Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2025.v07i01.001

OPEN ACCESS

ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Original Research Article

Modern Versus Traditional Irrigation Systems: Implications for Technical Efficiency and Input-Output Relationship in Northern Tanzania's Horticulture Sector

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Article History
Received: 02.01.2025
Accepted: 07.02.2025
Published: 10.02.2025

Abstract: This study evaluates the technical efficiency (TE) of modern and traditional irrigation methods and their subsequent impact on farm productivity, profitability, and sustainability. The research uses a sample of 540 smallholder farmers from water stress region of northern Tanzania. The study reveals significant differences between adopters of modern irrigation techniques (MITs) and non-adopters using furrow irrigation: tomato yield was 732.94 kg vs. 387.35 kg, onion yield was 2952.57 kg vs. 395.53 kg, and pepper yield was 552.34 kg vs. 505.02 kg; input usage also varied, with adopters using 1.58 vs. 1.38 acres (tomatoes), 1.30 vs. 1.50 acres (onions), and 1.56 vs. 1.18 acres (peppers), as well as differences in seed, fertilizer, and agrochemical quantities. Using Stochastic Frontier Analysis (SFA), this study estimated the technical efficiency scores for farmers, the findings reveal that land cultivated ($\beta 1=0.537$, $p=0.000$) and fertilizer use ($\beta 3=0.353$, $p=0.000$) were significant drivers of productivity, indicating that increasing these inputs substantially boosts agricultural output. In contrast, herbicide use negatively impacts productivity ($\beta 6=-0.268$, $p=0.005$), suggesting a need for more efficient or reduced usage of herbicides. The inefficiency effects model highlights that farming experience ($\delta 2=10.53$, $p=0.012$) positively influences technical efficiency, underscoring the value of practical expertise in optimizing resource use. The technical efficiency of the farmers varies widely, with a mean of 88.43%, a minimum of 45.28%, and a maximum of nearly 100%, suggesting room for improvement in less efficient operations. The analysis of technical efficiency across irrigation methods shows a significant advantage for modern irrigation techniques over furrow irrigation. For onions, sprinkler irrigation achieved a mean technical efficiency of 0.928 ($p=0.000$) compared to 0.589 under furrow irrigation. Similarly, for tomatoes, drip irrigation resulted in a mean efficiency of 0.850, substantially higher than 0.430 for furrow irrigation ($p=0.000$). For peppers, drip irrigation also outperformed furrow irrigation with mean efficiencies of 0.813 and 0.338, respectively ($p=0.000$). The study also revealed that while traditional irrigation methods had lower efficiency scores, proper management of resources such as fertilizers and pest control was crucial in mitigating inefficiency. The results highlight the importance of efficient farm management practices, including the use of appropriate technologies and optimized resource allocation, in achieving higher technical efficiency. The study recommends targeted subsidies, capacity-building programs, improved infrastructure, and public-private partnerships to promote the adoption of modern irrigation technologies among smallholder farmers.

Keywords: Technical Efficiency, Micro-Irrigation Technologies, Agricultural Productivity and Resource Use Efficiency.

Citation: Gerald Absanto, Josephine Mkunda, Anthony Nyangarika (2025). Modern Versus Traditional Irrigation Systems: Implications for Technical Efficiency and Input-Output Relationship in Northern Tanzania's Horticulture Sector; *Glob Acad J Econ Buss, 7*(1), 1-13.

1.0 INTRODUCTION

Agriculture remains a fundamental component of the global economy, particularly in developing countries, where it supports the livelihoods of a significant portion of the population (FAO, 2020) . In these regions, smallholder farmers are central to agricultural production, yet they face a myriad of challenges that undermine their productivity and sustainability (Bojago & Abrham, 2023; Kimaro *et al*., 2024). Among the most pressing challenges are water scarcity, unpredictable climate conditions, and the inefficiency of traditional irrigation methods (Agbenyo *et al*., 2022). Irrigation is vital for crop production, especially in regions with erratic rainfall patterns, yet conventional methods such as furrow irrigation are often inefficient, leading to excessive water usage and reduced crop yields (Singh & Singh, 2020). Consequently, smallholder farmers are increasingly turning to modern irrigation technologies (MIT) to overcome these limitations and improve water use efficiency (Mattoussi *et al*., 2023; Rouzaneh *et al*., 2021).

Modern irrigation systems, such as drip and sprinkler irrigation, have been widely recognized for their potential to enhance agricultural productivity by providing more precise and efficient water delivery (Absanto *et al*., 2025; Tan *et al*., 2021). Drip irrigation, for instance, delivers water directly to the root zone of plants, reducing water wastage and promoting better plant growth, particularly in regions facing water scarcity (Sarkar & Hanamashetti, 2002). Similarly, sprinkler systems, which mimic natural rainfall, offer advantages in areas where surface water resources are limited and unevenly distributed (Angold, 2023). MITs have been proven to significantly improve water use efficiency and yield outcomes compared to traditional irrigation methods (Silva *et al*., 2022).

Despite the recognized advantages of micro-irrigation systems, much of the existing research has focused on their technical and agronomic impacts, such as improving water efficiency and increasing crop yields (Belay *et al*., 2022). However, there is limited evidence on the direct relationship between the adoption of micro-irrigation technologies and economic efficiency of smallholder farmers, particularly in the horticulture sector (Prepeliță (Popovici) Bucur D *et al*., 2021). The economic impacts, including technical efficiency, input-output relationship, and resilience against climate variability and market price fluctuations, remain underexplored (Xiuling *et al*., 2023). This study seeks to bridge this gap by examining the financial implications of micro-irrigation technology adoption, offering region specific insights into the socio-economic realities of smallholder horticulture farmers.

