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Unlocking Productivity Gains: The Influence of Irrigation Adoption on Small-Scale Permanent Crop Farmers: Empirical Evidence from Banana crop in Tanzania.

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Abstract

Agricultural productivity including of permanent crops including banana remains low in Tanzania due to dependency on rain-fed agriculture and majority of small-scale farmers have not adopted irrigation. Fostering productivity of banana crop in Tanzania requires understanding on drivers of adopting irrigation and its effects among small-scale farmers. Studies on the productivity effect of adopting irrigation among small-scale permanent crop such as banana farmers are scanty in Sub-Saharan Africa including Tanzania. Also, extant studies on the productivity effect of adopting irrigation have not applied meta-frontier analysis method while accounting for selection bias. Thus, this study covered such lacuna by assessing the effect of adopting irrigation on productivity among small-scale banana farmers in Tanzania. This study applied dataset from the National Sample Census on Agriculture [NSCA] of 2019/2020 with the sample of 6,008 small-scale banana farmers in Tanzania. Our study found adoption of irrigation in banana farming is driven by irrigation scheme in the village, female-headed households, banana area and banana farmers residing in the central, eastern and northern agroecological zones. Also, we find adopting irrigation improves productivity of small-scale banana farmers. Furthermore, our study emphasizes on the designing of the sustainable irrigation schemes in villages as relevant policy options for adoption of irrigation and thus, improving productivity of small-scale permanent crops farmers particularly banana farmers.

Keywords: irrigation adoption, productivity, permanent crops, banana, small-scale farmers, Tanzania

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1. INTRODUCTION

Improving agricultural productivity in Sub-Saharan Africa is important in increasing food security and household welfare (Gao et al., 2026: Jatana, & Tesfahun, 2025; Tibamanya et al., 2022a; Castaneda et al., 2018), and thus, reduce both hunger and poverty (Kitole et al., 2022). Fostering productivity in agriculture including of banana crop in Tanzania is vital in increasing food supply and thus, help in meeting of food demand for the increasing population (Tibamanya et al., 2022c). According to FAO (2022) the number of people in Tanzania will reach 79 million in 2030 and 135 million in 2050 with the country's food demands expected to reach 18.8 million tones. However, the agricultural productivity including of permanent crops specifically banana crop remains low in Tanzania associated with dependency on rain-fed agriculture (Tibamanya et al., 2022a; URT, 2021; Ministry of Finance and Planning, 2021; Mpeta et al., 2018; United Republic of Tanzania, 2017). Productivity refers to the ratio of the amount of output produced to the quantity of resources used (Henningsen et al., 2015; Coelli et al., 2005; Fried et al., 2008). Productivity can be measured by efficiency including output-oriented technical efficiency (Henningsen et al., 2022; Coelli et al., 2005). Output-oriented technical efficiency is the ratio of the observed output quantity to the maximum output quantity that can be produced with the observed input quantities (Henningsen & Czekaj, 2019; Henningsen et al., 2022). Agricultural yields, productivity and food security are recently marked to be affected by altering occurrence of droughts, flooding and rainfall cycles due to climate change (Babakholov et al., 2022; Engler et al., 2016; Heumesser et al. 2012). In Sub-Saharan Africa including Tanzania, the agricultural productivity remains low due several reasons among are both dependency on rain-fed, low use of irrigation and use of small-scale irrigation farming including banana farming (Bryan and Mekonnen, 2023; United Republic of Tanzania (URT), 2021). In effort to promote the use of irrigation in permanent crops including banana crop in Tanzania, the government increased the irrigation budget from 46.5 billion in 2020/21 to 361.5 billion in 2022/23 (MoA, 2022). The allocated budget is expected to increase the irrigated farmlands include the banana farmland from 727,280.6 hectares to 822,285.6 hectares and to result into an increase in agricultural productivity by 50% in 2030 (MoA, 2022). However, in Tanzania still only 3.8 percent of the entire cultivated land is irrigated of which only 1.3 percent is cultivated with permanent crops including banana crop (National Bureau of Statistics, 2021, URT, 2021)[1].This result into not fully utilization of potentials in applying productivity enhancing inputs including improved seeds, fertilizers as well as pesticides (URT, 2021). The productivity of banana crop annually is only 5-7 tons per hectare (Lucas and Jomanga, 2021) compared to potential productivity of 25 tons per hectare (Kibona, 2020). Fostering adoption of irrigation among banana small-scale farmers requires knowledge on its drivers and its effects of productivity.

Numerous studies have explored the drivers of irrigation adoption and its effects on agricultural productivity (Gao et al., 2026; Sima and Aduna, 2026; Jatana, & Tesfahun, 2025; Olkeba et al., 2025; Abdelghany et al. 2025; Niu et al., 2025; Asfaw Eshetu and Mekonen, 2024; Gautam et al., 2024; Guo et al., 2023) yielding diverse results across different regions and farming scales. Studies on adoption drivers highlight household traits, socio-economic, and institutional factors influencing irrigation adoption in Sub-Saharan Africa (Ngango & Hong, 2021; Jordan & Speelman, 2020). Research on irrigation's productivity effects consistently shows positive effects, including on wine grape productivity in Chile (Bopp et al., 2022), maize yields in Rwanda (Ngango & Hong, 2021), and rice yield in India (Nayak et al., 2020). However, some studies, like Babakholov et al. (2022),

[1] National Sample Census on Agriculture Report (2021)

found negative influences, such as reduced cotton yields in Uzbekistan. Despite these varied findings, most studies emphasize the positive link between irrigation adoption and improved crop productivity.

Studies (Gao et al., 2026; Abdelghany et al. 2025; Niu et al., 2025; Yang et al., 2023) have shown that specific irrigation methods can significantly influence productivity. For instance, collective drip irrigation improved land productivity among cotton farmers in China (Guan et al., 2022), and transitioning to optimized furrow irrigation increased soybean yields in Mississippi (Bryant et al., 2022). Additionally, alternate wetting and drying (AWD) and furrow irrigation boosted wheat-rice yields and efficiency in China (Wang et al., 2018), while groundwater motor pumps increased output in Ghana (Owusu, 2016). However, most studies focus on annual crops, with few addressing permanent crops like banana. One exception is Kibona (2020), who found that drip irrigation led to higher banana yields in Northern Tanzania. Understanding the influence of irrigation on banana productivity is vital for improving food security and livelihoods in tropical countries like Tanzania (Madalla, 2023; Digo, 2022).

