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Optimizing Taro Profitability in Kenya: Watering Regimes, Planting Densities, and Economic Returns

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Assessing the economic feasibility of varying irrigation levels and planting densities offers essential insights for farmers, facilitating more informed decision-making. An on-farm experiment evaluated the financial returns of taro (*Colocasia esculenta*) production under different watering regimes and planting densities across three cropping seasons (2021- 2022). The watering regimes applied were 100%, 60%, and 30% of field capacity (FC), while planting densities were 0.5 m × 0.5 m (40,000 plants ha^{-1}), 1 m × 0.5 m (20,000 plants ha^{-1}), and 1 m × 1 m (10,000 plants ha^{-1}), representing high, medium, and low densities.

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Study Design and Methodology: The study employed a split-plot factorial design within a completely randomized block design with three replications.
Results: The net benefits realized under 100% FC for each planting density were 1 m × 1 m (USD 7183), 1 m × 0.5 m (USD 3407), and 0.5 m × 0.5 m (USD 1138). The net benefits from the 60% FC were 1 m × 1 m (USD 2048), 1 m × 0.5 m (USD 3258), and 0.5 m × 0.5 m (USD 7210), and those attained under the 30% FC were 1 m × 1 m (USD 1658), 1 m × 0.5 m (USD 3928), and 0.5 m × 0.5 m (USD 5950).
Conclusion: Marginal analysis identified the 100% FC with 1 m × 1 m spacing as the most financially viable option in Embu County. It offers the highest net benefit (USD 7183), a benefit-cost ratio of 21.11, and a marginal rate of return above 100%.

Keywords: Taro yields; partial budget analysis; financial returns.

1. INTRODUCTION

Taro (*Colocasia esculenta* (L.) Schott) is a perennial herbaceous root crop widely cultivated in tropical and subtropical regions (FAO, 2010). “Over the past ten years, the global taro production has more than doubled, elevating it to the position of the fifth most consumed root vegetable worldwide” (Macharia et al., 2014). “Taro ranks among the most ancient domesticated crops, with its cultivation history spanning over 9,000 years in regions such as Southeast Asia and India” (Rao et al., 2010). Despite being a fundamental component of many tropical diets, taro remains underexploited in Sub-Saharan Africa, notwithstanding its global significance (Mabhaudhi et al., 2019). In Kenya, this crop is locally referred to as *nduma.*

“Taro is typically ranked lower in productivity comparison to tubers such as sweet potato (*Ipomoea batatas*), potato (*Solanum tuberosum*), and cassava (*Manihot esculenta*)” (Palapala and Akwee, 2016). “Particularly in East Africa, taro yields remain considerably low, averaging less than 1 ton per hectare annually, whereas the average yield in Africa is 5.9 tons per hectare, and the global average stands at 6.6 tons per hectare” (Serem et al., 2008; Palapala and Akwee, 2016). This substantial yield gap highlights significant agricultural and infrastructural challenges that necessitate urgent intervention, especially regarding implementing efficient water management practices and adopting optimal planting techniques. Addressing these issues is imperative for increasing productivity and ensuring sustainable growth in agriculture.

Taro holds considerable economic promise, particularly in areas where it is a staple food. Its edible stem and corm are abundant in nutrients and lend themselves to diverse culinary uses (Dhanraj et al., 2013; Karuma et al., 2024). This crop is particularly valuable for smallholder farmers with limited resources, as it plays a crucial role in enhancing food security, increasing household income, and supporting rural development initiatives (Temesgen and Retta, 2015; Akwee et al., 2015). “Furthermore, taro is adaptable to upland cultivation and can be effectively grown in polythene-lined moisture beds, which curtail water loss due to lateral movement and seepage” (Mabhaudhi, 2012; Oxfarm, 2021). When this technique is integrated with drip irrigation, it significantly boosts yield while optimizing the use of limited water resources, a critical approach in arid and semi-arid regions (Wainaina, 2021).