While previous studies have highlighted the agronomic benefits of MITs, critical questions remain unanswered. These include the extent to which these technologies improve financial outcomes for farmers, their economic efficiency in resource-constrained settings, and their role in mitigating risks associated with unpredictable climatic and market conditions (Yadav A *et al*., 2022). Addressing these gaps is essential for providing actionable insights to policymakers, development practitioners, and farmers themselves.

The study contributes to existing knowledge by providing empirical evidence on the financial impacts of micro-irrigation technology adoption, offering recommendations for targeted interventions to scale its use, amplifying the perspectives of smallholder farmers, and enriching theoretical frameworks on the link between technology adoption and financial performance in agricultural economics. The study contributes to broader strategies for enhancing the financial and economic outcomes of smallholder horticulture farming through the adoption of micro-irrigation technologies.

2.0 METHODOLOGY

This study adopted a quantitative research design, utilizing Stochastic Frontier Analysis (SFA) to assess the economic efficiency of different irrigation systems in smallholder horticulture production. The analysis focused on three crop types that were onions, tomatoes, and peppers grown under two distinct irrigation methods: modern irrigation technologies (drip and sprinkler systems) and traditional methods (furrow irrigation). Economic efficiency, defined as the sum of technical efficiency and allocative efficiency, was central to this analysis (Arulmani *et al*., 2022). Technical efficiency measures the ability of farmers to maximize output with given inputs, while allocative efficiency evaluates the optimal allocation of resources to minimize costs. These components were analyzed to provide a holistic assessment of resource utilization and cost-effectiveness (Zou *et al*., 2013). The study also incorporated Partial Productivity Analysis to evaluate the output-to-input ratios for specific inputs such as land, labor, seeds, fertilizers, and agrochemicals. Additionally, Input-Output Analysis (Timothy Martin Lyanga, 2024) was employed to quantify the relationship between resource utilization and crop yields, enabling a comprehensive understanding of the efficiency dynamics across irrigation methods.

2.1 Sampling and Data Collection

The study was carried out in Arusha, Manyara and Kilimanjaro regions of northern Tanzania where smallholder farmers practice both traditional and modern irrigation methods. A stratified random sampling technique was employed to select 540 smallholder farmers, ensuring a balanced representation of farmers using both modern and traditional irrigation systems. This sampling method enables a more accurate representation of the target population, facilitating a better understanding of the comparative efficiencies of different irrigation practices across varying socio-economic backgrounds.

Data collection involved structured interviews and field surveys, designed to capture essential farm input data (e.g., water usage, seeds, fertilizers) and output data (e.g., crop yield). Additionally, socio-economic variables such as age, education level, farm size, access to credit, and training on irrigation techniques were collected. This multi-faceted data collection approach allows for a comprehensive analysis of both technical and socio-economic factors that could influence the adoption of irrigation technologies and their associated efficiency (Creswell, 2014; Saunders *et al*., 2012).

2.2 Stochastic Frontier Analysis (SFA)

The Stochastic Frontier Analysis (SFA) is a widely used econometric method for estimating the technical efficiency of production in the presence of random shocks. The SFA model assumes that there is an optimal production frontier, and the difference between the observed output and this frontier represents inefficiency, which can be caused by factors such as mismanagement, resource constraints, or suboptimal practices (Kumbhakar *et al*., 2020).

The general form of the SFA model is as follows.

$$Y_i = \beta_0 + \beta_1 ln(Land_i) + \sum_i \beta_i ln(Input\ Used) + \varepsilon_i \cdots\cdots\cdots\cdots\cdots\cdots [1]$$

Where:

Y_i presents the output for the i-th observation (e.g., yield, productivity, etc.).
β_0 is the constant term.
$\beta_1 - \beta_k$ are the coefficients for each input variable.
$\sum_i \beta_i ln(Input\ Used)$ are the log-transformed values of seed use, fertility use, booster use, pesticides use, herbicide use, and insecticide use, respectively.
ε_i is the error term (comprising the technical inefficiency and random error components).

Inefficiency Effect Model Equation.

$$u_i = \delta_0 + \delta_1 ln(Age_i) + \delta_1 ln(Farming\ experience_i) + \delta_1 ln(gender_i) + \delta_1 ln(Marital\ status_i) + \delta_1 ln(Education\ level_i) + v_1 \cdots\cdots\cdots\cdots\cdots [2]$$

Where:

Y_i presents the output for the i-th observation (e.g., yield, productivity, etc.).
δ_0 is the constant term.
$\delta_0 - \delta_k$ are the coefficients for each input variable
v_i represents the random error term associated with the inefficiency effect.

Technical Efficiency (TE):

Technical efficiency (TE) for the i-th observation was calculated as;

$$TE_i = \frac{Y_i}{Y_i^*} = \exp\,(-u_i) \cdots\cdots\cdots\cdots\cdots [3]$$

Where:

Y_i^* is the potential output (the frontier).
u_i is the inefficiency term from the inefficiency effect model.

Allocative Efficiency (AE)

Allocative efficiency measures how well input usage aligns with the optimal input cost ratio, which ensures the farm is producing at the lowest cost possible given the input prices. It is calculated as:

$$AE_i = \frac{\sum_{k=1}^{n} P_k * X_k}{C_i} \cdots\cdots\cdots\cdots\cdots [4]$$

Where:

P_k is a price of input k
X_k is a quantity of input k
C_i is a total cost of production for farm i

Allocative efficiency values range between 0 and 1, with higher values indicating greater efficiency in allocating resources.

