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Impact of microirrigation technologies on financial resilience of smallholder horticulture farmers: evidence from northern Tanzania

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ABSTRACT

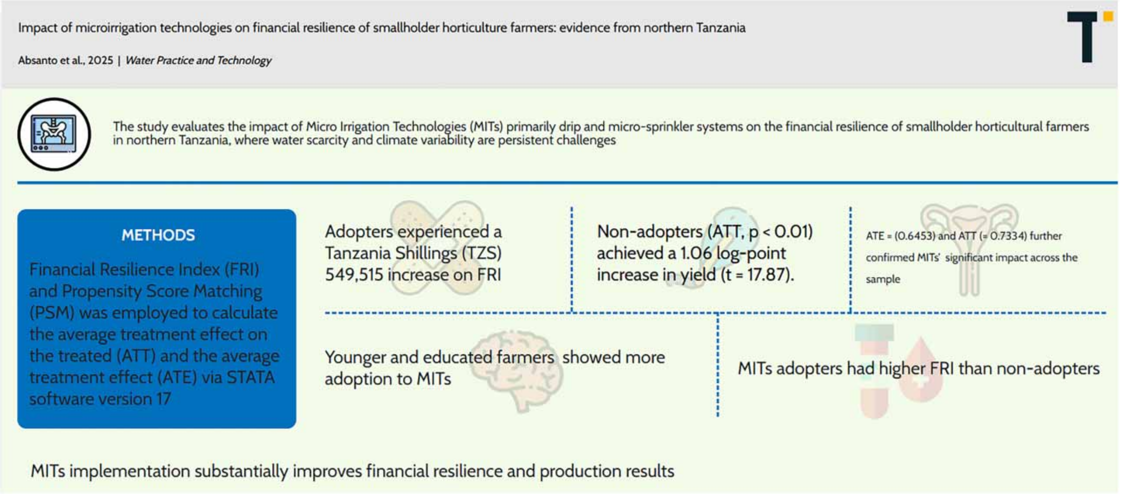
This study evaluates the impact of microirrigation technologies (MITs), primarily drip and microsprinkler systems, on financial resilience of smallholder horticultural farmers in northern Tanzania. A multistage sampling method was used to select 540 households, comprising 199 MITs adopters and 341 nonadopters. Data were collected through structured questionnaires capturing demographic, agroecological, and technical irrigation parameters, including emitter discharge rates (1.5–4.0 L/h), irrigation frequency two to three times per week, and water source quality (electrical conductivity, EC $<$ 2 dS/m). To quantify MITs' contribution to financial resilience, a Financial Resilience Index (FRI) was constructed using both objective and subjective indicators. Propensity score matching was employed to calculate the average treatment effect on the treated (ATT) and the average treatment effect (ATE). The results indicate that MITs adoption significantly enhances both financial and production outcomes. Adopters experienced an increase of 549,515 Tanzania Shillings on FRI compared to nonadopters (ATT, $p < 0.01$) and achieved a 1.06 log-point increase in yield ($t = 17.87$). The ATE (0.6453) and ATT (0.7334) further confirmed MITs' significant impact across the sample. Policies facilitating adoption of MITs, including subsidies, technical training, and enhanced access to capital, are crucial for amplifying MITs adoption.

Key words: financial resilience, horticultural production, microirrigation technologies, northern Tanzania, smallholder farmers

HIGHLIGHTS

- Existing studies on microirrigation technologies emphasize technical and agronomic benefits.
- However, their role in enhancing farmers' financial resilience, specifically their ability to manage economic shocks, stabilize income, and improve financial stability, remains underexplored.
- This study provides empirical evidence on the impact of MITs on financial resilience offering insights into sustainable farming practices and policy development.

GRAPHICAL ABSTRACT



Impact of microirrigation technologies on financial resilience of smallholder horticulture farmers: evidence from northern Tanzania

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The study evaluates the impact of Micro Irrigation Technologies (MITs) primarily drip and micro-sprinkler systems on the financial resilience of smallholder horticultural farmers in northern Tanzania, where water scarcity and climate variability are persistent challenges

METHODS

Financial Resilience Index (FRI) and Propensity Score Matching (PSM) was employed to calculate the average treatment effect on the treated (ATT) and the average treatment effect (ATE) via STATA software version 17

Adopters experienced a Tanzania Shillings (TZS) 549,515 increase on FRI

Non-adopters (ATT, p < 0.01) achieved a 1.06 log-point increase in yield (t = 17.87).

ATE = (0.6453) and ATT (= 0.7334) further confirmed MITs' significant impact across the sample

Younger and educated farmers showed more adoption to MITs

MITs adopters had higher FRI than non-adopters

MITs implementation substantially improves financial resilience and production results

1. INTRODUCTION

Efficient and sustainable water management is a critical concern in smallholder agricultural systems, particularly in semiarid regions of sub-Saharan Africa where climate variability and resource constraints intensify vulnerability (Bojago & Abrham 2023). Among the most pressing challenges is the inefficient use of irrigation water, which significantly limits productivity and resilience in horticulture-based livelihoods (Sashika *et al.* 2024). Microirrigation technologies (MITs) such as drip and microsprinkler systems have emerged as transformative, water-saving innovations that offer both agronomic and economic benefits (Su & Singh 2024). These technologies allow accurate water application, delivering water precisely to the root zones of crops, thus increasing water usage efficiency and minimizing waste (Agbenyo *et al.* 2022). In northern Tanzania, where water shortages and unpredictable rainfall present considerable obstacles, the implementation of microirrigation systems have transformational potential for smallholder farmers growing high-value commodities such as onions, tomatoes, and peppers (Singh & Dangi 2022). While the adoption of such technologies is primarily motivated by their potential to optimize water use, improve yields, and reduce production risk, understanding their broader socioeconomic impact remains critical (Williams *et al.* 2021).