Previous investigations have focused on a range of topics, including planting density (Tumuhimbise et al., 2009; Tsedalu et al., 2014; Sibiya, 2015; Boampong et al., 2020), genetic variation (Macharia et al., 2014; Akwee et al., 2015), and barriers to production (Serem et al., 2008). Nonetheless, a limited number have explored the financial implications of agronomic strategies. Undertaking financial assessments and cost-benefit analysis is crucial for understanding the practicality and potential expansion of suggested practices. In Kenya, such evaluations remain scarce within the taro value chain (Onsay et al., 2022). Examining the economic feasibility of various irrigation methods and planting densities can offer vital insights to farmers, aiding them in making informed choices. Consequently, this study aims to assess the financial outcomes of taro cultivation in the subhumid region of Embu, Kenya, under varying degrees of irrigation and plant spacing, to identify the most cost-efficient production methodologies.

2. MATERIALS AND METHODS

2.1 Study Site Description

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) – Embu Research Centre

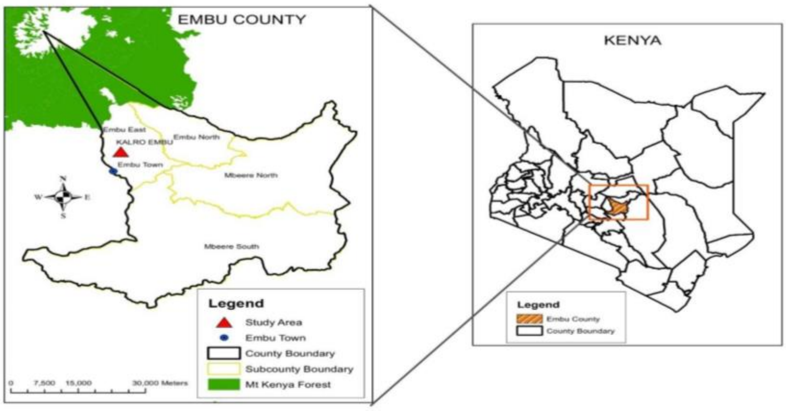

Fig. 1. Location of the study site (generated from ArcGIS)

for three growing seasons - long rains (LR) 2021, short rains (SR) 2021/2022, and long rains (LR) 2022. Embu County is located between latitudes 00 8’ and 00 50’ South and longitudes 370 3’ and 370 9’ East (Kangai et al., 2021) (Fig. 1). The Research Centre receives 1250 mm of annual rainfall in two rainy seasons: March to May (long rainy season) and October to December (short rainy season), with the amount varying with altitude. The temperatures range from 12°C in July to 30°C in March and September, with a mean of 21°C (Kisaka et al., 2015; Embu County Government, 2019).

2.2 Experimental Layout

A factorial experiment with a split-plot layout arranged in a completely randomized block design was used. The main factor was the irrigation level, whereas the subfactor was the planting density, with three replications. The three irrigation levels were 100%, 60%, and 30% based on the field capacity (FC). The planting densities used were 0.5 m × 0.5 m (40,000 plants ha-1), 1 m × 0.5 m (20,000 plants ha-1), and 1 m × 1 m (10,000 plants ha-1), which are representative of high, medium, and low planting densities, respectively (Njuguna et al., 2023a; Njuguna et al., 2023b).

2.3 Planting Material

Taro basal stems were sourced from farmers' fields in Kirinyaga County, ensuring high-quality planting materials. The materials included the apical 1–2 cm of the corm and the basal 15–20 cm of the attached petioles. The Dasheen variety stands out as the most commercially preferred landrace in the Kirinyaga region, characterized by its substantial, cylindrical main corm, making it the top choice among farmers.

2.4 Taro Yield Measurements

Six months after planting, the corm yield was assessed. The average experimental plot area was a basis for the corm yield calculation, which was then converted to metric tonnes per hectare (tonnes/ha = Mg ha-1).