Economic Efficiency (EE)

Economic efficiency is the product of technical and allocative efficiencies. It reflects both the technical ability of a farm to maximize output from its inputs and the ability to do so cost-effectively. Economic efficiency is calculated as.

$$EE_i = TE_i + AE_i \cdots\cdots\cdots\cdots\cdots [5]$$

Economic efficiency values range from 0 to 1, with higher values indicating better overall efficiency in utilizing inputs to generate output.

Partial Productivity Analysis (PPA)

Partial productivity analysis is used to assess the productivity of individual inputs, considering the specific output generated per unit of input. It is calculated as:

$$\text{Productivity}_k = \frac{Y_i}{X_{ik}} \cdots\cdots\cdots\cdots\cdots [6]$$

Y_i is the output of farm i
X_{ik} is the input k (land, seed, fertilizer, labor, etc.)

This analysis helps to measure the efficiency of different resources used in the production process, such as land, labor, and fertilizer.

Input-Output Analysis (IOA)

Input-output analysis assesses the cost-effectiveness of different irrigation methods by comparing input costs to the output value generated. The formula for the output-input ratio is:

$$Input\ output = \frac{Output\ Value\ (Kg/acre)}{Input\ Cost\ (USD/acre)} \ldots\ldots\ldots\ldots\ldots [7]$$

This analysis provides insight into the financial returns for each dollar spent on inputs, indicating which irrigation methods provide the highest return on investment.

3.0 PRESENTATION OF RESULTS AND DISCUSSION

3.1 Comparison of Agricultural Parameters under Different Irrigation Methods

Table 1 examines the impact of different MIT and furrow irrigation on agricultural productivity, focusing on key indicators such as yield, land cultivated, and input usage across three crops: Tomato, Onion, and Pepper. The findings reveal significant advantages of MIT over furrow irrigation in enhancing crop yields, optimizing land use, and improving resource efficiency. With higher yields observed in Tomato and Onion crops under drips and sprinkler, and efficient use of inputs such as seeds, fertilizers, and agrochemicals, MIT demonstrates its potential to transform agricultural practices.

3.1.1 Yield

The yield data across the three crops (Tomato, Onion, and Pepper) demonstrated significant differences between MIT and furrow irrigation methods. For Tomato, the mean yield under drip was 732.94 kg, markedly higher than the 387.35 kg achieved under furrow irrigation. The maximum yield achieved with drip was 2600.00 kg, while Furrow Irrigation reaches only 1050.00 kg. This substantial disparity emphasizes the efficiency of drip in promoting healthier plant growth and achieving higher yields. According to (Mačkić *et al*., 2023; J. Wang *et al*., 2022), modern irrigation technologies such as drip irrigation ensure precise water application to the root zone, thereby improving water use efficiency and plant productivity.

Similarly, Onion showed a dramatic improvement in yield with sprinkler, averaging 2952.57 kg compared to the much lower 395.53 kg under furrow irrigation. The maximum yield under sprinkler reached 15,000.00 kg, while for furrow irrigation remained at 1050.00 kg. This underscores sprinkler's superior ability to enhance productivity, especially for high-water-demand crops like Onion. As supported by the findings of (Senapti *et al*., 2021; H. Wang *et al*., 2022), advanced irrigation methods improve crop yields by minimizing water wastage and optimizing soil moisture content, creating favorable growing conditions for crops.

For Pepper, the yield under drip was slightly higher (552.34 kg) compared to furrow irrigation (505.02 kg), though the difference was less pronounced than in Tomato and Onion. This suggests that while MIT was effective across various crop types, the extent of its impact may vary depending on the crop's specific water and nutrient requirements. The results align with studies by (Bhatti *et al*., 2022; Sumari *et al*., 2018) , who highlight that advanced irrigation systems not only boost crop yields but also provide consistent outcomes for diverse agricultural applications. Overall, the data strongly indicates that MIT provides superior yield outcomes compared to Furrow Irrigation, reinforcing its efficiency and reliability as a modern agricultural practice.

3.1.2 Land Cultivated

The land cultivated under the two irrigation methods showed slight variations, with MIT generally supporting marginally larger areas than furrow irrigation. For Tomato, the average land under drip was 1.58 acres, slightly larger than the 1.38 acres under furrow irrigation. This could be attributed to the efficiency of drip, which ensures optimal water use, enabling farmers to manage larger plots of land with available water resources. (Guan *et al*., 2022; Sherpa *et al*., 2021) argue that efficient irrigation methods not only enhance productivity but also maximize the use of available arable land, making them particularly suitable for regions with water scarcity challenges.

For onion, the average land cultivated under sprinklers was 1.30 acres, slightly smaller than the 1.50 acres cultivated under furrow irrigation. This suggests that although sprinkler enhances productivity, its application may sometimes be limited to smaller plots due to the higher investment costs associated with its implementation. According to (Mattoussi *et al*., 2023; Rouzaneh *et al*., 2021) the adoption of modern irrigation techniques in developing countries is often constrained by financial and infrastructural barriers, limiting their use in larger fields.

In the case of pepper, the average land cultivated under drip was 1.56 acres, compared to 1.18 acres under furrow irrigation system. This demonstrates drip's potential to optimize land use while maintaining higher productivity. As noted by (Namara *et al*., 2007; Narayana Moorthy, 2022), the use of advanced irrigation methods allows for efficient water allocation, enabling farmers to expand their cultivable areas without compromising productivity. Overall, the findings indicate that MIT supports efficient and flexible land utilization, offering advantages in both small-scale and larger agricultural setups.