The necessity of microirrigation for smallholder farmers is linked to its capacity to resolve critical issues associated with conventional irrigation techniques (Mdemu *et al.* 2024). Furrow and other surface irrigation methods are often used by smallholder farmers; however, they are linked to inefficiencies, such as water losses from evaporation, infiltration, and runoff (Absanto *et al.* 2025b). Microirrigation enables farmers to improve water use, thus sustaining production despite restricted water supplies (Angold 2023). This efficiency is especially useful in water-scarce locations such as northern Tanzania, where agriculture relies largely on valuable and unpredictable water supplies (Bojago & Abrham 2023).

MITs enhance financial resilience of smallholder farmers by improving crop yields, enhancing produce quality, and stabilizing income, thereby reducing vulnerability to climate-induced production shocks (Dawid Mume *et al.* 2023). Research indicates that these systems increase the consistency of water distribution, promote optimum crop development, and minimize losses attributable to water stress (Ward *et al.* 2022; Absanto *et al.* 2025a). For horticultural producers, increased yields result in increased revenue and greater financial stability (Goodwin *et al.* 2022; Dawid *et al.* 2023). In areas characterized by erratic precipitation, such as northern Tanzania, microirrigation offers a reliable method for maintaining output, which is crucial for economic resilience (Van de Zande *et al.* 2024). A significant benefit of microirrigation systems is their capacity to reduce the labor intensity of irrigation methods (Kumar *et al.* 2023; Kumari *et al*. 2022; Nwosu & Oshunsanya 2021). Conventional techniques can require considerable physical work for water distribution and control, imposing time and effort limitations on smallholder farmers. Economical drip irrigation systems, which are widely used in Tanzania, provide a labor and time-efficient alternative, enabling farmers to concentrate on other agricultural tasks (Tan *et al.* 2021; Bhatti *et al.* 2022; Xiuling *et al.* 2023).

Ward *et al.* (2022) argue that microirrigation techniques increase the financial viability of smallholder farmers by lowering expenses related to water use and energy for pumping, making irrigation more economical over time (Dawid *et al.* 2023). Moreover, microirrigation conserves water, hence reducing the degree of environmental degradation linked to excessive water resource extraction and promoting the sustainability of agricultural practices (Jamil *et al.* 2021). These cost reductions are essential for smallholder farmers, who sometimes have restricted access to formal loans and banking institutions (Mdemu *et al.* 2024).

Horticultural farming in Northern Tanzania faces a range of interlinked biophysical and socioeconomic challenges that threaten productivity and sustainability. The most critical is water scarcity, exacerbated by erratic rainfall patterns, prolonged dry spells, and increasing competition for freshwater from nonagricultural uses (Maliki & Pauline 2023; Mdemu *et al.* 2024). Smallholder farmers, who dominate the horticultural sector, often lack access to reliable irrigation infrastructure, making them highly vulnerable to climate-induced production shocks. This vulnerability is further compounded by the region's fragmented terrain and varied agroecological zones, which influence soil moisture retention and irrigation feasibility (Agbenyo *et al.* 2022). Climate change projections indicate an intensification of rainfall variability, with adverse effects on crop cycles, pest outbreaks, and water availability (Jamil *et al.* 2021; Van de Zande *et al.* 2024). These environmental stressors interact with structural constraints such as limited access to credit, inadequate extension services, and poor post-harvest handling systems, further reducing farmers' adaptive capacity. In this context, the adoption of MITs offers a critical pathway to mitigate the effects of water scarcity and improve yield stability and financial resilience among horticultural producers.

Existing studies on MITs emphasize technical and agronomic benefits, such as water conservation and crop yield improvements (Jayant *et al.* 2022; Angold 2023). However, their role in enhancing farmers' financial resilience, specifically their ability to manage economic shocks, stabilize income, and improve financial stability, remains underexplored (Williams *et al.* 2021; Dawid *et al.* 2023).

While previous studies have examined the agronomic and water-use efficiency of MITs, limited empirical evidence exists on their direct influence on smallholder farmers' financial resilience, particularly in the context of sub-Saharan Africa. This study contributes to the literature by developing a composite Financial Resilience Index (FRI) that integrates income stability, access to savings, and credit and applying propensity score matching (PSM) to rigorously estimate the causal impact of MITs on economic outcomes. Likewise, the study contributes to the field of water practice and technology by examining how MIT's adoption influences the financial resilience of smallholder horticulture farmers in northern Tanzania, providing insights into the nexus of irrigation innovation, water efficiency, and farmer welfare. Moreover, the study contextualizes the analysis within the semiarid agroecological zones of northern Tanzania an underrepresented climate vulnerable region thereby addressing critical spatial and methodological gaps in existing literature.

Although the study adopts a socioeconomic analytical lens, its central focus is the adoption and impact of MITs as innovations designed to improve water-use efficiency in agriculture. These technologies, including low-pressure drip and microsprinkler systems, represent critical advancements in agricultural water management, particularly in water-stressed regions. The analysis demonstrates how MIT's adoption contributes to reducing irrigation water losses, enhancing yield stability, and promoting climate-resilient farming practices among smallholder horticulture farmers. By evaluating both technical and financial outcomes, the study addresses a critical intersection of water practice, irrigation innovation, and rural resilience in semiarid agroecological zones offering evidence-based insights into the role of water-saving irrigation systems in enhancing smallholder agricultural sustainability.

