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Sunflower Growth and Yield Responses to Variety Selection and Fertiliser Management in Semi-Arid Areas of Tanzania

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Sunflower (*Helianthus annuus* L.) is an important crop in semi-arid farming systems, yet its productivity remains low due to limited understanding of variety-specific responses to fertiliser management under local soil and climatic conditions. This study evaluated the effects of variety selection and fertiliser rate on growth and seed yield in Bahi and Mpwapwa districts, Tanzania, to identify optimal management strategies for smallholder systems. The study was conducted during the 2024/2025 cropping season. Three varieties (Records, Hysun 33, and a local type) were grown under five fertiliser regimes (unfertilized, 25%, 50%, 75%, and 100% of 190 kg ha⁻¹ organo-mineral compounds) in a randomised complete block design with four replications. Results showed that fertiliser application enhanced vegetative growth at Bahi, with plant height increasing from 54.7 cm in the control to 84.2 cm at 75%, and head diameter from 17.8 cm to 25.2 cm. Despite these improvements, seed yield differences were statistically non-significant ($p = 0.203$), ranging from 720.8 to 845.8 kg ha⁻¹ across treatments. Varietal differences were observed only for stem diameter ($p = 0.006$), while yield remained comparable across varieties. The study reveals a research gap concerning how excess fertiliser application interacts with soil properties and rainfall patterns to influence sunflower yield in semi-arid systems. The results support the hypothesis that moderate fertiliser levels and appropriate variety choice can improve growth without causing nutrient imbalances or yield decline. Further research is needed to refine nutrient management strategies for different varieties under variable rainfall conditions.

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INTRODUCTION

Sunflower (*Helianthus annuus* L.) ranks among the world's leading oilseed crops, with global production exceeding 50 million tons annually (Khurana & Singh, 2021; Dogra, 2024). It is cultivated across a wide range of climatic conditions, from temperate to semi-arid regions, and completes its growth cycle within 90 to 120 days (Puttha et al., 2023; Ahmed et al., 2024). This adaptability supports its inclusion in diverse cropping systems and enables multiple harvests in some regions (Casadebaig et al., 2022; Vilvert et al., 2023). Major producers such as Russia, Ukraine, Argentina, and Turkey dominate global trade, supplying much of the sunflower oil market (Soare et al., 2022; Premović, 2023). The crop's high content of unsaturated fatty acids makes its oil suitable for food, cosmetics, and emerging biofuel industries (Muzammil et al., 2021; Petraru et al., 2021). Such attributes have spurred a global increase in sunflower production and land use.

In Africa, sunflower is mainly cultivated in eastern and southern countries, including Ethiopia, South Africa, Tanzania, and Zambia (Isinika & Jeckoniah, 2021; Beteri et al., 2024). Growth in production and trade has been supported by rising demand for

affordable and healthier edible oils (Mustafa & Iqbal, 2021; Joshi et al., 2025). Nevertheless, yields remain lower than the global average because of restricted access to improved seeds, inadequate fertiliser use, and variable rainfall patterns (Debaeke et al., 2021; Tanti et al., 2024). These constraints hinder productivity and limit farmers' income potential.

Within East Africa, Tanzania is a key sunflower producer, particularly in semi-arid districts such as Mpwapwa and Bahi in the Dodoma region, as well as in parts of Manyara, Singida, and Tabora (Lyanga, 2024). The semi-arid climate, though challenging, is suitable for sunflower, which contributes significantly to local edible oil supplies and reduces dependence on imports (Awaad & Awaad, 2022; Murphy, 2025). Sunflower farming provides income for smallholders through seed sales and by-products, while linking rural producers to urban and regional markets (Isinika & Jeckoniah, 2021; Sainz-Ramírez et al., 2021). Despite this potential, Tanzania's national average yield remains modest compared to global standards, primarily due to limited access to improved varieties, inconsistent fertiliser practices, and drought stress typical of semi-arid regions (Msafiri et al., 2023; Gao et al., 2025).

Sunflower's versatility extends to its by-products, which include protein-rich seed cake used as livestock feed, contributing to integrated crop–livestock systems (Sarkar et al., 2021; Marques et al., 2025). Its short growth cycle enables crop rotation that can improve soil structure and nutrient recycling (Kussul et al., 2022). Additionally, sunflower farming generates employment along the value chain, from seed production to oil processing (Kajimbwai & Mhangaii, 2022; Lohosha et al., 2023). However, many smallholder farmers face challenges such as limited credit, weak extension services, and poor access to quality inputs, all of which restrict the adoption of efficient agronomic and fertiliser practices (Shilomboleni et al., 2023; Zozimo et al., 2023).