3.1.3 Input Used

The analysis of input usage reveals notable differences in the quantities of seeds, fertilizer, booster, and other agrochemicals used under the two irrigation methods, with MIT generally demonstrating greater resource efficiency. For Tomato, the seed quantity under drip averaged 1.70 packs, slightly higher than the 1.28 packs used under furrow irrigation. This reflects drip's capacity to support larger cultivated areas while ensuring efficient seed utilization. Fertilizer use was marginally lower under drip (6.93 packs) than furrow irrigation (7.29 packs), indicating that MIT systems enhance nutrient uptake efficiency by delivering water and nutrients directly to the root zone (Bhardwaj *et al*., 2019). The quantities of boosters, pesticides, and herbicides were comparable under both methods, suggesting that MIT reduces the need for excessive chemical applications by promoting healthier plant growth environments.

For onion, the input usage differences were more pronounced. The seed quantity under sprinklers was significantly lower (7.94 packs) compared to furrow irrigation (12.86 packs), reflecting sprinkler's efficiency in seed distribution and crop establishment. Fertilizer use under sprinkler was also drastically lower (46.74 packs) compared to furrow irrigation (161.84 packs), highlighting the reduced resource requirements associated with modern irrigation methods. As supported by (Deng *et al*., 2021; Priyan & Panchal, 2018), advanced irrigation technologies improve the delivery and absorption of fertilizers, minimizing waste and reducing costs for farmers.

In the case of pepper, the seed quantity under drip (2.00 packs) was much lower than furrow irrigation (32.82 packs), further emphasizing drip's efficiency in utilizing resources. Fertilizer use was higher under drip (8.16 packs) compared to furrow irrigation (2.68 packs), which may reflect the system's ability to enhance plant growth and yield potential through precise nutrient delivery. Pesticides, herbicides, and insecticides are generally used in lower quantities under sprinkler, with notable reductions in insecticide use (3.71 packs for drip compared to 7.43 packs for furrow irrigation). This aligns with findings by (Khanal *et al*., 2018; Yadav A *et al*., 2022), which highlight the potential for modern irrigation techniques to reduce dependency on chemical inputs by fostering healthier crop conditions.

Table 1: Comparison of Agricultural Parameters under Different Irrigation Methods

Crop type	Parameters	Unit	Irrigation Methods					
			MITs (Drip and sprinkler)			Furrow		
			Mean	Minimum	Maximum	Mean	Minimum	Maximum
Tomato	Yield	Kg	732.94	1.00	2600.00	387.35	300.00	1050.00
	Land Acre	Acre	1.58	0.00	5.00	1.38	1.00	3.00
	Seeds quantity	Pack	1.70	0.50	50.00	1.28	1.00	2.00
	Fertilizer_quantity	Pack	6.93	1.00	20.00	7.29	2.00	15.00
	Booster_quantity	Pack	3.40	0.50	13.00	3.46	1.00	9.00
	Pesticides_quantity	Pack	4.11	1.00	15.00	4.43	3.00	8.00
	Herbicides_quantity	Pack	6.15	0.50	27.50	6.53	4.00	12.00
	Insecticides_quantity	Pack	4.71	1.00	21.00	4.92	1.00	13.00
Onion	Yield	Kg	2952.57	35.00	15000.00	395.53	300.00	1050.00
	Land Acre	Acre	1.30	0.50	3.00	1.50	1.00	3.00
	Seeds quantity	Pack	7.94	0.50	48.00	12.86	3.00	45.00
	Fertilizer_quantity	Pack	46.74	1.50	300.00	161.84	3.00	2000.00
	Booster_quantity	Pack	3.86	1.00	16.00	2.36	1.50	6.00
	Pesticides_quantity	Pack	4.84	1.00	12.00	3.22	1.00	11.00
	Herbicides_quantity	Pack	6.74	2.00	20.00	4.36	2.00	13.00
	Insecticides_quantity	Pack	6.45	2.00	20.00	3.37	1.50	13.00
Pepper	Yield	Kg	552.34	288.00	1050.00	505.02	300.00	1620.00
	Land Acre	Acre	1.56	1.00	3.00	1.18	1.00	3.00
	Seeds quantity	Pack	2.00	1.00	3.00	32.82	1.00	72.00
	Fertilizer_quantity	Pack	8.16	3.00	15.00	2.68	1.00	4.00
	Booster_quantity	Pack	2.12	1.00	4.00	7.47	2.00	12.00
	Pesticides_quantity	Pack	7.49	3.00	12.00	9.73	4.00	12.00
	Herbicides_quantity	Pack	6.90	3.00	14.00	4.13	4.00	8.00
	Insecticides_quantity	Pack	3.71	2.00	6.00	7.43	1.00	12.00

3.2 Stochastic Frontier Model Estimates for Agricultural Inputs and Technical Efficiency

3.2.1 Production Frontier Estimates

The results from the stochastic frontier model provided valuable insights into the relationship between agricultural inputs and productivity. The coefficient for the area of land cultivated was 0.5374, indicating that a 1% increase in the land cultivated leads to a 0.5374 increase in agricultural output, holding other factors constant. This strong and statistically significant effect highlights the pivotal role of land in agricultural production, aligning with findings from previous studies emphasizing land as a primary factor in farming systems (Mauki *et al*., 2023).

Fertilizer use also demonstrated a significant positive effect on productivity, with a coefficient of 0.3530, reinforcing the role of fertilizers in replenishing soil nutrients and enhancing crop growth. These findings resonate with the conclusions drawn by (Han *et al*., 2023) who identified fertilizers as essential inputs for improving yields in smallholder farming systems.