This study aimed to assess the impact of MITs on the financial resilience of smallholder horticulture farmers in northern Tanzania, focusing on their ability to manage economic shocks, stabilize income, increase productivity, and enhance financial stability. By employing PSM, the study compares key indicators of financial resilience and productivity between MITs adopters and nonadopters, aiming to provide empirical evidence that informs strategies for bridging the gap between agricultural innovation and financial security, ultimately supporting the long-term sustainability of smallholder farming.

2. RESEARCH METHODOLOGY

2.1. Agroecological and environmental characteristics of the study area

The study was conducted in three regions of Northern Tanzania, Arusha, Kilimanjaro, and Manyara, which exhibit diverse agroecological and topographical conditions influencing horticultural practices and irrigation suitability. The annual rainfall ranges from 600 to 1,200 mm, with bimodal distribution occurring between March–May and October–December (Bhatti *et al.* 2022). The regions are characterized by volcanic loam, sandy loam, and clay soils, known for their moderate to high water retention capacities, which are critical for vegetable production (Mauki *et al.* 2023; Mojahedimotlagh *et al.* 2024). The terrain varies from highland zones (1,200–1,800 m above sea level (masl)) with sloping fields to lowland plains (800–1,000 masl), influencing both runoff and irrigation infrastructure (UTR 2021). In terms of landforms, the area includes undulating valleys and elevated plateaus, often requiring gravity-fed or pressurized irrigation systems (Malchev *et al.* 2022). Farmers access water from boreholes, shallow wells, and seasonal rivers, with average electrical conductivity (EC) values below 2 dS/m, indicating suitability for horticultural crops (Mukherjee *et al.* 2023; Nasab *et al.* 2023). The demographic profile is dominated by smallholder farming households, averaging 5.2 members per household, with limited access to formal credit and extension services (Lugamara *et al.* 2022).

The study also captured key irrigation system parameters. Among adopters, the most common systems were low-pressure drip kits and microsprinklers, with emitter discharge rates ranging from 1.5 to 4.0 L/h. Emitter spacing varied by crop, typically 20–30 cm for tomatoes and 40 cm for peppers. This contrasts with nonadopters relying on traditional furrow irrigation with higher water loss due to runoff and deep percolation. Irrigation frequency was two to three times per week, depending on evapotranspiration rates and soil type. These technical specifications were validated through interviews with farmers and local extension agents.

2.2. Study design and data collection

This study employed a cross-sectional research design to investigate the impact of MITs on the financial resilience for smallholder horticultural farmers in northern Tanzania. Following the approach of Hirose & Creswell (2022) for research design, a proportional stratified sampling method was utilized to ensure balanced representation.

Data were collected through structured interviews and surveys, capturing information on household demographics, agricultural practices, adoption of MITs, and key outcomes such as water-use efficiency, resilience, and crop yield stability. The cross-sectional design allowed for a snapshot analysis of the influence of MITs across diverse agroecological settings, providing empirical insights into their role in enhancing smallholder sustainability.

The study relied on primary and data sources to capture a comprehensive picture of the impact of MITs on smallholder financial resilience. Primary data were collected through structured household questionnaires. This survey covered demographic and economic information, income levels, production volumes (log-transformed to capture production trends), input costs, and household financial resilience indicators. The survey also gathered data on MITs adoption and related agricultural practices.

2.3. Sampling and sample size

A multistage sampling approach was employed to ensure a representative selection of 540 households. The sample size of 540 households was determined using Cochran's formula and validated against the frameworks of Krejcie & Morgan (1970) and Bartlett *et al.* (2001) to ensure statistical representativeness and precision. Although no formal power analysis was conducted, this approach provided sufficient power for subgroup comparisons and robust PSM analysis. The sample comprising 199 MITs adopters using drip and sprinkler systems and 341 furrow irrigators allowed for balanced stratification. Furthermore, the size aligns with prior empirical studies on irrigation impact in sub-Saharan Africa, reinforcing both methodological consistency and comparability of results.

In the initial stage, the regions were purposefully selected based on their high engagement in horticulture and MITs adoption rates (UTR 2021). Within each region, districts characterized by active MIT use were randomly selected. Households were then stratified into MIT adopters and nonadopters to facilitate comparison through systematic random sampling based on MITs qualification. This method enabled a balanced analysis of the impact of the MITs across diverse heterogeneous smallholder farmer populations.

2.4. Data analysis methods

2.4.1. Descriptive analysis

Descriptive statistical analysis was conducted to explore and summarize household demographic information, income levels, MITs adoption rates, and financial resilience indicators. Tests such as chi-square tests and *t* tests were employed to detect statistically significant differences between MIT adopters and nonadopters. All analyses were performed via STATA version 17.

2.4.2. Measuring financial resilience

The FRI was developed to capture the multidimensional nature of resilience among smallholder horticulture farmers by incorporating both objective and subjective indicators. Objective components included income stability, yield reliability, access to credit, household savings, investment, debt management, multiple income streams, and nonhorticultural income sources. To account for production efficiency, the variable 'total yield (log of production)' was used, with yield data log-transformed to ensure analytical consistency.

Subjective indicators encompassed farmers' perceptions of coping capacity and anticipated income stability, measured through a five-point Likert scale. Respondents rated their confidence in handling unexpected income shocks and their ability to recover from adverse events. This inclusion of perception-based data aligns with resilience assessment frameworks from FAO (2020) and Birkmann *et al.* (2013), emphasizing the role of self-assessed agency in resilience, especially within resource constrained environments.

The weighting of FRI components was guided by a combination of expert consultation, empirical precedence, and contextual relevance to Tanzanian smallholder settings. Income stability (weight = 0.35) and yield reliability (weight = 0.25) received higher emphasis due to their critical roles in buffering climate and market shocks. Access to credit and savings (weight = 0.20) supported financial flexibility, while information access and perceived coping ability (each weight = 0.10) captured enabling conditions and adaptive attitudes. This structure was informed by existing indices in development economics, notably by Dawid Mume *et al.* (2023), and refined through consultations with agricultural economists and extension officers to ensure contextual accuracy and policy relevance.