Furthermore, the extant studies on productivity effect of irrigation have not accounted for selection bias associated with both observed and unobserved traits as well as not applied meta-frontier analysis in assessing the productivity effect of irrigation in the context of small-scale banana farmers. These gaps are covered in this study. Unlike conventional methods such as Endogenous Switching Regression (ESR), Instrumental Variables (IV), and Doubly Robust Estimation, which primarily estimate the causal effects of participation while assuming a common production technology, this study combines selection bias correction with meta-frontier analysis to account for technology heterogeneity between contract and non-contract farmers. The meta-frontier approach enables the estimation of group-specific technical efficiency, technology gap ratios, and meta-frontier technical efficiency, thereby distinguishing efficiency differences arising from farmers' performance from those attributable to disparities in production technology. By jointly addressing non-random participation and heterogeneous technologies, this approach provides a more comprehensive assessment of the impact of contract farming on farmers' productivity and technical efficiency.

Thus, applying the production theory developed by Wicksteed (1894) in studying the effect of adoption of irrigation on productivity among small-scale banana crop farmers in Tanzania is important in improving National Agricultural Policy of 2013, National Irrigation Policy of 2010, National Irrigation Master plan of 2018, National Irrigation Strategy of 2015 and Agenda 10/30 (that striving to reach 10 percent of agricultural sector growth by 2030) under Ministry of Agriculture in Tanzania. Also, this study provides necessary information to policy makers regarding the public spending on irrigation programs or government-developed irrigation schemes. Furthermore, our study contributes to the Building a Better Tomorrow (BBT) program under Ministry of Agriculture in Tanzania which emphasize on the adoption of irrigation or irrigation schemes in crops block farming. Finally, the study provides relevant information to the policy makers with regards to developing an effective irrigation system in the country which is demand-driven considering the drivers of adoption. Our study contributes to literature in two aspects; firstly, it examines the relationship between agroecological zones and adoption of irrigation, which is largely ignored by previous studies. Secondly, it analyses the effect of irrigation on productivity of banana using meta-frontier analysis.

The next section presents the theoretical framework. In Section 3, we present the context and data used in the analysis. Section 4 presents the results of the study. In Section 5, we discuss the results. The final section presents a brief summary and conclusions.

1.2 Banana production, irrigation and productivity in Tanzania

Tanzania is the second-largest banana producer in East Africa and the highest consumer globally, with an average consumption rate of 280-500 kg per person (Kibona, 2020; Lucas & Jomanga, 2021). Banana is the fourth most produced crop in Tanzania, meeting 30% of household food demand and 70% in local markets (Meya et al., 2020). The crop is mainly grown in the Lake Zone, with notable production in regions like Kagera, Kilimanjaro, and Mbeya (NBS, 2012; Lucas & Jomanga, 2021). It is cultivated in monocropping or mixed cropping systems, often alongside coffee and other crops (URT, 2021; Lucas & Jomanga, 2021). Banana is a crucial crop for food security and income generation, especially for small-scale farmers (Madalla et al., 2023; URT, 2021). In 2021, Tanzania's banana production reached 2,039,433 tons, with small-scale farmers contributing the majority (URT, 2021).

In Tanzania, banana production relies heavily on seasonal rainfall and irrigation, particularly during the short rainy season. Irrigation sources include rivers, wells, and dams, with various techniques such as pumps and gravity irrigation (URT, 2021; United Republic of Tanzania, 2017). However, irrigation coverage for permanent crops like bananas is limited, occupying only 1.3% of the total planted area (URT, 2021; National Bureau of Statistics, 2021). Challenges to banana production include moisture stress, diseases, poor infrastructure, and over-reliance on rainfall, resulting in low productivity (Kibona, 2020; Meya et al., 2020; Lucas & Jomanga, 2021). Despite government policies and strategies aimed at promoting irrigation, adoption remains low among small-scale farmers, hindering agricultural growth (URT, 2013; Ministry of Agriculture, 2022). Addressing barriers to irrigation adoption is crucial to improving productivity (Ngango & Hong, 2021).

2. MATERIALS AND METHODS

2.1 Data and study site

The study applied secondary data from the National Sample Census on Agriculture [NSCA] of 2019/2020 involving about 6,008 small-scale banana farmers in 31 regions in Tanzania. In Tanzania, small-scale banana farmers are majority with higher contribution in banana yields than large-scale banana farmers (United Republic of Tanzania, 2021; Kibona, 2020). The 31 regions in Tanzania are used in our study because they address for external validity of previous studies (e.g., Moursy et al., 2023; Babakholov et al., 2022; Bopp et al., 2022; Bryant et al., 2022; Guan et al., 2022; Ngango and Hong, 2021; Nayak et al., 2020; Kukal et al., 2020) on effects of irrigation on productivity which mostly did not cover many regions in particular country. The analysis included both descriptive statistics analysis such as independent sample t-test as well as chi-square test and econometric model analysis based on equations or models specified in section 2.2. Our study applied statistical software environment R as a statistical tool (R Core Team, 2022) using the add-on packages including sample selection (Henningsen and Toomet, 2020), MatchIt (Ho et al., 2011), Matching (Sekhon, 2011) , lmtest (Zeileis and Hothorn, 2002) as well as sfaR (Dakpo et al., 2022).