2.5 Irrigation and Moisture Bed Preparation

The drip irrigation system comprised a 5000-liter tank, a water filter, a water meter, a ball valve, nine valves, nine T-joins, button drippers, start connectors, PVC pipes, drip lines, end lines, end caps, and L-bows. The tank was elevated to a height of 1.5 meters to deliver water to the crops. The system also featured a one-inch diameter disc filter, which was highly effective against waterborne debris and ensured that no particles or contaminants passed through. Water was then distributed to the crops via a one-inch diameter mainline, connected to a sub-main line that branched into the drip lines within each plot. The button drippers or emitters along the drip lines supplied water directly to the individual plants. End caps were employed to seal the water flow at the termination points. The spacing of the drip lines was tailored to accommodate the varying plant spacings established in each plot. Each emitter had a discharge rate of 5.6 liters per hour. Each plot measured 4 meters by 4 meters, spaced 2 meters apart, and was dug to a depth of 50 centimeters. The plots were lined with a double-folded black polythene sheet to create a moisture-retentive bed, effectively preventing seepage and lateral water movement between plots. The excavated soil from each plot was decisively mixed with manure at a 2:1 ratio and returned to the moisture bed, creating a noticeable depression of 10 centimeters (Njuguna et al., 2023a; Njuguna et al., 2023b)

2.6 Financial Analysis

The economic feasibility of taro cultivation under varying irrigation methods and planting densities was evaluated through a partial budget analysis as described by CIMMYT (1988). This approach allowed for the assessment of both the benefits and costs associated with the treatments over three growing seasons. Yield data from each treatment were reduced by 10% to account for losses in the field and during postharvest handling, following standard guidelines (CIMMYT, 1988). The adjusted yields were then multiplied by the average market price of taro at the time of harvest (USD 0.40 per kilogram) to calculate gross income.

The total variable costs (TVCs) were determined by aggregating the expenses associated with taro basal stems, labor, irrigation water, weeding, and harvesting. These TVCs were then subtracted from the gross income to calculate the gross margins (net benefits). To gain a deeper understanding of profitability, the benefit-cost ratio (BCR), also known as cost-benefit ratio, is defined as the ratio of gross income to total variable costs, was computed, providing a valuable measure of return on investment.

Following the partial budget analysis, a marginal analysis was performed to evaluate the additional costs and benefits associated with various treatment combinations. This included a dominance analysis, in which the treatments were arranged in ascending order of total variable costs. Treatments that presented both higher costs and lower net benefits compared to their alternatives were deemed dominated and subsequently excluded from further analysis (CIMMYT, 1988; Fadipe et al., 2015; Tesfaye et al., 2015).

The marginal rate of return (MRR) was computed for the nondominated treatments. The MRR indicates the incremental net benefit derived per unit of additional cost when transitioning from one nondominated treatment to another (Melese et al., 2018; Karuma et al., 2020). This analysis is instrumental in refining farmer recommendations by emphasizing treatment combinations that present the most advantageous trade-offs between increased costs and enhanced benefits.

Based on the findings from the MRR analysis, treatments yielding an MRR greater than 100% were deemed financially viable for farmers to adopt. Consequently, the final recommendation emphasized the treatment combination that offered the highest net benefit while meeting an acceptable MRR threshold, thereby ensuring both economic efficiency and practical relevance for smallholder farmers.

3. RESULTS AND DISCUSSION

3.1 Taro Corm Yield

The highest yields of taro corms were achieved with a planting density of 0.5 m × 0.5 m, under both the 60% field capacity (FC) and 30% FC irrigation conditions, resulting in 21.40 t/ha and 17.79 t/ha, respectively (Table 2). In contrast, under the 100% FC watering regime, the highest yield (21.23 t/ha) was achieved with the 1 m × 1 m planting density. Interestingly, the lowest yields under the 60% FC (6.70 t/ha) and 30% FC (5.58 t/ha) regimes were also observed at the 1 m × 1 m spacing, whereas the lowest yield under 100% FC (4.39 t/ha) was recorded at the highest planting density (0.5 m × 0.5 m). These results represent a 219% increase in yield from the 1 m × 1 m to the 0.5 m × 0.5 m spacing under the 60% and 30% FC treatments, but a 79% decrease under the 100% FC regime. The 1 m × 0.5 m spacing consistently produced intermediate yields across all watering regimes and cropping seasons (Njuguna, 2023).