The FRI was calculated as follows:

$$\mathrm{FRI} = \sum W_j F_j$$

where W_j represents the assigned weight of each resilience indicator F_j, such as income stability, yield levels, and credit access (Mzuyanda & Ajuruchukwu 2018).

2.4.3. Estimating the impact of MITs on income stability and financial resilience

PSM was employed to estimate the impact of MITs on income stability and financial resilience. Given the observational and cross-sectional nature of the data, PSM was selected as the most appropriate impact assessment technique. In the absence of random assignment to treatment (MITs adoption), there existed a risk of selection bias based on observable characteristics. PSM addresses this by matching adopters and nonadopters on observed covariates, thereby approximating a counterfactual scenario and improving causal inference.

Alternative methods such as instrumental variable (IV) regression were considered but rejected due to the absence of valid instruments that affect MITs adoption without influencing financial resilience directly. Likewise, Difference-in-Differences was unsuitable because it requires panel data and the parallel trends assumption, which could not be met with the cross-sectional dataset used.

Therefore, PSM provided a statistically rigorous approach for estimating the average treatment effect on the treated (ATT), enhancing the robustness and credibility of the findings. The average treatment effect on the treated (ATT) was calculated to quantify the impact of MITs adoption on income stability and financial resilience (Williams *et al.* 2021).

The ATT was estimated via the following formula:

$$\mathrm{ATT} = E[Y(1)|D = 1] - E[Y(0)|D = 1]$$

where $Y(1)$ denotes the observed outcome for MITs adopters and $Y(0)$ represents the hypothetical outcome for nonadopters if they had adopted MITs. This estimation enabled an assessment of the contribution of the MITs to income stability and efficiency, as used by Kumari *et al.* (2022). Following a standard six-step PSM procedure, propensity scores were estimated, and a matching algorithm was selected as per variables shown in Table 1. The covariate balance was checked, and ATT was calculated, facilitating a robust comparison of financial resilience between MITs adopters and nonadopters.

3. RESULTS AND DISCUSSION

3.1. Preliminary characteristics of farmers

The descriptive statistics in Table 2 show the socioeconomic characteristics of adopters and nonadopters of MITs. In terms of gender, the results indicated that households that adopted MITs had more males than females. Because female-headed individuals are more socioeconomically disadvantaged than male-headed individuals in many ways, they are slower in adopting small-scale irrigation activities, which require time, energy, and capital. The variation between genders for females and males was 62.2 and 68.6%, respectively, suggesting that gender does not have a very uneven distribution across the adoption of the MIT for financial resilience. This observation aligns with findings by Julien *et al.* (2023), who emphasized the importance of gender-equitable access to agricultural technologies to improve adoption rates and resilience among smallholder farmers.

However as per Table 2, age was significantly associated with adoption. Specifically, a greater proportion of MITs adopters were in the 36–45-year age group (55.1%), indicating that younger and middle-aged farmers are more likely to adopt MITs than older farmers. This finding aligns with the notion that younger farmers may be more open to adopting innovative technologies because of their greater risk tolerance and adaptability (Rouzaneh *et al.* 2021).

Education level was strongly associated with MIT adoption. None of the MIT adopters lacked formal education, whereas 5.8% of nonadopters had no schooling. Furthermore, vocational education was more

Table 1 | Variables and measurement criteria

Variable	Measurement
Gender	Male, female
Age	18–35, 36–45, 46, and above
Marital status	Single, married, divorced, widowed, separated
Education level	Not attended, primary, secondary, university/college, vocational
Household size	Below 3, 3–5, above 5
Farming experience	Below 5, 5–10, above 10 years
Farm size	Measured in acres
Access to extension services	Yes, no
Access to credit	Yes, no
Access to weather information	Yes, no
Adoption of MIT	Yes, no
Total yield (log of production)	Log-transformed production volume
Total FRI	Composite index of income stability, yield stability, credit and financial access

Table 2 | Descriptive statistics for socioeconomic characteristics of horticulture farmers ($n = 540$)

		Adopters		Nonadopters		Total		Pearson chi-square tests		
Variable	**Category**	**Freq**	**Per (%)**	**Freq**	**Per (%)**	**Freq**	**Per (%)**	χ^2	**df**	**Sig.**
Gender	Male	125	62.8	233	68.3	358	66.3	1.71	1	0.191
	Female	74	37.2	108	31.7	182	33.7			
Age	18–35	2	1.0	19	5.6	21	3.9	7.013	2	0.030[a]
	36–45	108	54.3	176	51.6	284	52.6			
	46 and above	89	44.7	146	42.8	235	43.5			
Marital status	Single	4	2.0	9	2.6	13	2.4	4.823	3	0.185
	Married	191	96.0	312	91.5	503	93.1			
	Divorced	0	0.0	0	0.0	0	0.0			
	Widowed	3	1.5	17	5.0	20	3.7			
	Separated	1	0.5	3	0.9	4	0.7			
Education level	Not attended	0	0.0	20	5.9	20	3.7	63.584	4	0.000[a]
	Primary	104	52.3	202	59.2	306	56.7			
	Secondary	50	25.1	107	31.4	157	29.1			
	University/college	8	4.0	7	2.1	15	2.8			
	Vocational education	37	18.6	5	1.5	42	7.8			
Household size	Below 3	0	0.0	3	0.9	3	0.6	5.827	2	0.054[a]
	3–5	19	9.5	53	15.5	72	13.3			
	Above 5	180	90.5	285	83.6	465	86.1			
Farming experience	Below 5	0	0.0	7	2.0	7	1.3	30.423	2	0.000[a]
	5–10	5	2.6	59	17.2	64	11.9			
	Above 10	191	97.4	278	80.8	469	86.9			
Access to extension service	Yes	165	82.9	112	32.9	277	51.4	125.492	1	0.000[a]
	No	34	17.1	228	67.1	262	48.6			
Access to credit	Yes	189	97.4	276	80.9	465	86.9	29.546	1	0.000[a]
	No	5	2.6	65	19.1	70	13.1			
Access to weather information	Yes	188	95.4	199	58.7	387	72.2	83.745	1	0.000[a]
	No	9	4.6	140	41.3	149	27.8			