2.2 Econometric model specification on the productivity effect of irrigation

The productivity effect of adopting irrigation is analyzed using meta-frontier analysis suggested by Villano et al. (2015). The framework includes three steps (e.g., Villano et al., 2015; Henningsen et al., 2015; Tibamanya et al., 2022b). First step, use the propensity score matching which address the self-selection bias due to observable variables and gives adequate control group (e.g., Villano et al., 2015; Henningsen et al., 2015; Tibamanya et al., 2022b).The Propensity Score Matching [PSM] by Rosenbaum and Rubin (1983), Imbens (2000) and Caliendo and Kopeinig (2008) establishes two matched samples of adopter and non-adopter farmers of irrigation with similar traits. Some studies (e.g., Ngango and Hong, 2021; Adebayo et al., 2018; Nonvide, 2017) have recently analyzed irrigation effects using PSM. However, our study used one-to-one nearest neighbor matching without replacement as identification strategy by matching each adopter farmer with exactly one non-adopter farmer (e.g., Tibamanya et al., 2022b; Henningsen et al., 2015). Nearest-neighbour matching without replacement was presented as the main specification because it provides the closest one-to-one comparison between irrigators and non-irrigators and avoids assigning excessive weight to repeated control observations. Robustness checks using kernel and radius matching generated similar results, confirming that the estimated productivity effects of irrigation are not sensitive to the choice of matching algorithm.

Second, our study estimate productivity using two stochastic frontier models by Villano et al. (2015) as suggested by Greene (2010) and applied by Bravo-Ureta et al. (2012), Henningsen et al. (2015) and Tibamanya et al. (2022b). The one stochastic frontier is for adopters of irrigation and another for non-adopters of irrigation by eliminating bias. According to Greene (2010)[2] the model also accounts for the non-random sample selection. The model can be specified as[3]:

$$y_i = \beta' x_i + {}_{\gamma} d_i + \epsilon_i \tag{1}$$

$$d_i = 1\,[\propto' z_i + w_i > 0] \;\;,\;\; w_i \sim \mathrm{N}\,(0, 1) \quad, \epsilon_i = v_i - u_i \tag{2}$$

However, estimating the two stochastic frontiers prevent a comparison of the productivity of the two groups of farmers as a reference estimator is required (Henningsen et al., 2015; Tibamanya et al., 2022). Thus, a meta-frontier[4] that encloses the production frontiers of the two groups of farmers is a relevant estimator (Villano et al., 2015; Tibamanya et al. 2022; Henningsen et al., 2015). Meta-frontier[5] (O'Donnell et al., 2008; Villano et al., 2015; Henningsen et al., 2015; Tibamanya et al. 2022b) is written as:

$$y_i^* = f\left(x_i \beta^{*'}\right) = e^{x_i \beta^{*'}} \tag{3}$$

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[2] Greene (2010) extended Heckman's approach to take sample selection into account a stochastic frontier framework assuming that the "unobserved characteristics (w_i) in the selection equation are correlated with the noise (v_i) in the stochastic frontier" (Henningsen et al., 2015, p.8).

[3] Where y_i denotes the logarithmic output quantity of farmer i = 1, . . . ,N, x_i is a vector of logarithmic input quantities (and potentially interaction terms and quadratic terms thereof), d_i is a binary dummy variable that is one for irrigating farmers and zero otherwise, z_i is a vector of covariates in the sample selection equation, ϵ_i is the error term of the stochastic frontier model that takes into account noise (v_i) and inefficiency (u_i), w_i is the error term of the selection equation, and $_\gamma$, $\propto$and β' are parameter vectors to be estimated

[4]The deterministic portion of the adopter and non-adopter group frontiers is enveloped by the meta-frontier (Henningsen et al., 2015). As a result, it makes it easier to estimate the meta-technology ratio [MTR], which is the difference between the meta-frontier and each particular group frontier (Henningsen et al., 2015).

[5] Where y_i^* is the meta-frontier output, $\beta^{*\prime}$ denotes the vector of parameters such that $\beta^{*\prime} x_i \geq \max(\beta^{c'} x_i, \beta^{n'} x_i)$, while $\beta^{*'} x_i$ and $\beta^{n'} x_i$ are parameters obtained from the adopter and non-adopter farmers group frontiers.

The estimated parameters of the meta-frontier function (β^{*}) is determined by minimizing the sum of the absolute differences between the meta-frontier and the respective group-specific frontier at all observations (Villano et al., 2015; Tibamanya et al. 2022; Henningsen et al., 2015). The meta-frontier usually is above any of the group-specific frontiers (Rao et al., 2012; Henningsen et al, 2015):

$$min_{\beta^*} \sum_{i=1}^{N} |\beta^{*\prime} x_i \quad - \quad \beta^{a\prime} x_i d_i - \quad \beta^{n\prime} x_i (1 - \ d_i)|, \tag{4}$$

$$s.t. \quad \beta^{*\prime} x_i \ \geq \ \beta^{a\prime} x_i \quad \forall \quad i \tag{5}$$

$$\beta^{*\prime} x_i \ \geq \ \beta^{n\prime} x_i \ \ \forall \ \ i \tag{6}$$

The linear programming is used in resolving the minimization above because β^{c} and β^{n} are assumed to be fixed (Henningsen et al., 2015):

$$min_{\beta^*} \beta^{*'} \bar{x} \tag{7}$$

$$\beta^{*\prime} x_i \geq \ \max\left(\beta^{a'} x_i, \beta^{n'} x_i\right) \ \forall \, i \,, \tag{8}$$

Where $\bar{x} \ = \ N^{-1} \sum_{i=1}^{N} x_i$, is a vector that contains the average values for each component of x_i throughout the entire sample (Villano et al., 2015; Henningsen et al., 2015). The meta-technology ratios [MTRs] of the two groups of farmers can be obtained using the parameters of the meta-frontier function (β^{*}) as follows (Tibamanya et al., 2022; Henningsen et al., 2015):

$$MRT_i = \begin{cases} \dfrac{\beta^{a'} x_i}{\beta^{*\prime} x_i} \quad \text{if } \ d_i = 1 \\ \dfrac{\beta^{n\prime} x_i}{\beta^{*\prime} x_i} \quad \text{if } \ d_i = 0 \end{cases} \tag{9}$$

The meta-technology ratio is ratio of the largest attainable group output to the largest possible meta-frontier output (lie between zero and one) (e.g., Villano et al., 2015; Henningsen et al., 2015). The MTRs indicate how close the group-specific frontiers are to the meta-frontier (Henningsen et al., 2015). Thus, the meta-frontier technical efficiency [TE_i^*] consist of the group specific technical efficiency and the MTR (Tibamanya et al., 2022; Henningsen et al., 2015; Villano et al., 2015):

$$TE_i^* \ = \ TE_i \ \cdot \ MRT_i \tag{10}$$

Some scholars (e.g., Rao et al.,2012; Villano et al., 2015; Henningsen et al., 2015; Tibamanya et al., 2022) used similar approach in analysis of technical efficiency and productivity but not in context of effects of adoption of irrigation.