However, other inputs such as seed use and pesticide application had minimal or statistically insignificant effects on productivity. For instance, the coefficient for seed use was 0.0046, which, despite being positive, suggests that seeds contribute marginally to output under the current conditions. This could be attributed to issues such as low-quality seeds or suboptimal planting practices, a problem noted in previous research (Ebrahimian *et al*., 2019; Sharda *et al*., 2017).

Conversely, herbicide use exhibited a negative and significant effect on productivity, with a coefficient of -0.2677, indicating potential misuse or overreliance on herbicides. This finding raises environmental and economic concerns, emphasizing the need for farmer education on proper herbicide application. Similarly, booster use, and insecticide use showed statistically insignificant effects, suggesting limited utility or improper application under current farming practices. This finding aligns with earlier studies by (Bhardwaj *et al*., 2019) which highlight the risks of improper chemical usage and its potential adverse effects on productivity and the environment.

3.2.2 Inefficiency Effect Model

The inefficiency effect model provides insights into the socio-demographic factors influencing technical inefficiency. Farming experience emerged as a critical factor, with a coefficient of 10.5283, indicating that greater experience significantly reduces inefficiency. This aligns with findings by (Belay *et al*., 2022) who argued that experienced farmers tend to adopt more effective production strategies and better manage resources. Policies aimed at fostering knowledge sharing among farmers through cooperatives or peer-learning platforms could amplify these benefits.

On the other hand, the coefficient for age was -1.9275, which, while suggesting a potential reduction in inefficiency with increasing age, was only marginally significant ($p = 0.071$). This highlights the potential benefits of accumulated knowledge with age but also suggests a diminishing return as farmers grow older. Gender, marital status, and education showed limited or statistically insignificant effects on inefficiency. For instance, the coefficient for education was 0.3573, suggesting that while education is important, its direct influence on inefficiency may depend on the type and relevance of the education received. These results indicate the need for targeted training programs tailored to farmers' specific needs, as emphasized by (Ndubueze-Ogarak, 2021).

4.2.3 Variance Parameters and Technical Efficiency

The variance parameter estimates revealed that inefficiency contributes significantly to deviations from the production frontier, with the gamma value indicating that over 85% of the variations in productivity were due to inefficiency. This underscores the importance of addressing inefficiency to unlock the full potential of agricultural productivity. The technical efficiency scores, which ranged from a minimum of 45% to a maximum of nearly 100%, with an average of 88%, suggest that while many farmers operate efficiently, there was substantial room for improvement among the less efficient farmers. These findings are consistent with studies by (Consesa Mauki *et al*., 2023; Wu & Zhu, 2023), who highlight the potential for improving efficiency through targeted interventions such as extension services and resource optimization.

Table 2: Stochastic Frontier Model Estimates for Agricultural Inputs and Technical Efficiency

Variables	Parameters	Coefficients	Std.Errors	T-values	P-values
Ln land cultivated	β_1	.537356	.0978612	5.60	0.000
Ln seed use	β_2	.0045779	.0032974	1.39	0.083
Ln fertility use	β_3	.3530195	.037471	9.42	0.000
Ln booster use	β_4	-.0910394	.0869259	-1.05	0.295
Ln pesticides use	β_5	.1692521	.1042515	1.62	0.104
Ln herbicide use	β_6	-.2676903	.0948	-2.82	0.005

Variables	Parameters	Coefficients	Std.Errors	T-values	P-values
Ln insecticide use	β_7	-.1035191	.0901875	-1.15	0.251
Inefficiency Effect Model					
Constant	δ_0	-36.00884	13.54878	-2.66	0.008
Ln Age	δ_1	-1.927477	1.06651	-1.81	0.071
Ln Farming experience	δ_2	10.52828	4.184021	2.52	0.012
Ln Gender	δ_3	.7420621	.7905357	0.94	0.348
Ln Marital_status	δ_4	.5934565	.6802724	0.87	0.383
Ln Education	δ_5	.3572785	.2802983	1.27	0.202
Variance Parameters					
Sigma² u	$\alpha^2 u$	.8569192	-	-	-
Sigma² v	$\alpha^2 v$	.7689601	-	-	-
Sigma²	α^2				
Gamma (α² u/ α²)	$\alpha^2 u/_{\alpha^2}$	1.32561	-	-	-
Technical efficiency					
Mean	X_{mean}	.8842584	-	-	-
Minimum	X_{min}	.4527604	-	-	-
Maximum	X_{max}	.9999987	-	-	-

3.3 Economic Efficiency of Crop Types under Different Irrigation Methods

The economic efficiency (EE) of different crop types under modern and traditional irrigation systems, as presented in Table 3, highlights notable disparities across irrigation methods. Economic efficiency, derived as the product of technical efficiency (TE) and allocative efficiency (AE), underscores the combined effectiveness of resource utilization and cost optimization in crop production.

3.3.1 Onion Cultivation

Onions cultivated using sprinkler irrigation achieved a high mean economic efficiency of 0.799, significantly outperforming furrow irrigation, which recorded a mean EE of 0.365. This notable difference, validated by a t-test value of 4.214 (p = 0.000), reflects the superior capability of sprinkler systems in aligning input allocation with optimal output production.

The higher TE of 0.928 and AE of 0.86 for sprinkler irrigation demonstrate its effectiveness in maximizing both resource use and cost efficiency. In contrast, furrow irrigation, with TE and AE values of 0.589 and 0.62, respectively, lags significantly, emphasizing inefficiencies in water delivery and cost allocation. These findings align with previous research (Mačkić *et al*., 2023; Vanghele C., 2019) , which highlighted the advantages of precision irrigation techniques in reducing production inefficiencies.