[a] The chi-square statistic was significant at the 0.05 level.

prevalent among adopters (18.9%) than nonadopters (1.5%). This suggests that farmers with more specialized training or technical knowledge are more likely to adopt MIT, which requires understanding modern irrigation techniques (Mattoussi *et al.* 2023).

The higher adoption rates of MITs among younger and more educated farmers can be explained by a combination of behavioral, informational, and institutional factors. Younger farmers are generally more receptive to innovation and willing to undertake the risks associated with the initial investment in MITs (Singh & Dangi 2022). They are also more likely to be exposed to agricultural extension services, digital platforms, and training programs that promote awareness of water-efficient technologies. Educational attainment further strengthens adoption by enhancing farmers' capacity to comprehend technical information, assess the cost–benefit trade-offs of technology use, and operate MIT systems effectively (Saxena *et al.* 2022). In addition, educated farmers are better positioned to navigate credit mechanisms, access subsidies, and apply agronomic recommendations, which are critical enablers of technology uptake. These findings are consistent with previous empirical studies that link human capital variables such as age, literacy, and cognitive ability to agricultural technology adoption in smallholder contexts (Asfaw *et al.* 2016; Van Campenhout 2021).

Similarly, access to extension services, which provide technical support, was significantly greater among adopters (82.7%) than nonadopters (33.4%). This finding indicates that access to advisory services plays a crucial role in MIT adoption, which is consistent with previous research showing that extension services can increase farmers' capacity to integrate new technologies into their farming systems (Zhang & Song 2024).

Moreover, access to financial resources and weather information also showed strong correlations with MIT adoption. A significantly greater proportion of adopters (94.9%) had access to credit (81.1%), compared to non-adopters, supporting the findings of Goodwin *et al.* (2022), who emphasize that access to financial resources is essential for acquiring irrigation technologies due to their capital-intensive nature. Similarly, adopters were much more likely to have access to weather information, 94.4% against 58.7% of nonadopters, enabling them to optimize irrigation timing and reduce water waste. These findings suggest that financial and informational resources are critical enablers of MIT adoption, in line with studies emphasizing that access to credit and weather information can reduce the financial and operational risks associated with new agricultural technologies (Khalatur *et al.* 2023).

3.2. Adoption level of MIT across regions

The regional distribution of MIT adoption shows varying levels of uptake across the three regions. Arusha had the highest proportion of MITs adopters, with 41.9% of farmers using MITs compared with Kilimanjaro (33.9%) and Manyara (32.1%), as shown in Figure 1. This suggests that the adoption of MITs is more prevalent in Arusha, potentially because of better access to irrigation resources, infrastructure, or support services in the region. These regional disparities are important for targeting interventions that can increase MIT adoption where it is less common, as supported by the literature on regional factors influencing technology adoption (Bhatti *et al.* 2022).

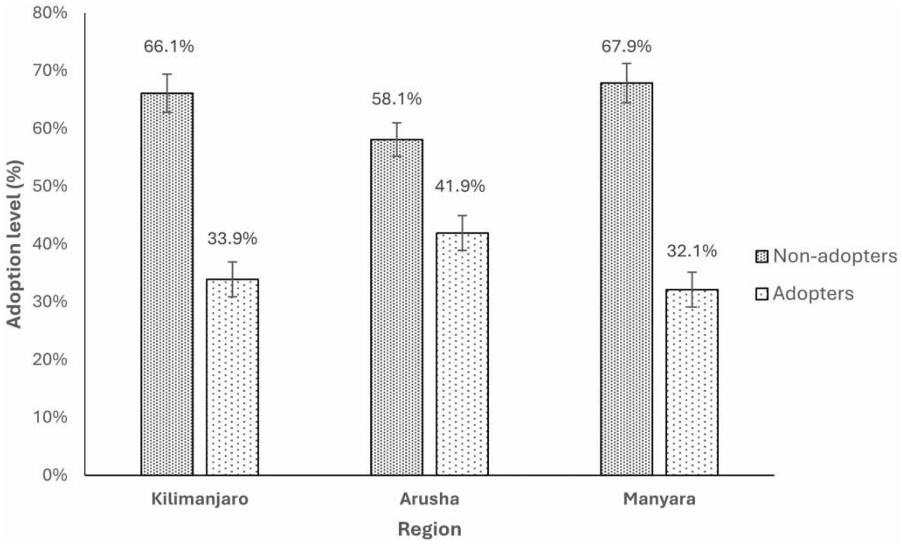

Figure 1 | MIT adoption level across regions (*Source*: Researcher survey, 2024).

3.3. Propensity score matching

3.3.1. Summarizing the matching by propensity score

The descriptive statistics of the propensity scores presented in Table 3 indicate that the average estimated probability (propensity score) of adopting MITs across the sample was 0.485, with a standard deviation of 0.418. This suggests moderate variation in the likelihood of adoption among farmers, as evidenced by the wide range of scores from a minimum of 0.018 to a maximum of 0.989. Farmers with higher propensity scores are much more likely to adopt MITs, whereas those with lower scores are less likely, reflecting differences in socioeconomic characteristics such as education, access to resources, and farming experience that influence adoption decisions. This aligns with Verma & Das (2021) and Kumari *et al.* (2022) showing the disparity between the adopters and nonadopters mainly those not adopting irrigation technology regardless of their welfare status.