3. RESULTS

3.1 Descriptive results

3.1.1 Descriptive results comparing adopters and non-adopters of irrigation

Table 1 presents descriptive statistics comparing variables for irrigation adopters and non-adopters in banana farming. Significant differences were found in factors such as banana area, mixed crop banana area, irrigation schemes, access to agricultural credit, and extension services. Adopters tend to have smaller banana areas and harvests, larger households, and higher expenditures on seeds and fertilizer. They are also more likely to receive irrigation extension services, have access to credit, and reside in areas with irrigation schemes. Additionally, adopters are more often located in specific agroecological zones (central, eastern, and northern) and have higher off-farm income. These findings highlight key factors influencing irrigation adoption among small-scale banana farmers.

Table 1: Descriptive results of adopters and non-adopters of banana irrigation

Variable	All	Irrigators	Non-irrigators	P-value
Banana area [acres]	0.021	0.019	0.021	0.0768
Mixed crop banana area [acres]	0.608	0.560	0.617	0.0008
Multiple plots of banana [number]	0.062	0.065	0.062	0.6677
Received extension on irrigation [yes]	0.026	0.090	0.013	0.0000
Adopt irrigation extension [yes]	0.018	0.084	0.005	0.0000
Access to credit for agriculture [yes]	0.027	0.046	0.023	0.0006
Irrigation scheme in village [yes]	0.055	0.136	0.038	0.0000
Female-headed household [yes]	0.216	0.175	0.224	0.0003
Household size [number]	0.509	0.542	5.019	0.0041
Roof made of modern material [yes]	0.900	0.943	0.892	0.0000
Floor made of modern material [yes]	0.479	0.624	0.449	0.0000
Walls made of modern material [yes]	0.74	0.807	0.719	0.0000
Banana harvest [kilogram]	1,126.2	733.5	1,205.6	0.0000
Expenditure on seeds [TZS]	2,532.52	4,505.06	2,133.43	0.0106
Expenditure on fertilizer [TZS]	3098.20	4,662.82	2,781.6	0.0161
Expenditure on other inputs [TZS]	1,045.57	1,430.9	967.60	0.1623
Household member can read and write [yes]	0.963	0.991	0.957	0.0000
Household member has title deed [yes]	0.251	0.264	0.248	0.2870
Household member in farmer group [yes]	0.046	0.052	0.045	0.3441
Household member of cooperative [yes]	0.126	0.138	0.124	0.2171
Off-farm income [yes]	0.617	0.714	0.597	0.0000
Service of district capital [yes]	0.911	0.900	0.914	0.1827
Service of primary market [yes]	0.666	0.680	0.664	0.3237
Service of tarmac road [yes]	0.883	0.903	0.882	0.0398
Central agroecological zone [yes]	0.020	0.05	0.015	0.0000
Eastern agroecological zone [yes]	0.379	0.444	0.366	0.0000
Western agroecological zone [yes]	0.063	0.033	0.070	0.0000
Lake agroecological zone [yes]	0.203	0.122	0.219	0.0000
Northern agroecological zone [yes]	0.40	0.214	0.125	0.0000

Southern agroecological zone [yes]	0.021	0.0109	0.023	0.0022
Observations	6,008	1,011	4,997	

3.2 Econometric results

3.2.1 Drivers of adopting irrigation among small-scale banana farmers

Table 2 shows the results of estimated probit model and marginal effects on probability of adopting irrigation among small-scale banana farmers for both unmatched and matched samples. The results of all explanatory variables for matched sample are insignificant after matching indicating covariates balance i.e., no significant difference between irrigators and non-irrigators of banana farms. The results presented in this section are on the drivers of adopting irrigation among small-scale banana farmers based on unmatched sample. Our study finds female-headed household are less likely to adopt irrigation than male-headed household at 1 percent level, whereas being female household head reduces the probability of adopting irrigation by 0.03 percentage points, holding other factors constant. This is in line with our theoretical expectation that female-sex is negatively related to the adoption of irrigation. Our results are consistent with earlier studies (Nonvide, 2017; Nonvide, 2019; Ngango and Hong, 2021) which found male-headed household is positive related to adoption of irrigation. The difference in results is associated with fact that small proportion (18%) of female-headed banana farmers are irrigators, which also confirm preliminary results in Table 2.

Our study found banana area is positive and significant associated with adoption of irrigation at 1 percent level, whereas it indicates non-linear relationship between banana area and adoption of irrigation. The banana farmers increase a banana area which increases the adoption of irrigation until a certain point and then after irrigation will increase at decreasing rate. The result further indicates that the larger the banana farm area, the higher the probability of adopting irrigation by 0.03 percentage points, holding other factors constant. The result confirms the theoretical explanation that banana farm area is positively related to adoption of irrigation. Also, our results concur with earlier studies (Ngango and Hong, 2021; Engler et al., 2016).

Multiple banana plot is found positive and significant associated with adoption of irrigation at 1 percent level. The result indicates that the large the number of banana plots increases the probability of adopting irrigation by 0.05 percentage points, at ceteris paribus. This confirms our theoretical expectations that multiple banana plots are positively associated with adoption of irrigation.