Sunflower productivity is often constrained by unbalanced fertiliser application and insufficient nutrient supply, particularly nitrogen, phosphorus, potassium, calcium, and magnesium, which are deficient in many Tanzanian soils (Jarecki, 2022; Crista et al., 2023). Rainfall variability and recurrent drought further reduce crop performance, especially in semi-arid environments (Harsányi et al., 2021; Ali et al., 2024). Few varieties are bred specifically for tolerance to such stresses, leaving farmers with limited options (Akimowicz et al., 2021; Krstić et al., 2023). Furthermore, knowledge gaps persist regarding how sunflower varieties interact with fertiliser regimes under local semi-arid conditions, and research addressing these relationships remains scarce (Nungula et al., 2023; Nungula et al., 2024a). This knowledge gap forms the basis of the present study, which hypothesises that the response of sunflowers to fertiliser application depends on both the variety and the rate of nutrient supply under semi-arid conditions. The study aims to determine how different fertiliser levels influence the growth and yield of selected sunflower varieties, using organo-mineral fertilisers containing balanced proportions of nitrogen, phosphorus, potassium, calcium, and magnesium applied at planting and as top-dressing. Unlike

previous work focusing on single factors, this study integrates both varietal and fertiliser interactions under field conditions in Tanzania's semi-arid zones, providing new insight into the mechanisms that limit yield performance and offering direction for improved nutrient management and variety selection. Therefore, the specific objectives of the study were to: (1) evaluate the effects of different organo-mineral fertiliser rates on sunflower growth and seed yield in semi-arid environments of Tanzania. (2) Assess the performance of selected sunflower varieties under varying fertiliser levels to identify the most responsive types for local conditions. (3) Examine the interaction between variety and fertiliser rate to determine combinations that optimise growth and yield performance.

MATERIALS AND METHODS

Description of the Study Sites

The study was conducted in Bahi and Mpwapwa districts within the Dodoma Region of Tanzania, situated at coordinates 05°57'10"S 35°18'43"E and 6.3478°S 36.4851°E, respectively. These districts experience semi-arid climatic conditions characterised by consistently high temperatures throughout the year. Although both sites share a semi-arid climate, they differ in elevation, rainfall distribution, and soil characteristics. Bahi is located at approximately 950 m above sea level and receives an average annual rainfall of about 580 mm, with rainfall events that are short and intense. Mpwapwa lies at a higher altitude of around 1,100 m and receives slightly more rainfall, averaging 650 mm, which tends to be better distributed across the growing season. Soils in Bahi are predominantly shallow clay loams with low organic matter and poor water-holding capacity, while Mpwapwa soils are moderately deep sandy-clay loams with relatively better drainage and nutrient retention.

The area features a distinct bimodal rainfall pattern, with a wet season spanning from November to April and a dry season from May to October.

Temperatures range from 18°C to 33°C, with mean annual temperatures slightly higher in Bahi than in Mpwapwa. Both sites experience high evapotranspiration rates, which influence soil moisture availability and crop performance during the growing season (Mayaya et al., 2015). The soils in these areas are low in fertility and often deficient in phosphorus, potassium, and nitrogen, factors that strongly influence sunflower growth and yield (Mramba & Mapunda, 2025).

Soil Analysis

Composite soil samples were collected prior to planting from several locations within each experimental plot between September and October 2024. Sampling was carried out in a zig-zag pattern to capture variability in vegetation, soil colour, and topography. Samples were taken from the 0–30 cm depth and composited. The physical and chemical properties of the soils were analysed following procedures described by Okalebo et al. (2002).

Particle size distribution was determined using the hydrometer method with 5% sodium hexametaphosphate ($\text{Na}_6[(\text{PO}_3)_6]$) as the dispersing agent, following the approach of Gee & Bauder (1986). Bulk density was assessed from undisturbed soil cores oven-dried at 105°C for 24 hours. Soil pH and electrical conductivity were measured in a 1:2.5 soil-to-water suspension using potentiometric methods (Lindsay & Norvell, 1978). Organic carbon was quantified using the Walkley-Black wet oxidation procedure (Nelson & Sommers, 1982). Total nitrogen was analysed using the micro-Kjeldahl method (Bremner & Mulvaney, 1982), while available phosphorus was determined with the Bray-Kurtz-1 method (Bray & Kurtz, 1945).

Cation exchange capacity was measured using the neutral ammonium acetate ($\text{NH}_4\text{-Ac}$, pH 7.0) extraction followed by Kjeldahl distillation, as described by Chapman (1965). Exchangeable cations (Ca, Mg, K, Na) were extracted using 1N $\text{NH}_4\text{-Ac}$ (pH 7.0). Magnesium and calcium were quantified using atomic absorption spectroscopy (AAS), whereas potassium and sodium were determined with a flame photometer. Micronutrients (Fe, Cu, Zn, Mn) were extracted with Diethylenetriamine pentaacetate (DTPA) and measured by AAS (Lindsay & Norvell, 1978). Extractable sulphur was determined using the turbidimetric method (Okalebo et al., 2002).