Table 3 | Descriptive statistics of propensity scores

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
pscore	540	0.485	0.418	0.018	0.989

The estimation of the propensity score via the binary logistic model (Table 4) reveals that several variables significantly influence the likelihood of adopting MITs. Education level, farming experience, farm size, access to extension services, access to credit, and access to weather information were all significant predictors of MIT adoption. Notably, education had a strong positive effect (Coef. = 2.263, $p < 0.001$), indicating that higher educational attainment significantly increases the likelihood of adoption as aligned by Sabbagh & Gutierrez (2022) and Tan *et al.* (2021) who show the importance of education in adoption. Similarly, farming experience (Coef. = 4.410, $p = 0.005$) suggests that more experienced farmers are more likely to adopt MITs, as experience enhances their capacity to engage with new technologies.

Table 4 | Estimation of propensity score (binary logistic model) ($n = 540$)

Variables	**Coef.**	**SE**	***t*-value**	***p*-value**	**Marginal effect (dy/dx)**
Gender	1.350	0.335	1.210	0.227	1.061
Age	0.692	0.165	−1.540	0.124	0.930
Marital status	1.027	0.285	0.100	0.922	1.005
Education level	2.263	0.358	5.160	0.000[a]	1.176
Household size	1.180	0.477	0.410	0.682	1.034
Farming experience	4.410	2.305	2.840	0.005[a]	1.342
Farm size	0.420	0.074	−4.890	0.000[a]	0.842
Access extension	0.245	0.075	−4.590	0.000[a]	0.757
Access to credit	0.240	0.095	−3.610	0.000[a]	0.754
Access to weather information	0.146	0.063	−4.480	0.000[a]	0.683
Constant	1.222	2.475	0.100	0.921	

[a] Significant at 0.005 ($p < 0.05$).

3.3.2. Assessing the balance after matching

The balance check in Table 5 shows a significant improvement in covariate balance between the treatment (MIT adopters) and control groups (nonadopters). Covariate balance between MIT adopters and nonadopters was evaluated using standardized mean differences (SMDs), variance ratios, and visual inspection of covariate distributions before and after matching. SMDs below 10% were considered indicative of sufficient balance, following established guidelines (Rosenbaum & Rubin 1985). Balance diagnostics were performed for all key covariates, including age, education, land size, access to credit, and household size. The reduction in SMDs from pre- to postmatching was used to assess the effectiveness of the matching algorithm. In addition, balancing

Table 5 | Balance after matching ($n = 540$)

Variable	Unmatched Matched	Mean		Bias		*T* test		V(T)/V (C)
		Treated	Control	%	% reduction	*t*-value	*p*-value	
Gender	U	1.378	1.314	13.40		1.500	0.133	1.09
	M	1.378	1.270	22.50	−68.5	2.280	0.023	1.19
Age	U	2.429	2.378	9.10		1.000	0.316	0.77
	M	2.429	2.286	25.80	−182.0	2.770	0.006	1.04
Marital status	U	2.026	2.099	−16.00		−1.700	0.090	0.43[a]
	M	2.026	2.005	4.40	−72.2	0.620	0.538	1.46[a]
Education level	U	2.888	2.346	57.20		6.860	0.000	2.80[a]
	M	2.888	2.674	22.60	60.5	2.280	0.023	3.18[a]
Household size	U	2.903	2.817	23.60		2.520	0.012	0.49[a]
	M	2.903	2.903	0.00	100.0	0.000	1.000	0.74[a]
Farm experience	U	2.974	2.788	54.60		5.540	0.000	0.12[a]
	M	2.974	2.980	−1.50	97.3	−0.340	0.737	1.24
Farm size	U	1.378	1.676	−36.00		−3.820	0.000	0.44[a]
	M	1.378	1.372	0.60	98.3	0.070	0.943	0.71[a]
Access extension	U	1.173	1.666	−114.90		−12.470	0.000	0.65[a]
	M	1.173	1.224	−11.90	89.6	−1.260	0.207	0.82
Access credit	U	1.051	1.189	−43.40		−4.530	0.000	0.32[a]
	M	1.051	1.061	−3.20	92.6	−0.440	0.662	0.84
Access weather	U	1.056	1.413	−92.70		−9.550	0.000	0.22[a]
	M	1.056	1.056	0.00	100.0	0.000	1.000	1.00

[a] If variance ratio outside [0.75–1.33] for U and [0.75–1.33] for M.

plots and histograms of propensity scores were examined to ensure overlap and common support. These checks confirmed that the matched sample achieved satisfactory covariate balance, allowing for unbiased estimation of treatment effects.

For unmatched data, several variables, such as education level, farm experience, farm size, access to extension, and access to weather information, exhibited substantial bias, with *p*-values <0.05 and high bias percentages (e.g., education level with 57.2% bias). After matching, the bias was significantly reduced across almost all the variables, as indicated by the percentage reduction in bias. For example, education level shows a 60.5% reduction, farm experience a 97.3% reduction, and farm size a 98.3% reduction. The variance ratios ($V(T)/V(C)$) also fall within the acceptable range of [0.75–1.33] for most variables after matching, confirming that the treatment and control groups were more balanced. This improved balance suggests that PSM effectively reduces bias and creates comparable groups for further analysis of the impact of MITs (Dawid *et al.* 2023). However, there were still small imbalances in some variables, such as gender and marital status, but these imbalances were less concerning given their reduced magnitude.