We find that adopting irrigation extension is related to an increase of the probability of adopting irrigation by 0.43 percentage points and significant at 1 percent level. Also, our study found positive and significant influence of access to credit for agriculture, on adoption of irrigation at 1 percent level. The result shows that banana farmers with access to credit for agriculture is more likely to adopt irrigation by 0.08 percentage points, at ceteris paribus. We also find that having irrigation scheme in the village increases the probability of adopting irrigation by 0.15 percentage points. The result shows a banana farmer who is residing in village with irrigation scheme is more likely to adopt irrigation at 1 percent level of significant.

Table 2: Results of estimated probit model

	Unmatched sample			**Matched sample**		
	Estimate	**S. E**	**ME**	**Estimate**	**S. E**	**ME**
Intercept	-2.209***	0.197	-	0.105	0.368	-
Banana area	-0.598***	0.113	-0.133	0.147	0.163	0.057
Banana area squared	0.137***	0.030	0.031	-0.015	0.033	-0.006
Mixed crop banana area	-0.041	0.042	-0.009	-0.063	0.059	-0.025
Multiple plots of banana	0.244***	0.087	0.054	-0.070	0.120	-0.028
Received extension on irrigation	-0.282	0.243	-0.063	0.324	0.408	0.127
Adopt irrigation extension	1.913***	0.279	0.427	0.524	0.428	0.204
Access to credit for agriculture	0.366***	0.115	0.082	-0.044	0.139	-0.017
Irrigation scheme in village	0.662***	0.0779	0.148	-0.088	0.085	-0.034
Female-headed household	-0.132**	0.052	-0.029	0.106	0.076	0.0413
Household size	0.0007	0.0005	0.0002	0.0008	0.0007	0.0003
Roof made of modern material	0.158*	0.082	0.035	0.040	0.127	0.0158
Floor made of modern material	0.217***	0.048	0.048	0.035	0.070	0.014
Walls made of modern material	0.136**	0.057	0.030	-0.016	0.081	-0.006
Household member can read and write	0.517***	0.158	0.1152	-0.179	0.321	-0.070
Household member has title deed	-0.019	0.047	-0.004	-0.004	0.065	-0.001
Household member in farmer group	0.088	0.095	0.020	0.052	0.133	0.020
Household member of cooperative	-0.004	0.062	-0.0009	0.063	0.087	0.025
Off-farm income	0.115**	0.046	0.026	-0.027	0.066	-0.010
Service of district capital	-0.006	0.082	-0.001	0.029	0.112	0.011
Service of primary market	0.075	0.047	0.017	0.028	0.065	0.011
Service of tarmac road	0.030	0.076	0.007	-0.003	0.109	-0.001
Central agroecological zone	0.937***	0.131	0.209	-0.248	0.150	-0.097
Eastern agroecological zone	0.299***	0.066	0.067	-0.117	0.095	-0.046
Western agroecological zone	-0.049	0.109	-0.011	0.214	0.194	0.084
Lake agroecological zone	0.050	0.077	0.011	-0.083	0.118	-0.032
Northern agroecological zone	0.477***	0.075	0.106	-0.018	0.107	-0.007
Southern agroecological zone	-0.071	0.177	-0.016	-0.293	0.269	-0.114
Observations	6,008			2,022		

Notes: *P = <0.10; **P = <0.05; ***P = <0.01, S. E = Standard error and ME = Marginal effects

This study reveals that a banana farmer having a house made of modern materials of roof, floor and walls increases the probability of adopting irrigation at 1 percent, 10 percent and 5 percent level. The results show that probability of adopting irrigation is increased by 0.04, 0.05 and 0.03 percentage points for a banana farmer who has a house made of modern materials of roof, floor and walls respectively. The results are due to the fact that having house with modern materials motivates the household to develop modern sources of water for irrigation such as tap water and buckets, hand pump as well as motor pump as method of irrigating banana farms.

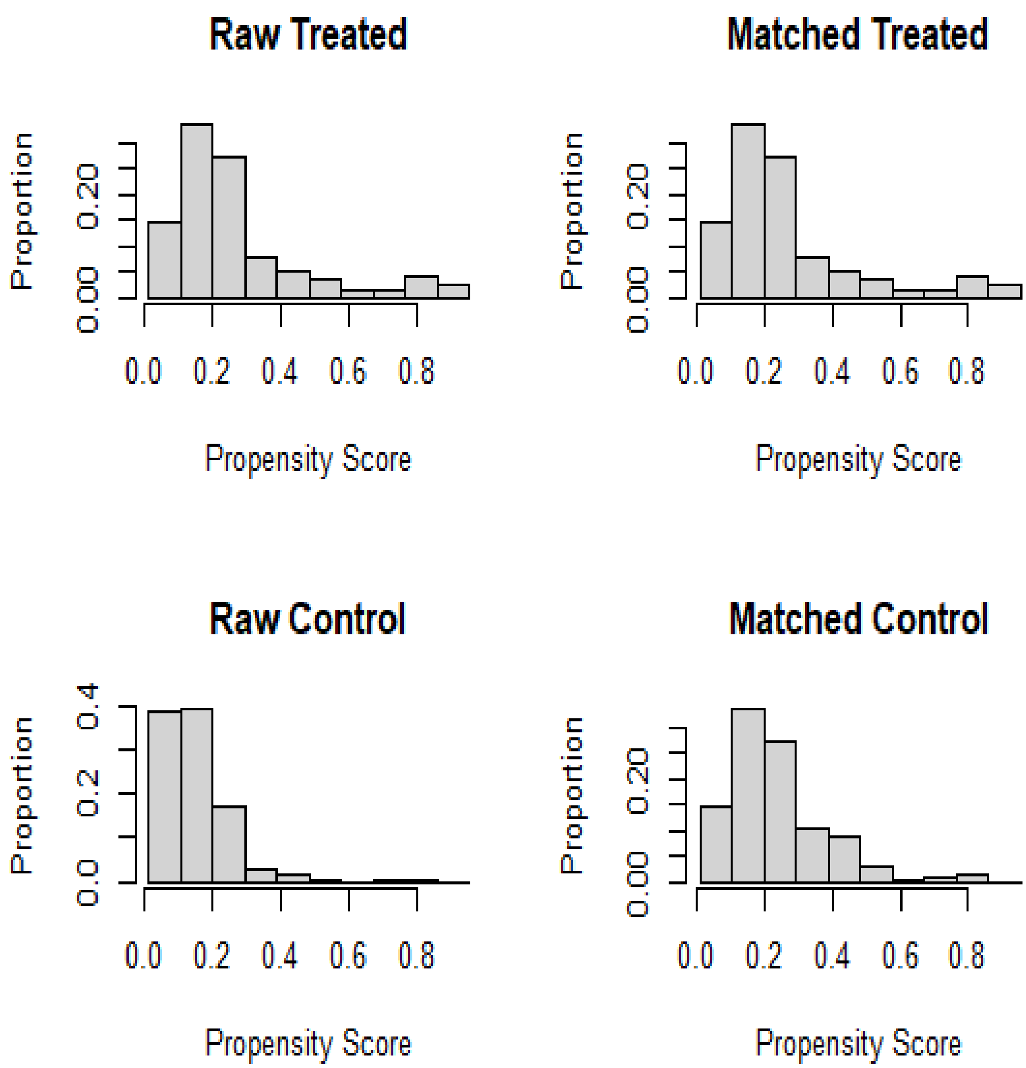
Our analysis shows that literacy in the household significantly increases the probability of adopting irrigation in banana farming, with a 1% level of significance. Specifically, having someone in the household who can read and write increases the likelihood of irrigation adoption by 0.12 percentage points. Additionally, off-farm income is positively associated with irrigation adoption at the 5% level. Households with at least one member earning off-farm income are 0.03 percentage points more likely to adopt irrigation compared to those without off-farm income..