The superior performance of the high-density planting (0.5 m × 0.5 m) under moderate and low irrigation levels can be attributed to the greater number of plants per unit area, which enhances solar radiation interception, improves photosynthetic efficiency, and promotes better ground cover (Scheffer et al., 2005; Tumuhimbise et al., 2009; Boampong et al., 2020). The yields recorded in this study outstrip the reported averages for East Africa (1 t/ha), the continental average (5.6 t/ha), and the global mean (6.6 t/ha) (Serem et al., 2008; Palapala and Akwee, 2016). Notably, the saturated conditions at 100% field capacity seemed to hinder yields at the highest planting density, likely due to the stress caused by waterlogging. In contrast, these conditions appeared to boost performance at the lowest density. The combination of a 60% field capacity watering regime and a planting density of 0.5 m × 0.5 m proved to be the most effective, indicating that this treatment is ideal for maximizing yields in water-limited environments. These insights offer valuable implications for enhancing taro productivity and optimizing resource use, especially in subhumid and water-scarce areas.

3.2 Partial Budget Analysis

Table 2 summarizes the results from the partial budget analysis of different watering regimes and planting densities. The planting density of 0.5 m × 0.5 m resulted in the highest drip installation costs (see Table 1) among the three watering regimes. This surge in costs stems from the increased number of plants in these plots, which requires additional drip lines, button drippers, and valves. As a result, total input costs were greatest for the 0.5 m × 0.5 m planting density, largely due to the need for more taro planting material and higher water expenses tied to the greater number of emitters on the drip lines. The analysis showed a trend in total variable costs under different planting densities within each watering regime: 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m, with values ranging from USD 319.35 to USD 417.35 (Tables 1 and 2). This trend is primarily due to the high drip installation costs and input expenses associated with the 0.5 m × 0.5 m density, particularly concerning water costs and the procurement of taro basal stems. More emitters along the drip lines and more taro plants in the plots result in higher water and basal stem costs for taro.

The average net benefit/gross margins for the 100% Field Capacity (FC) followed a trend of 1 m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m. Conversely, within the 60% FC and 30% FC watering regimes, a decreasing trend was observed: 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m, with corresponding values ranging from USD 1137.76 to USD 7209.90 (as shown in Table 2). The 0.5 m × 0.5 m configuration under the 60% FC yielded the highest corm production (21.40 t/ha) alongside the greatest net benefit (USD 7209.90) (Table 2). The lower net benefit for the 100% FC at the 0.5 m × 0.5 m density can be attributed to its lower yield combined with higher costs. This observation aligns with findings by Melese et al. (2018), which evaluated the partial budget analysis of pepper cultivation in Ethiopia.

The benefit-cost ratio (BCR), also known as cost-benefit ratio, remained within an acceptable range (> 1), as reported by Tafa et al. (2021), across various treatments, with values spanning from 3.73 to 22.11. This suggests that the costs associated with taro production under different watering regimes and planting densities were effectively recouped through the corresponding benefits. This finding aligns with a study by Karuma et al. (2020) on the financial returns from maize and bean production in Kenya. A notable trend emerged for the 100% field capacity (FC), which ranked as follows: 1 m × 1 m > 1 m × 0.5 m > 0.5 m × 0.5 m. In contrast, the 60% FC and 30% FC watering regimes displayed a trend of 0.5 m × 0.5 m > 1 m × 0.5 m > 1 m × 1 m. A higher BCR signifies increased net returns from these treatments, whereas a lower BCR indicates rising production costs (Aurangzeb et al., 2007; Karuma et al., 2020). Based on the comprehensive results of this study, it is recommended that farmers in the area adopt the 100% FC under the 1 m × 1 m planting density, which exhibits the highest BCR value.

3.3 Marginal Analysis

3.3.1 Dominance analysis

Table 3 summarizes the findings from the dominance analysis. Treatments with lower variable costs generally provide lower or comparable benefits (CIMMYT, 1988). The analysis indicates that the 1 m × 0.5 m configurations under 60% FC and 100% FC, as well as the 0.5 m × 0.5 m configurations under 30% FC and 100% FC, are dominated due to their significantly lower gross margins (net benefits), which disqualifies them from further consideration. The high planting density under the 30% FC and 100% FC regimes is supported by the high total costs and minimal gains in net benefits, as illustrated in Tables 2 and 3.