Soil analysis revealed nutrient constraints at both Mpwapwa and Bahi sites (Table 1). Soils were acidic, with Mpwapwa (pH 5.47) more acidic than Bahi (pH 5.98), below the optimal range for sunflower growth. Total nitrogen was low (0.11–0.12%), while organic carbon was modest (1.07–1.25%), indicating poor fertility, limited microbial activity, and weak soil structure. The most critical deficiency was available phosphorus, with Mpwapwa (1.66 mg/kg) and Bahi (2.84 mg/kg) values far below crop requirements, posing a major yield limitation. Cation balances varied: Mpwapwa showed higher potassium (1.11 cmol(+)/kg), beneficial for seed quality, while Bahi contained more calcium (0.68 cmol(+)/kg) and magnesium (258.62 mg/kg), supporting plant structure and metabolism. Sodium levels were slightly higher in Bahi (0.25 cmol(+)/kg) than in Mpwapwa (0.08 cmol(+)/kg) but remained low overall. These findings highlight severe phosphorus and nitrogen deficiencies across both sites, requiring targeted soil amendments and site-specific fertiliser strategies to enhance sunflower productivity.

Table 1: Soil Properties of Mpwapwa and Bahi Sites Before Experiment

Site	pH (1:2.5) H ₂ O	EC	N	OC	P	Ca	K	Mg	Na
		$\mu\text{S/cm}$	%		mg/kg		cmol+/kg		
Mpwapwa	5.47	248	0.11	1.07	1.66	0.42	1.11	107.1	0.08
Rating:	Strongly acid	Normal	Low	Low	Very low	Low	Adequate	Low	Very low
Bahi	5.98	152.7	0.12	1.25	2.84	0.68	0.85	258.62	0.25
Rating:	Slightly acid	Normal	Low	Low	Very low	Medium	Adequate	Medium	Low

Key: EC = electrical conductivity, N = nitrogen, OC = organic carbon, P = phosphorus, Ca = calcium, K = potassium, Mg = magnesium, Na = sodium.

Experimental Design

The experiment followed a Randomised Complete Block Design (RCBD) with four replications. Treatments combined three sunflower varieties (Records, Hysun 33, and Local) with organo-mineral compound fertilizer ([9% N, 22% P₂O₅, 4% K₂O, 13% CaO, 2% MgO] and [22% N, 8% K₂O, 4% CaO, 2% MgO]) application regimes (control, 25%, 50%, 75% and 100% of 190 kg of each compound fertilizer per hectare), resulting in a factorial arrangement tested across fifteen plots per replication, hence total of 60 experimental plots per replicate block. Each plot measured 4.2 m × 3.0 m, with 0.5 m spacing between plots and 1.0 m between replicate blocks and field borders.

Sunflower was planted at a spacing of 0.6 m between rows and 0.3 m within rows, giving six rows of 15 plants each and a total of 90 plants per plot, equivalent to a density of 71,429 plants per hectare. Fertiliser treatments consisted of an initial basal application of organo-mineral compound fertiliser (9% N, 22% P₂O₅, 4% K₂O, 13% CaO, 2% MgO) at planting, followed by a top-dressing of organo-mineral compound fertiliser (22% N, 8% K₂O, 4% CaO, 2% MgO) 14 days after planting. A single control plot (unfertilized) was included for each sunflower variety to establish a reliable baseline for comparison across fertiliser treatments. Delayed onset of rainfall shifted planting from the usual mid-December schedule to January 23, 2025, at Mpwapwa and February 26, 2025, at Bahi,

aligning crop establishment with the late rainfall peak.