Our study revealed three agroecological zones such as central agroecological zone, eastern agroecological zone and northern agroecological zone to positively and significantly influence adoption of banana irrigation at 1 percent level. The result show that a banana farmer resides in central agroecological zone, eastern agroecological zone and northern agroecological zone increases of the probability of adopting banana irrigation by 0.21, 0.07 and 0.11 percentage points respectively irrigation than the banana farmer reside in southern highlands agroecological zone.

3.2.2 The distribution of propensity scores for adopters and non-adopters of banana irrigation

Figure 1 shows the distribution of propensity score before and after matching using one-to-one nearest neighbor matching (NNM) without replacement. The nearest neighbor matching indicates 1,011 adopters of banana irrigation are matched 1,011 non-adopters of banana irrigation and hence, makes a matched sample of 2022 small-scale banana farmers (Table 6) for the analysis in productivity. The distribution after matching indicates the same distribution of propensity scores between adopters of banana irrigation (matched treated) and non-adopters of banana irrigation (matched control). Thus, the results suggest the substantial overlap of two groups of small-scale banana farmers and covariates balance between adopters and non-adopters of banana irrigation.

Figure 1: The distribution of propensity scores before and after matching for banana farmers



3.2.2 Effect of irrigation on productivity among small-scale Banana farmers

Table 3 shows the estimated results of translog stochastic frontier model for matched sample of adopters as well as non-adopters of banana irrigation. Our study presents the estimated results translog functional form instead of results of cobb-douglas functional form because the cobb-douglas functional form results were rejected in favour of translog results at 1 percent level for both irrigators and non-irrigators of banana from estimation results of likelihood ratio test (see Table 1A in Appendix). The result in Table 8 indicates that the on average the technical efficiency of adopters of banana irrigation (0.982) is slightly lower than technical efficiency of non-adopters of banana irrigation (0.986). This means adopters of banana irrigation are technically efficient on average but not slightly higher than non-adopters of banana irrigation, this is because irrigators of banana dispersion parameter value for the inefficiency term is low (0.0005). The mean technical efficiency was 0.982 for irrigators and 0.986 for non-irrigators, indicating that both groups operated close to their respective production frontiers. The small difference suggests that technical efficiency alone does not explain the higher productivity observed among irrigators. The findings show that technical efficiency is slightly increased by adoption of irrigation among small-scale banana farmers. This means adoption of irrigation improve the productivity of banana but slightly higher for non-adopters of irrigation relative to adopters of irrigation among small-scale banana farmers.

Table 3: Translog stochastic frontier estimates for matched sample of banana farmers

	Irrigators Estimates	S. E	**Non-irrigators** Estimates	S. E
Intercept	1.596*	0.841	1.698	1.152
log(area_Banana)	-2.485***	0.106	-2.574***	0.101
log(cost_fertilizer_ban)	-0.316***	0.087	0.025	0.102
log(cost_seed_ban)	-0.725***	0.168	-0.628*	0.268
log(cost_other_ban)	0.052	0.481	-0.386	0.588
I(0.5 * log(area_Banana)^2)	-0.675***	0.030	-0.695***	0.029
I(0.5*log(cost_fertilizer_ban)^2)	0.112***	0.018	0.064***	0.021
I(0.5 * log(cost_seed_ban)^2)	0.156***	0.031	0.119**	0.052
I(0.5 * log(cost_other_ban)^2)	0.043	0.086	0.071	0.108
I(log(area_Banana) * log(cost_fertilizer_ban))	0.029**	0.011	0.085***	0.013
I(log(area_Banana) * log(cost_seed_ban))	-0.031	0.020	-0.029	0.023
I(log(area_Banana) * log(cost_other_ban))	0.014	0.030	-0.026	0.026
I(log(cost_fertilizer_ban) * log(cost_seed_ban))	-0.019***	0.005	-0.013*	0.007
I(log(cost_fertilizer_ban) * log(cost_other_ban))	-0.031***	0.0072	-0.008	0.010
I(log(cost_seed_ban) * log(cost_other_ban))	-0.010	0.007	0.008	0.011
Dummy_Central zone	-0.801**	0.342	-1.154***	0.305
Dummy_Eastern zone	0.528***	0.203	0.346*	0.201
Dummy_Western zone	-0.841**	0.386	-0.356	0.429
Dummy_Lake zone	0.433*	0.253	0.687***	0.248
Dummy_Northern zone	0.156	0.232	0.340	0.246
Dummy_Southern zone	0.091	0.628	1.001*	0.542
Sigma (σ_u)	0.0005		0.0003	
Sigma (σ_v)	3.898		3.638	
Mean efficiency	0.982		0.986	
Lamda	0.012		0.009	
Gamma	0.0001		0.00008	
Number of observations	1,011		1,011	