3.3.2 Marginal rate of return (MRR)

The marginal rate of return (MRR) serves as a key indicator for evaluating the economic advantage of shifting from one treatment option to another. Since dominated treatments are excluded from marginal analysis, the resulting MRR values are inherently positive (CIMMYT, 1988; Soha, 2014). In this study, the MRRs of the nondominated treatment combinations ranged from 0.82% to 378.51% (Table 4). For crops with relatively short growing cycles (4–5 months), farmers typically consider MRRs between 50% and 100% acceptable. However, crops with longer production cycles, such as taro, require proportionally higher MRRs to justify investment due to increased time and resource commitments (CIMMYT, 1988; Arebu et al., 2019).

Table 1. Average seasonal cost of production for taro under various watering regimes and planting densities in Embu, Kenya (n = 3 cropping seasons)

Variable Costs (USD)	**100% FC Watering Regime**			**60% FC Watering Regime**			**30% FC Watering Regime**		
	1 m × 1 m	**1 m × 0.5 m**	**0.5 m × 0.5 m**	**1 m × 1 m**	**1 m × 0.5 m**	**0.5 m × 0.5 m**	**1 m × 1 m**	**1 m × 0.5 m**	**0.5 m × 0.5 m**
Drip Installation/Conveyance Costs									
Drip Irrigation Materials (drip lines, button drippers, valves, 5000-liter tank and tank stand, filter, elbows, tees, endcaps, PVC pipes)	168.10	172.35	179.79	168.10	172.35	179.79	168.10	172.35	179.79
Drip Irrigation Installation	48.12	48.12	48.12	48.12	48.12	48.12	48.12	48.12	48.12
Transport	8.75	8.75	8.75	8.75	8.75	8.75	8.75	8.75	8.75
Total Drip Installation Costs	225.00	229.22	236.65	225.00	229.22	236.65	225.00	229.22	236.65
Labor Costs (Field)									
Land clearing and levelling	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37
Moisture bed preparation	18.37	18.37	18.37	18.37	18.37	18.37	18.37	18.37	18.37
Polythene layering and Planting	12.60	12.60	12.60	12.60	12.60	12.60	12.60	12.60	12.60
Weeding	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90	18.90
Harvesting	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
Total labor costs	57.40	57.40	57.40	57.40	57.40	57.40	57.40	57.40	57.40
Inputs									
Polythene rolls	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
Taro basal stems	3.78	6.61	11.57	3.78	6.61	11.57	3.78	6.61	11.57
Water costs	27.91	48.86	85.50	13.96	24.57	40.92	6.98	12.21	21.37
Total input costs	57.94	81.72	123.31	43.98	57.43	78.74	37.00	45.07	59.20
Total variable costs (drip + labor + input costs)	340.28	368.32	417.35	326.33	344.03	372.78	319.35	331.68	353.23

where USD = US dollars, 1 USD = KES 127

Table 2. Partial budget analysis of taro production under various watering regimes and planting densities in Embu, Kenya (n = 3 cropping seasons)

Variable Costs	100% FC Watering Regime			60% FC Watering Regime			30% FC Watering Regime		
	1 m × 1 m	**1 m × 0.5 m**	**0.5 m × 0.5 m**	**1 m × 1 m**	**1 m × 0.5 m**	**0.5 m × 0.5 m**	**1 m × 1 m**	**1 m × 0.5 m**	**0.5 m × 0.5 m**
Taro corm Yield (t/ha)	21.23	10.65	4.39	6.70	10.17	21.40	5.58	12.02	17.79
Adjusted Yields (t/ha)	19.11	9.59	3.95	6.03	9.15	19.26	5.02	10.82	16.01
TGI (USD)	7,523.62	3,775.60	1,551.12	2,374.02	3,602.40	7,582.68	1,976.38	4,259.84	6,303.15
TVC (USD)	340.28	368.32	417.35	326.33	344.04	372.78	319.35	331.68	353.23
NB/Gross Margins (USD)	7,183.34	3,407.27	1,137.76	2,047.70	3,258.33	7,209.90	1,657.03	3,928.17	5,949.92
BCR	21.11	9.25	2.73	6.36	9.47	19.34	5.18	11.84	16.84

where TGI = Total Gross Income, TVC = Total Variable Costs, NB = Net Benefits, BCR = Benefit Cost Ratio, and 1 USD = KES 127.