3.3.2 Tomato Cultivation

For tomatoes, drip irrigation exhibited a mean EE of 0.689, significantly higher than the 0.202 observed under furrow irrigation. This stark contrast, supported by a t-test value of 7.512 (p = 0.000), underscores the critical role of modern irrigation technologies in enhancing both technical and allocative efficiencies. Drip irrigation's high TE (0.85) and AE (0.81) reflect its precision in water and nutrient delivery, which minimizes waste and optimizes input usage. In comparison, furrow irrigation, with TE and AE values of 0.43 and 0.47, respectively, suffers from inefficiencies such as uneven water distribution and nutrient loss. These results are consistent with findings by (Musabekov *et al*., 2022; Ndubueze-Ogarak, 2021), who emphasized the economic benefits of adopting advanced irrigation systems for water-intensive crops.

3.3.3 Pepper Cultivation

Drip irrigation also proved superior for pepper cultivation, achieving an EE of 0.635 compared to the much lower 0.126 observed with furrow irrigation. The significant difference, confirmed by a t-test value of -4.305 (p = 0.000), highlights the economic advantage of drip systems in optimizing resource allocation and minimizing inefficiencies.

With TE and AE values of 0.813 and 0.782, respectively, drip irrigation ensures effective resource utilization and cost management, particularly critical for high-value crops like peppers. Furrow irrigation, with TE and AE values of 0.338 and 0.372, respectively, struggles to achieve comparable performance, likely due to waterlogging and uneven resource distribution. These findings corroborate prior studies (Asante, 2013; Mattoussi *et al*., 2023) that advocate for the adoption of modern irrigation systems to enhance efficiency and profitability.

Table 3: Economic Efficiency of Crop Types under Different Irrigation Methods

Crop Type	Irrigation Method	Obs	Technical Efficiency (TE)	Allocative Efficiency (AE)	Economic Efficiency (EE)	T-Test	P-Value
Onion	Sprinkler	40	0.928	0.86	0.799	4.214	0.000
	Furrow	95	0.589	0.62	0.365		
Tomato	Drip	100	0.85	0.81	0.689	7.512	0.000
	Furrow	171	0.43	0.47	0.202		
Pepper	Drip	59	0.813	0.782	0.635	-4.305	0.000
	Furrow	75	0.338	0.372	0.126		

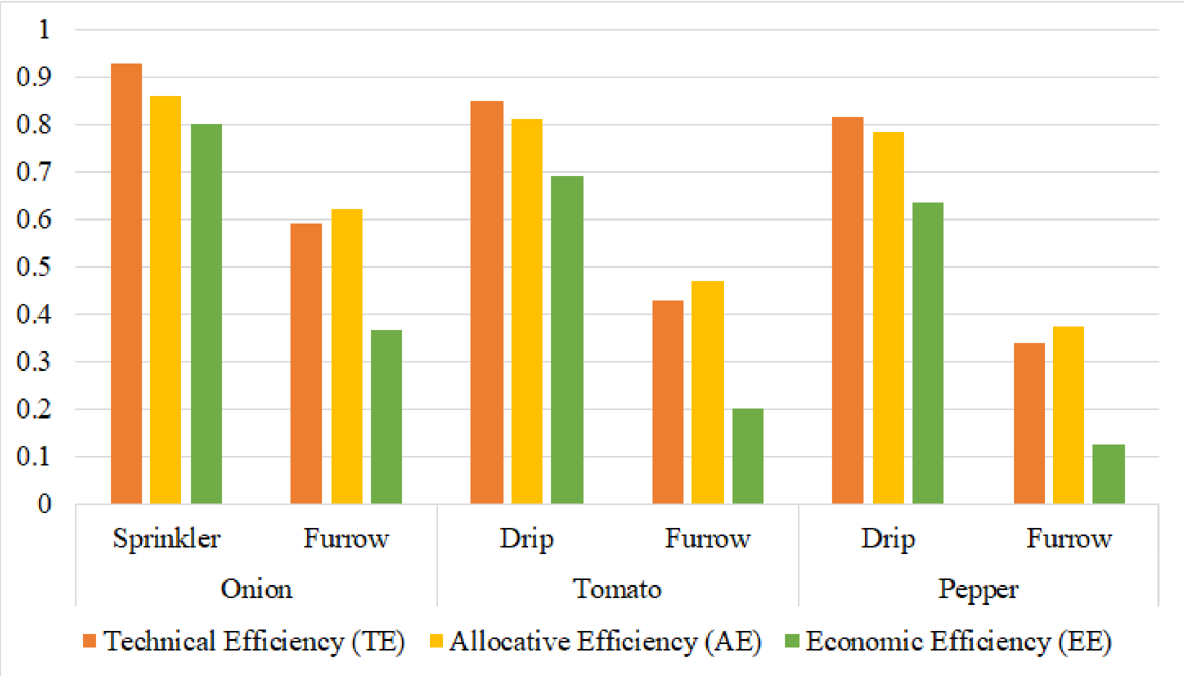

Fig. 1: Efficiency analysis of MITs vs Furrow Irrigation

3.4 Partial productivity analysis micro vs traditional irrigation technologies

Table 4 presents the partial productivity analysis for onion, tomato, and pepper crops under sprinkler and drip irrigation systems (micro irrigation) compared with furrow irrigation (traditional method). The analysis includes land productivity (kg/acre), seed productivity (kg/pack), fertilizer productivity (kg/pack), and labor productivity (kg/person-day), providing a comprehensive assessment of how different irrigation methods influence the efficiency of input use.