3.3.3. Common support

The results from Table 6 and Figure 2 show that all observations in both the treated (MIT adopters) and untreated (nonadopters) groups lied within the region of common support, meaning that there were no observations of support. Specifically, all 199 treated observations and 341 untreated observations lied within the overlap region, confirming that there was sufficient overlap in the propensity scores between the two groups to ensure comparability. This is a crucial condition for PSM because it ensures that every treated individual has a counterpart in the

Table 6 | Results for common support tests for treatment categories ($n = 540$)

Treatment	Support		Total
	Off support	On support	
Untreated	0	341	341
Treated	0	199	199
Total	0	540	540

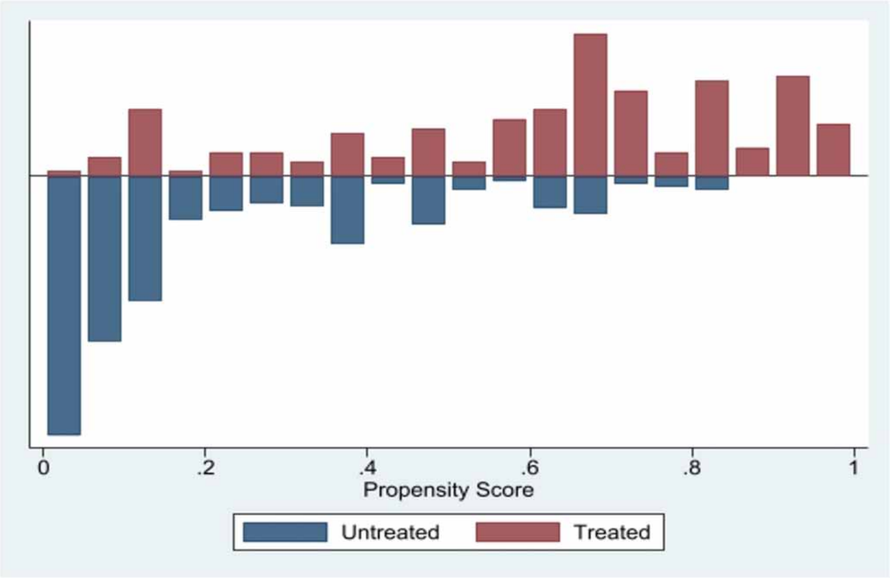

Figure 2 | Score distribution across treatments.

untreated group with a similar propensity score, which enhances the reliability of causal inference from the matching process (Jena *et al.* 2023). All observations on common support indicate that there were no extreme propensity scores that would lead to a lack of comparable untreated units for some treated units, which is essential for minimizing bias in the estimation of treatment effects (Azadi *et al.* 2021). This strong overlap ensures that the treatment effect can be estimated without significant extrapolation beyond the data, leading to more robust and generalizable results.

3.3.4. Assessment of treatment effects across production and financial resilience scores

Table 7 presents the treatment effect of MIT on income and production, comparing the treated and control groups in terms of two main outcome indicators. For the FRI, the unmatched comparison showed a significant difference of 706,771 Tanzanian Shillings (TZS), with a high *t* statistic of 11.71, suggesting that treated individuals had notably greater financial resilience. After adjusting for treatment effects (ATT), the difference decreased to 549,515 TZS, with a *t* statistic of 8.10, indicating a substantial effect of microirrigation on improving financial resilience. Similarly, for total yield, the unmatched data showed a difference of 1.22 with a *t* statistic of 20.34, which decreased to 1.06 after ATT adjustment, with a *t* statistic of 17.87, indicating a positive but slightly smaller impact on production compared with the raw comparison. These results are consistent with Geda (2023), who observed that irrigation technologies significantly enhance financial stability and yields among smallholders, and with Nikam & Pawar (2022), who emphasized the role of technology adoption in improving agricultural productivity and economic resilience.

Table 8 provides further insight into the treatment effects of MIT by comparing adopters and nonadopters via two estimations: the average treatment effect (ATE) and the average treatment effect on the treated (ATT). The ATE coefficient was 0.6453 with a standard error (SE) of 0.082, and the *z* statistic was 17.81, which was highly significant (p-value < 0.000), indicating a strong overall impact of microirrigation on financial resilience and production outcomes for the entire sample, including both adopters and nonadopters. The confidence interval for

Table 7 | Treatment effect on income and production

Outcome indicators	Sample	Treated	Controls	Difference	SE	*T*-stat
Total FRI	Unmatched	1,250,000	543,229	706,771	253,926	11.71
	ATT	901,918	352,403	549,515	145,064	8.10
Total yield (log of production)	Unmatched	4.79	3.57	1.22	1.64	20.34
	ATT	4.69	3.63	1.06	1.85	17.87

Table 8 | ATE and ATT estimation for adopters and nonadopters ($n = 540$)

Adopters vs nonadopters	Coefficient	SE	z	$P > z$	95% conf. interval
ATE	0.6453	0.082	17.81	0.000	0.4807–1.833
ATT	0.7334	0.021	33.86	0.000	0.6759–0.6910

ATE ranged from 0.4807 to 1.833, further confirming the positive effect. The ATT coefficient was slightly greater at 0.7334, with an extremely low SE (0.021) and a z statistic of 33.86, suggesting a significant treatment effect for those who adopted the technology. The confidence interval for ATET was tight, ranging from 0.6759 to 0.6910, reinforcing that the technology has a substantial positive effect on those who adopted it. These results align with Jena *et al.* (2023), who demonstrated the importance of agricultural technologies in enhancing productivity and resilience among smallholders, and with Nyang'au *et al.* (2021) and Jarwar *et al.* (2019), who found that adoption of innovative irrigation practices leads to significant improvements in economic stability and yield outcomes.