Table 3. Dominance analysis of costs and returns in taro production under different watering regimes and planting densities in Embu, Kenya

Watering Regime	Planting Density	TVC (USD)	NB (USD)
30% FC	1 m × 1 m	319.35	1657.03
60% FC	1 m × 1 m	326.33	2047.76
30% FC	1 m × 0.5 m	331.68	3928.17
100% FC	1 m × 1 m	340.28	7183.34
60% FC	1 m × 0.5 m	344.03	3258.33**D**
30% FC	0.5 m× 0.5 m	353.23	5949.92**D**
100% FC	1 m × 0.5 m	368.32	3407.27**D**
60% FC	0.5 m × 0.5 m	372.78	7209.90
100% FC	0.5 m × 0.5 m	417.35	1137.76**D**

TVC = total variable cost, NB = net benefit, 1 USD = KES 127

Table 4. Financial returns of the nondominated watering regimes and planting densities in Embu, Kenya

Watering Regime	Planting Density	Taro Yields (t/ha)	Adjusted Yields (t/ha)	TGI (USD)	TVC (USD)	Net Benefit (USD)	MAC	MNB	MRR	BCR
30% FC	1 m × 1 m	5.58	5.02	1,976.38	319.35	1,657.03				5.18
60% FC	1 m × 1 m	6.70	6.03	2,374.02	326.33	2,047.76	6.98	390.73	55.98	6.36
30% FC	1 m × 0.5 m	12.02	10.82	4,259.84	331.68	3,928.17	5.35	1880.41	351.48	11.84
100% FC	1 m × 1 m	21.23	19.11	7,523.62	340.28	7,183.34	8.60	3255.17	378.51	21.11
60% FC	0.5 m × 0.5 m	21.40	19.26	7,582.68	372.78	7,209.90	32.50	26.56	0.82	19.34

where TGI = total gross income, MAC = marginal cost (USD/ha), MNB = marginal net benefits (USD/ha), MRR = marginal rate of return, BCR = benefit cost ratio, 1 USD = KES 127

The analysis reveals that incremental shifts between specific treatment combinations can significantly influence profitability. For instance, farmers would realize improved returns by moving from 30% FC to 60% FC under the 1 m × 1 m planting density. Even greater benefits are observed when shifting from 60% FC at 1 m × 1 m to 30% FC at 1 m × 0.5 m spacing. However, the most substantial marginal gain is achieved by transitioning from 30% FC at 1 m × 0.5 m to 100% FC at 1 m × 1 m, yielding the highest marginal net benefit (USD 7,183.34) and an MRR of 378.51%. Conversely, a shift from 100% FC at 1 m × 1 m to 60% FC at 0.5 m × 0.5 m is not economically advisable, given the minimal marginal benefit (USD 26.56) and the low MRR of 0.82%.

When selecting the most appropriate treatment for farmer recommendation, emphasis should be placed not only on the highest net benefit, but also on ensuring the MRR meets or exceeds the minimum acceptable threshold. As such, the combination of 100% FC and 1 m × 1 m spacing emerges as the most financially viable option. It delivers a strong balance between profitability and investment efficiency, and thus represents a sound recommendation for maximizing returns in taro production under the conditions observed in this study.

4. CONCLUSION

Given the notable differences in production costs and net benefits observed across various irrigation levels and planting densities, agricultural policy frameworks and extension services in Embu County should advocate for the adoption of 100% field capacity (FC) irrigation in conjunction with a 1 m × 1 m planting density for taro (*Colocasia esculenta*) cultivation. This combination has exhibited the highest benefit-cost ratio (BCR) and a satisfactory marginal rate of return (MRR > 100%), yielding substantial net benefits and establishing it as the most financially viable option for smallholder farmers.

Future agronomic interventions and recommendations should consistently incorporate economic analyses, such as partial budget and marginal analyses, to bolster evidence-based decision-making. This approach will ensure that the suggested practices are agronomically effective and economically sustainable, facilitating their widespread adoption.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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