,0955]
Education	-0,051048	0,0387	-1,3200	0,1870	[-0,1270, 0,0249]
Farming_experience	-0,087116***	0,0200	-4,3600	0,0000	[-0,1263, -0,0480]
Household_size	-0,027906	0,0658	-0,4200	0,6720	[-0,1569, 0,1011]
Income	0,000035*	0,00002	1,8500	0,0640	[0,0000, 0,0001]
Fertilizer	0,000727	0,0007	1,1200	0,2630	[-0,0005, 0,0020]

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Farm_size	-0,020060	0,0449	-0,4500	0,6550	[-0,1082, 0,0680]
Livestockqt	0,006734	0,0083	0,8100	0,4180	[-0,0095, 0,0230]
Credit_access	-0,150782	0,2405	-0,6300	0,5310	[-0,6221, 0,3205]
Access_to_climate_inform	-0,441080	0,5920	-0,7500	0,4560	[-1,6014, 0,7192]
Extension_services	-0,018090	0,2964	-0,0600	0,9510	[-0,5989, 0,5628]
_cons	-0,416121	1,0016	-0,4200	0,6780	[-2,3792, 1,5470]
Number of Obs = 194; Wald $chi^2(10)$ = 27,34; Prob > chi^2 = 0,0112; Log Pseudolikelihood = -204,0124; Pseudo R^2 = 0,0965					
Significance codes: *** <1 %, ** <5 %, * <10 %; Author's calculation using Stata 15MP					

DISCUSSION

The findings of this study demonstrate that simple irrigation adoption significantly improves both maize productivity and household income among smallholder farmers in Kamudidi, Malawi. The Propensity Score Matching (PSM) analysis shows that irrigation adopters produce an average of 244,21 more units of maize than non-adopters. This aligns with previous studies highlighting the role of small-scale irrigation in mitigating rainfall variability and improving yields.[1] Consistent water availability allows farmers to optimize input use, reduce drought-related losses, and potentially engage in multiple cropping cycles per year.[2]

In terms of economic impact, irrigation adopters experience an increase of 6562,79 Malawian Kwacha in household total expenditure, serving as a proxy for income.[18,19,20] These findings support earlier research indicating that irrigation not only boosts crop yields but also enhances farm profitability and overall household welfare.[3] Increased farm revenues enable farmers to afford better nutrition, education, and healthcare services, reducing vulnerability to economic shocks.[4] Furthermore, access to irrigation reduces dependence on rain-fed agriculture, improving resilience against climate variability and market fluctuations.[5]

Despite these benefits, several challenges hinder widespread irrigation adoption. Logistic regression analysis reveals that income and age positively influence adoption, suggesting that older, wealthier farmers are more likely to invest in irrigation technologies.[6] Conversely, farming experience has a negative association with adoption, possibly indicating resistance among long-established farmers who rely on traditional methods.[7] Similar findings have been reported in studies where experienced farmers show reluctance towards new technologies due to scepticism or risk aversion.[8] Additionally, limited access to credit remains a barrier, as irrigation infrastructure requires initial investment beyond the means of many smallholder farmers.[9]

The study also highlights the potential of Artificial Intelligence (AI) in optimizing irrigation use through predictive analytics and real-time monitoring.[1,2,3] However, challenges such as digital literacy, affordability, and infrastructure limitations must be addressed for AI-driven solutions to be accessible to rural farmers.[10] The results underscore the transformative impact of simple irrigation on food security and economic stability in Malawi. Policies should focus on expanding irrigation access, improving financial support mechanisms, and integrating digital innovations to enhance agricultural productivity and resilience.[22,22,23,24]

Policy support; is another critical factor. Governments and development agencies should promote AI adoption through subsidies, incentives, and public-private partnerships. By addressing these barriers, AI can become a powerful tool for smallholder farmers in Kamudidi, enabling them to achieve greater agricultural productivity, food security, and economic resilience. The integration of AI into irrigation systems represents a promising pathway toward sustainable farming practices and improved livelihoods in the region.

CONCLUSION

This study provides empirical evidence on the impact of simple irrigation adoption among smallholder farmers in Kamudidi, Malawi, highlighting its role in agricultural productivity, household income, and food security. Propensity Score Matching (PSM) analysis shows that irrigation adopters produce 244,21 more kilograms of maize than non-adopters, emphasizing its importance in stabilizing output, mitigating erratic rainfall effects, and enabling multiple cropping cycles. By ensuring a reliable water supply, irrigation allows farmers to optimize inputs and reduce climate vulnerability. The study also finds that irrigation adoption boosts household economic well-being, as reflected in a 6562,79 Malawian Kwacha increase in household total expenditure.

This suggests that higher farm productivity translates into greater income, enabling investments in food, education, and healthcare. Additionally, irrigation reduces reliance on rain-fed agriculture, strengthening resilience against climate variability and market fluctuations. Despite these benefits, barriers to adoption persist. Logistic regression analysis indicates that age and income positively influence adoption, whereas farming experience negatively correlates, suggesting resistance among traditional farmers. Limited access to credit further restricts investment in irrigation infrastructure. Addressing these challenges requires targeted policies, including subsidies, affordable loans, and farmer training programs to enhance irrigation awareness and adoption.

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The study also highlights the potential of AI-driven solutions in optimizing irrigation through predictive analytics and smart irrigation management. AI can enhance decision-making and water efficiency, but digital literacy, affordability, and infrastructure limitations must be addressed for accessibility. In conclusion, expanding irrigation adoption is essential for agricultural productivity, economic stability, and food security in Malawi. Policymakers and development agencies should focus on enhancing irrigation access, financial support mechanisms, and digital innovations to build a resilient and sustainable agricultural sector.

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