3.4.1 Onion Cultivation

For onions, the data reveal significant differences in productivity between sprinkler and furrow irrigation methods. Land productivity under sprinkler irrigation is notably higher at 2,270.30 kg/acre compared to 1,350.50 kg/acre under furrow irrigation. This suggests that sprinkler irrigation enhances the overall output per unit area, likely due to its more efficient water distribution, which optimizes soil moisture and nutrient uptake.

Seed productivity also follows a similar pattern, with sprinkler irrigation yielding 372 kg/pack, compared to only 132.4 kg/pack with furrow irrigation. Fertilizer productivity is also more efficient with sprinkler irrigation, at 63.2 kg/pack, in contrast to 29.8 kg/pack under furrow irrigation. The labor productivity for sprinkler irrigation is 28.5 kg/person-day, a substantial increase over the 15.2 kg/person-day under furrow irrigation. These results demonstrate that sprinkler irrigation offers higher productivity across all input measures, confirming its role in enhancing crop output efficiency.

3.4.2 Tomato Cultivation

In tomato cultivation, drip irrigation outperforms furrow irrigation in all productivity measures. The land productivity for tomatoes under drip irrigation is 1,785.40 kg/acre, significantly higher than the 820.3 kg/acre achieved under furrow irrigation. This can be attributed to drip irrigation's precision in water application, ensuring uniform moisture levels and reducing water wastage.

Seed productivity is also substantially greater under drip irrigation, with 492.3 kg/pack, compared to just 237.5 kg/pack under furrow irrigation. Fertilizer productivity stands at 105.7 kg/pack for drip irrigation, compared to 52.3 kg/pack under furrow irrigation, illustrating the greater efficiency in nutrient usage. Additionally, labor productivity is 42.6 kg/person-day for drip irrigation, far exceeding the 20.4 kg/person-day achieved under furrow irrigation. These results demonstrate the superiority of drip irrigation in improving productivity and resource efficiency in tomato farming.

3.4.3 Pepper Cultivation

Similarly, for pepper cultivation, drip irrigation shows higher productivity across all input categories. Land productivity is 2,012.40 kg/acre under drip irrigation, significantly surpassing the 1,143.80 kg/acre under furrow irrigation. This difference reflects the ability of drip irrigation to deliver water efficiently to the plants, minimizing runoff and ensuring optimal soil conditions for growth.

Seed productivity under drip irrigation is 701.5 kg/pack, almost double the 324.8 kg/pack seen with furrow irrigation. Fertilizer productivity is also greater with drip irrigation at 98.6 kg/pack, compared to 41.7 kg/pack under furrow irrigation. In terms of labor productivity, drip irrigation achieves 36.2 kg/person-day, compared to 18.9 kg/person-day under furrow irrigation. These results suggest that drip irrigation not only enhances crop yields but also leads to more efficient use of labor, seed, and fertilizer.

Table 4: Partial productivity analysis of micro vs traditional irrigation technologies

Crop Type	Irrigation Method	Obs	Land Productivity (kg/acre)	Seed Productivity (kg/pack)	Fertilizer Productivity (kg/pack)	Labor Productivity (kg/person-day)
Onion	Sprinkler	40	2,270.30	372	63.2	28.5
	Furrow	95	1,350.50	132.4	29.8	15.2
Tomato	Drip	100	1,785.40	492.3	105.7	42.6
	Furrow	171	820.3	237.5	52.3	20.4
Pepper	Drip	59	2,012.40	701.5	98.6	36.2
	Furrow	75	1,143.80	324.8	41.7	18.9

3.5 Input output analysis of micro vs traditional irrigation technologies

Table 5 presents the input-output analysis for onion and tomato crops grown under sprinkler and drip irrigation systems (micro irrigation) compared to furrow irrigation (traditional method). The table includes data on input costs (USD/acre), output values (USD/acre), and output-input ratios, which offer a clear comparison of the economic efficiency of different irrigation methods.

3.5.1 Onion Cultivation

For onions, the input-output analysis shows that sprinkler irrigation yields a significantly higher output-input ratio compared to furrow irrigation. The input cost for onions under sprinkler irrigation is 300 USD/acre, while the output value is 1,500 USD/acre, resulting in an output-input ratio of 5. This high ratio indicates that sprinkler irrigation is highly efficient, generating 5 USD in output for every 1 USD spent on input.

In contrast, onion cultivation under furrow irrigation requires an input cost of 250 USD/acre, but the output value is only 850 USD/acre, leading to a lower output-input ratio of 3.4. This suggests that furrow irrigation is less economically efficient than sprinkler irrigation, as it yields lower returns relative to the costs incurred. The results underscore the economic advantages of adopting sprinkler irrigation for onion farming, as it not only improves technical efficiency but also delivers higher financial returns.

3.5.2 Tomato Cultivation

The input-output analysis for tomatoes demonstrates a similar trend. Drip irrigation requires an input cost of 350 USD/acre, with an output value of 2,100 USD/acre, yielding an output-input ratio of 6. This is considerably higher than the 3.21 ratio observed for tomatoes grown under furrow irrigation, which has an input cost of 280 USD/acre and an output value of 900 USD/acre. The results clearly indicate that drip irrigation is more cost-effective for tomato production, as it provides a greater return on investment.

The high output-input ratio for drip irrigation (6) suggests that the technology is significantly more efficient in converting input costs into revenue, which is consistent with the findings from the technical efficiency analysis, where drip irrigation showed superior productivity. These results suggest that drip irrigation not only enhances the technical efficiency of tomato farming but also ensures higher economic returns.