Notes: **P* = <0.10; ***P* = <0.05; ****P* = <0.01, S.E = Standard Error

3.2.3 Translog meta frontier estimates for matched sample

Table 4 shows the estimated results of translog meta frontier along with the estimated coefficients of the group-specific translog stochastic production frontiers for comparison purpose. The results indicate that on average technical efficiency of adopters as well as non-adopters of banana irrigation are higher than that of meta frontier (enveloped). The results mean majority of banana farmers both irrigators and non-irrigators are more technically efficient than banana farmers in an enveloped frontier (meta frontier). Also, the most of coefficients of meta frontier are higher than group specific stochastic frontiers, which is consistent with assumption of the meta frontier analysis. Table 4 further shows that the inputs such as banana area, expenditures on seeds and fertilizer significantly reduces the banana harvest for adopters of banana irrigation as well as for meta frontier at percent level. The meta-technology ratios shown in Figure 2 (Appendix) further support this finding.

Table 4: Estimated results of translog meta frontier against groups specific translog stochastic frontier

	Irrigators Estimates	**Non-irrigators** Estimates	**Metafrontier** Estimates	**MF** S. E
Intercept	1.596*	1.698	1.888***	0.019
log(area_Banana)	-2.485***	-2.574***	-2.512***	0.009
log(cost_fertilizer_ban)	-0.316***	0.025	-0.068***	0.009
log(cost_seed_ban)	-0.725***	-0.628*	-0.747***	0.016
log(cost_other_ban)	0.052	-0.386	-0.216***	0.051
I(0.5 * log(area_Banana)^2)	-0.675***	-0.695***	-0.678***	0.003
I(0.5*log(cost_fertilizer_ban)^2)	0.112***	0.064***	0.077***	0.002
I(0.5 * log(cost_seed_ban)^2)	0.156***	0.119**	0.155***	0.003
I(0.5 * log(cost_other_ban)^2)	0.043	0.071	0.084***	0.009
I(log(area_Banana) * log(cost_fertilizer_ban))	0.029**	0.085***	0.061***	0.001
I(log(area_Banana) * log(cost_seed_ban))	-0.031	-0.029	-0.037***	0.002
I(log(area_Banana) * log(cost_other_ban))	0.014	-0.026	-0.003	0.003
I(log(cost_fertilizer_ban) * log(cost_seed_ban))	-0.019***	-0.013*	-0.020***	0.001
I(log(cost_fertilizer_ban) * log(cost_other_ban))	-0.031***	-0.008	-0.028***	0.001
I(log(cost_seed_ban) * log(cost_other_ban))	-0.010	0.008	-0.0008	0.001
Dummy_Central zone	-0.801**	-1.154***	-1.002***	0.028
Dummy_Eastern zone	0.528***	0.346*	0.403***	0.017
Dummy_Western zone	-0.841**	-0.356	-0.452***	0.032
Dummy_Lake zone	0.433*	0.687***	0.651***	0.021
Dummy_Northern zone	0.156	0.340	0.350***	0.020
Dummy_Southern zone	0.091	1.001*	0.897***	0.041
Sigma (σ_u)	0.0005	0.0003	0.195	
Sigma (σ_v)	3.898	3.638	0.010	
Mean efficiency	0.982	0.986	0.726	

Lamda	0.012	0.009	4.388	
Gamma	0.0001	0.00008	0.951	
Number of observations	1,011	1,011	2,022	

Notes: **P* = <0.10; ***P* = <0.05; ****P* = <0.01, S.E = Standard Error, MF= meta frontiers

4. DISCUSSION

Our study found irrigation scheme in the village is positive and significant related to adoption of irrigation among small-scale banana farmers. The finding means that availability of irrigation schemes in village is important motivation behind the use or adoption of irrigation by small-scale banana farmers. Considering the nature of banana farmers with their limited capacity to develop own-irrigation, this finding is relevant due to the fact that majority of banana farmers use the rivers available in their village as main source of irrigation. Our result concurs with our theoretical expectations that irrigation scheme in village is positively related to adoption of irrigation. Furthermore, the result is similar to earlier study of Jordan and Speelman (2020).

Also, the study revealed banana farmers with access to credit for agriculture to have higher chance of adopting irrigation than those without access to credit for agriculture. The credit for agriculture has been suggested important for small-scale farmers in Tanzania (Ministry of Agriculture, 2022). In context of banana farmers, most of the irrigators noted to depend on credit to finance their method of irrigation particularly use of buckets as well as for agro-inputs such as fertilizer, pesticides and insecticides as they involve high cost. Our result is similar to earlier studies (Salazar and Rand, 2016; Engler et al., 2016; Wang et al., 2016; Nonvide, 2017; Adebayo et al., 2018; Nonvide, 2019; Ngango and Hong, 2021; Jatana and Tesfahun, 2025).

Adoption of irrigation is found positive and statistically significant associated with adoption of irrigation extension. This means banana farmers who adopt extension on irrigation have higher chances of adopting irrigation than banana farmers who do not adopt extension on irrigation. The result is due the fact that adoption of irrigation depends on awareness or knowledge on how to use irrigation which in Tanzania context the banana farmers can acquire it through government extension agents who are employed to offer the extension services in different villages (e.g., Ministry of Agriculture, 2022). Thus, majority of banana irrigators obtain such services from agricultural extension services. Our result confirms our theoretical prediction that there is direct relationship between adopting extension on irrigation and adopting irrigation. The finding is consistent with the earlier studies of Salazar and Rand (2016), Nonvide (2017), Nonvide (2019), Ngango and Hong (2021), Olkeba et al. (2025) and Jatana and Tesfahun (2025).