The adoption of microirrigation appears to increase both the financial resilience and agricultural yield of farmers, providing them with increased financial stability and more reliable production outcomes. Studies such as those by Sisay *et al.* (2024) have shown that microirrigation not only improves crop yields but also enhances farmers' ability to manage financial risks by optimizing water use and reducing the cost of irrigation. Furthermore, microirrigation has been shown to significantly reduce vulnerability to income shocks, as it helps farmers use water more efficiently and thus increases productivity even in times of water scarcity (Agholor *et al.* 2024; Katic 2024). These results underscore the role of microirrigation in creating sustainable and resilient farming systems that can withstand both economic and environmental stresses (Agholor *et al.* 2024; Katic 2024; Sisay *et al.* 2024). Further analysis in Table 8, which estimates the ATE and the average treatment effect on the treated (ATT), reinforces these conclusions by offering a more nuanced understanding of the treatment effects. The ATE suggests that technology has a significant overall impact on improving financial resilience and production outcomes across the sample, even for those who did not initially adopt it (Jatana & Tesfahun 2024). This supports the findings of Jamil *et al.* (2021), who reported that the introduction of microirrigation in a community had positive spillover effects, benefiting nonadopters indirectly through changes in the local agricultural ecosystem. However, ATT, which focuses specifically on those who have adopted the technology, has an even stronger effect, indicating that the benefits of microirrigation are most pronounced when farmers actively engage with the technology. This is in line with the work of Auci & Pronti (2023), who reported that farmers who fully adopted microirrigation achieved the greatest increases in crop yields because of optimized water use and improved farming practices. Similarly, Langemeyer *et al.* (2021) and Халатур *et al.* (2023) noted that adopters of microirrigation often have better management practices, which lead to greater benefits in terms of both yield and financial returns.

4. CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

The adoption of MITs has emerged as a pivotal intervention for transforming smallholder farming systems, particularly in regions prone to water scarcity and economic volatility. These advancements not only improve the economic well-being of individual households but also have a cascading effect on entire farming communities by fostering shared knowledge and innovation.

The findings demonstrate that MIT adoption benefits both adopters and nonadopters by reinforcing the inclusive nature of this technology. Adopters' success stories act as catalysts, inspiring wider acceptance and further enhancing the technology's reach and effectiveness. Moreover, MITs contribute to environmental sustainability by reducing water waste and mitigating the adverse effects of climate change. These adaptive capabilities are critical for ensuring long-term food security and safeguarding livelihoods in horticulturally active regions such as northern Tanzania. The study emphasized that promoting the MITs can serve as a cornerstone for building climate-resilient farming systems, aligning with broader national and global goals for sustainable agriculture.

The broader adoption of MITs also paves the way for financial stability within farming communities, encouraging reinvestment in innovative practices and infrastructure. This reinvestment cycle is essential for fostering a culture of continuous improvement and technological adaptation in agriculture. MITs represents a transformative opportunity to address persistent challenges in agricultural productivity, water management, and financial resilience. Its adoption is not merely a technical upgrade but also a paradigm that has shifted toward more sustainable and equitable farming systems. By empowering smallholder farmers to achieve greater economic and environmental resilience, MITs have the potential to catalyze lasting improvements in rural livelihoods and contribute to broader developmental objectives. Future research should focus on scaling up adoption, understanding long-term socioeconomic impacts, and exploring complementary innovations to further enhance the effectiveness of MITs in diverse agricultural contexts.

4.2. Recommendation

4.2.1. Expanding access to MITs

To maximize the transformative benefits of MITs, policies should focus on expanding accessibility and affordability for farmers. Governments and development partners could implement subsidy programs or tax incentives to reduce the initial cost of purchasing MIT equipment. In addition, integrating MIT training into agricultural extension programs can equip farmers with the skills necessary to optimize its use. Partnerships between governments, private sector stakeholders, and financial institutions should foster targeted credit and leasing facilities tailored to smallholder farmers. By creating favorable conditions for MIT adoption, these measures can address barriers to entry and scale up its benefits across farming communities.

4.2.2. Strengthening financial inclusion and support services

Policy frameworks should prioritize the expansion of financial inclusion to complement MIT adoption. Governments and financial institutions can develop microfinance products tailored to agricultural needs, such as low-interest loans for irrigation technologies and crop insurance schemes, to mitigate income risk. Policymakers should also encourage the formation and capacity building of community savings groups such as Village Community Banks (VICOBA) and Accumulative Savings and Credit Associations (ASCAS), which can serve as grassroots platforms for mobilizing resources. Investments in mobile banking infrastructure and digital literacy can enhance access to financial services in underserved areas, promoting resilience and sustained productivity among rural farmers.

4.2.3. Policy implications for sustainable agriculture

Policymakers must recognize the broader implications of MIT adoption for sustainable agriculture. By incorporating MITs into national agricultural policies and water resource management plans, governments can promote climate-resilient farming practices that align with environmental conservation goals. In addition, policies that incentivize the adoption of the MITs should be coupled with measures to safeguard natural water sources and prevent overextraction. Encouraging public–private partnerships to invest in research and innovation for improved irrigation technologies can ensure that MITs remain adaptable to evolving agricultural challenges. These policy actions not only enhance food security and rural livelihoods but also contribute to achieving Sustainable Development Goals.

5. AREA FOR FURTHER STUDY

Following the results of this study, future research should explore the long-term impacts of MITs on farmers' livelihoods, with a focus on multidimensional outcomes such as food security, household welfare, and environmental sustainability. In addition, further research should assess the scalability and replicability of MITs adoption in different agroecological zones, considering variations in socioeconomic and cultural contexts.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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