Table 5: Input output analysis of micro vs traditional irrigation technologies

Crop Type	Irrigation Method	Obs	Input Cost (USD/acre)	Output Value (USD/acre)	Output-Input Ratio
Onion	Sprinkler	40	300	1,500	5
	Furrow	95	250	850	3.4
Tomato	Drip	100	350	2,100	6
	Furrow	171	280	900	3.21
Pepper	Drip	59	400	1,600	4
	Furrow	75	300	800	2.67

4.0 CONCLUSION AND RECOMMENDATION

4.1 Conclusion

This study evaluated the impact of modern irrigation technologies (MIT), specifically drip and sprinkler irrigation, on the technical efficiency of onion, tomato, and pepper farming. The findings demonstrate that MIT significantly outperforms traditional furrow irrigation in terms of both technical efficiency and yield across all crop types analyzed. Onions exhibited the highest efficiency gains under sprinkler irrigation, with a mean efficiency of 0.928, while furrow irrigation lagged behind at 0.589. Similarly, tomatoes and peppers grown under drip irrigation achieved efficiencies of 0.850 and 0.813, respectively, as compared to significantly lower efficiencies of 0.430 and 0.338 under furrow irrigation. These results underscore the transformative potential of adopting modern irrigation methods to improve agricultural productivity and resource utilization, particularly in water-scarce environments.

The study also highlights that MIT not only enhances technical efficiency but also enables larger cultivated areas and reduces input wastage, promoting sustainable agricultural practices. However, challenges such as high initial costs, lack of technical knowledge, and limited access to financing may hinder the widespread adoption of these technologies, particularly among smallholder farmers. Addressing these barriers is critical to scaling up the use of modern irrigation methods in developing agricultural economies.

4.2 Recommendation

4.2.1 Policy Support and Subsidies

Governments and policymakers should prioritize the creation and implementation of targeted subsidy programs aimed at reducing the financial burden associated with adopting modern irrigation technologies (MIT) for smallholder farmers. Such subsidies can cover part of the installation, maintenance, and operational costs of irrigation systems. To further incentivize investment in MIT, tax incentives or grants can be offered to farmers, agricultural cooperatives, and even private companies involved in the supply and installation of these systems. Furthermore, governments could explore partnerships with international development organizations to provide financial support, ensuring that small-scale farmers, who are typically the most vulnerable to climate change and water scarcity, have the opportunity to access these technologies. This financial assistance will not only encourage the adoption of efficient irrigation systems but will also facilitate the transition to more sustainable agricultural practices, improving productivity while conserving water resources.

4.2.2 Capacity Building

To ensure the proper and efficient use of modern irrigation systems, it is essential to implement extensive training programs for farmers. These programs should focus not only on the installation of drip and sprinkler irrigation technologies but also on their operation, maintenance, and troubleshooting. Such training will equip farmers with the necessary skills to maximize the benefits of MIT, reducing wastage and improving technical efficiency. Extension services should be at the forefront of this initiative, with local agricultural officers providing ongoing guidance and technical assistance to farmers. These services can be delivered through workshops, field demonstrations, and digital platforms, ensuring that information reaches a broad audience. Additionally, training should incorporate sustainable farming practices, including water conservation techniques, to promote the long-term benefits of MIT, especially in areas facing significant water shortages.

4.2.3 Infrastructure Development

For modern irrigation technologies to become widely accessible, there must be a concerted effort to develop the necessary infrastructure. This includes improving access to irrigation equipment through local markets and strengthening supply chains for materials and parts. Government interventions could include providing incentives to local businesses or cooperatives that manufacture or distribute irrigation equipment. Furthermore, enhancing financing mechanisms such as microcredit facilities, loans with favorable terms, or agricultural cooperatives would make MIT more affordable for smallholder farmers. By making access to financing easier and more affordable, farmers can acquire the necessary equipment to implement MIT without the strain of heavy upfront costs. Additionally, expanding rural infrastructure such as reliable electricity and transport networks will ensure that modern irrigation technologies can be delivered and maintained efficiently.

4.2.4 Public-Private Partnerships (PPPs)

Collaboration between governments, private companies, and development organizations is crucial for ensuring the successful and widespread adoption of modern irrigation systems. Public-private partnerships (PPPs) can help leverage the strengths of both sectors, combining public policy support and private sector expertise and efficiency. Governments can offer regulatory support and create conducive environments for private companies to operate, while private sector players can bring innovation, technological advancements, and efficiency to the provision of irrigation systems. These partnerships can also facilitate the establishment of affordable leasing options or financing programs for farmers, making modern irrigation technologies more accessible. Additionally, by involving development organizations, these partnerships can ensure that smallholder farmers, particularly in underserved areas, benefit from equitable access to MIT. Through joint ventures, the affordability, availability, and sustainability of irrigation systems can be vastly improved.

4.2.5 Further Research

Continued research into the long-term impacts of modern irrigation technologies on various aspects of agriculture, including environmental sustainability, crop diversity, and resilience to climate change, is crucial. Studies should focus on understanding how MIT can enhance not only the efficiency of water use but also the overall sustainability of farming practices. Research should also explore how MIT affects soil health, water tables, and ecosystems in regions where these systems are widely adopted. In addition, region-specific research is needed to tailor irrigation solutions to local conditions, ensuring that technologies are adaptable to different climates, soil types, and crop varieties. Furthermore, research should investigate the potential benefits of integrating MIT with other sustainable farming practices, such as precision agriculture, to further optimize resource use and minimize environmental impact. Finally, evaluating the economic and social impacts of MIT, such as increased income and improved food security, will help guide future policies and interventions aimed at scaling up these technologies.

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