Our study further reveals banana farmers reside in three agroecological zones such as central agroecological zone, eastern agroecological zone and northern agroecological zone have higher chance of adopting irrigation than those reside in southern highlands agroecological zone. The result is associated with fact that zones including eastern and northern zones are having larger proportion of irrigating banana farms compared to other zones. Also, the results is because of the reason that those agroecological zones are located closer to river basins and lakes which are important source of water for irrigating banana farms. This confirms our theoretical expectation and study by Asfaw Eshetu and Mekonen (2024) that agroecological zone matters in adoption of irrigation.

The study finds that the adoption of irrigation improves technical efficiency/productivity for small-scale banana farmers, but not significantly more than non-adopters. The positive relationship between irrigation adoption and productivity should be interpreted with consideration of potential selection effects. While PSM reduces bias by comparing farmers with similar observable characteristics, differences in unobserved factors such as managerial ability, motivation, and risk preferences may still influence both irrigation adoption and productivity outcomes. This result contradicts theoretical expectations and previous studies, which typically found higher technical efficiency and productivity in irrigators (Gao et al., 2026; Abdelghany et al. 2025; Niu et al., 2025; Yang et al., 2023; Merza et al., 2023; Babakholov et al., 2022; Bopp et al., 2022; Bryant et al., 2022). The discrepancy may stem from the focus on perennial crops like banana in this study, while prior studies concentrated on annual crops. Additionally, the use of meta frontier analysis differentiates this study from others. The slightly lower technical efficiency of irrigators does not contradict their higher productivity because technical efficiency measures performance relative to a group's own frontier, whereas irrigation raises the production frontier through improved technology. Consequently, irrigators can achieve higher output despite marginally lower efficiency.

5. CONCLUSION

Despite the importance of irrigation adoption in developing countries like Tanzania, small-scale banana farmers still show low adoption rates. To promote irrigation and benefit from its effects, understanding the drivers of adoption and its impact on productivity is crucial. This study used meta-frontier analysis to explore these aspects while accounting for sample-selection bias. Key drivers of adoption included village irrigation schemes, access to credit, irrigation extension, and certain agroecological zones (eastern, central, and northern). While irrigation adoption was found to increase productivity, it did not significantly outperform non-adopters in Tanzania. Irrigation improves productivity primarily by enhancing production technology rather than increasing technical efficiency. Therefore, policies should expand irrigation access while improving farmers' capacity to utilize the technology more efficiently.

The main limitation of our study, we did not use the quantity of inputs used in banana farming instead we follow the inspiration of previous studies (Rammer et al., 2020; Benini and Cattani, 2022) to use expenditures of those inputs. Also, due to low variation in variables such as quantity of insecticides, pesticides as well as fungicides, we excluded these variables in our analysis of effect of irrigation on productivity among small-scale banana farmers. Another limitation of this study is that PSM controls only for observable characteristics and cannot completely eliminate bias arising from unobserved heterogeneity. Therefore, the estimated impact of irrigation should be interpreted as an association rather than definitive causal evidence, and future studies should consider methods such as instrumental variables, panel data, or experimental approaches to strengthen causal identification. Despite the limitations, our study can draw the following recommendations:

Our study emphasizes on the need to develop fulltime and effective banana irrigation schemes in villages particularly in three agroecological zones such as central agroecological zone, eastern agroecological zone and northern agroecological zone in order to motivate adoption of irrigation and improve the productivity of banana crop. This study also draws attention to agricultural as well as well irrigation policy makers regarding the effective development and promotion of agricultural credit facilities in agroecological zones dealing with banana production, as our study found access to credit for agriculture is significant driver of adopting banana irrigation.

Our study revealed expenditures on seeds as well as fertilizer reduces the banana harvests similarly the provision of credit for agriculture is suggested in this study as a relevant option in reducing the expenditure burden of agricultural inputs by small-scale banana farmers. Due to limitations in the availability and reliability of physical input data among small-scale banana farmers, input variables were measured using expenditure values for seeds and fertilizers. Expenditure-based measures capture the economic intensity of input use and reflect farmers' actual investment decisions in production. However, these measures may also capture variations in input prices, quality, and purchasing behaviour; therefore, the estimated coefficients should be interpreted as the effect of input expenditure rather than the pure physical quantity of inputs applied.

Additionally, our study emphasizes on the need to provide extension on irrigation as well as promote the adoption of irrigation extension through agricultural extension agents in banana producing agroecological zones, our study revealed of adoption of banana irrigation is influenced by use of extension on irrigation. Our study suggests future research to analyse long- effect of irrigation on term the productivity among small-scale banana farmers using longitudinal data. Furthermore, considering the limited external validity of our study and other studies on effect of irrigation on productivity, a study using multiple-country data of permanent crops can offer results with much higher external validity.

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Disclosure statement

There are no competing interests to declare.

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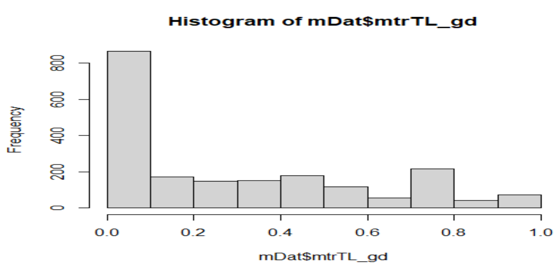
APPENDIX

Table 1A: The estimated results of likelihood ratio test of cobb-douglas against translog stochastic frontier for matched sample

	Matched Irrigators				
Model	Df	LogLik	Df	Chisq	Pr(>Chisq)
Cobb-douglas	13	-2251.6			
Translog	23	-2087.4	10	328.29	< 2.2e-16 ***
	Matched non-irrigators				
Model	Df	LogLik	Df	Chisq	Pr(>Chisq)
Cobb-douglas					
Translog	23	-2122.3	10	391.27	< 2.2e-16 ***

Figure 2: Meta-technology ratios ot translog



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