Data Collection

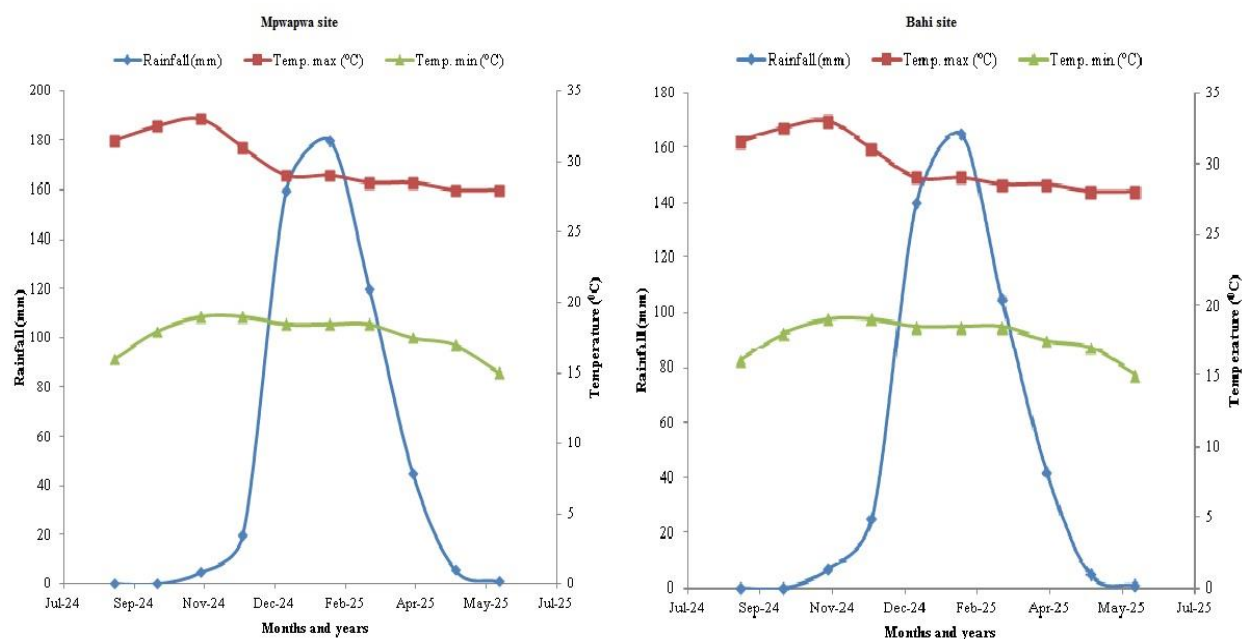
Growth and yield parameters were systematically recorded to assess the response of sunflower varieties to different fertiliser treatments. Plant height (cm) was measured from the base to the tip of the tallest leaf at multiple growth stages. The leaf area index (LAI) was calculated based on the leaf area per plant multiplied by the plant population per plot. Stem diameter (mm) was measured at both the base and mid-height of the plants, while the number of leaves per plant (count) was recorded at various developmental stages. Phenological data, including days to flowering (days) and days to maturity (days), were also recorded. At physiological maturity, total above-ground biomass (g/plant) was harvested and weighed, and grain yield (kg/plot) was determined by weighing the seeds harvested from each plot.

Climatic data for the two sites were generated for the period September 2024 to June 2025, covering rainfall, maximum temperatures, and minimum temperatures (Fig. 1). Monthly rainfall distribution and temperature ranges were examined in relation to the normal planting calendar of mid-December and the delayed onset of rains that shifted sowing to January in Mpwapwa and February in Bahi. At both sites, the season began with almost no rainfall from September through November, followed by below-normal rains in December. This delay prevented the

usual mid-December planting window. Substantial rainfall was only recorded from January through March, with Mpwapwa receiving 160 mm in January, 180 mm in February, and 120 mm in March, while Bahi received 140 mm, 165 mm, and 105 mm in the same months. These totals coincided with the actual planting times, ensuring adequate moisture for crop establishment and vegetative growth but reducing the effective length of the growing season. Temperatures at both sites remained within the optimal range for sunflower growth, with maximums between 28–33°C and

minimums between 15–19°C. These conditions supported physiological processes and reduced risks of temperature-related stress. However, rainfall declined from April onward, with totals of only 45 mm in Mpwapwa and 42 mm in Bahi, indicating limited water availability during the late reproductive and grain-filling stages. The shortening of the effective season due to delayed onset likely constrained yield potential, as plants had less time to complete their cycle under adequate soil moisture conditions.

Figure 1: Monthly Rainfall and Temperature Patterns at Mpwapwa and Bahi from September 2024 to June 2025.



Statistical Data Analysis

A two-way analysis of variance (ANOVA) was employed to evaluate the individual and interactive effects of sunflower varieties (Records, Hysun 33, and local) and fertiliser treatments on growth and yield parameters. This approach facilitated the assessment of the independent influence of each factor as well as their combined impact on sunflower performance. Given the notable differences in environmental conditions between the two study sites, the analyses were conducted

separately for Bahi and Mpwapwa to account for site-specific variability. In addition to ANOVA, regression analysis was performed to investigate the relationship between fertiliser application rates and sunflower seed yield at both sites. Multivariate analysis of variance (MANOVA) was also conducted to assess the overall effect of fertiliser rate on yield variation, considering the combined influence of multiple dependent variables. All statistical analyses, including the regression and MANOVA procedures, were conducted using

PAST software version 4.03. Significance levels were set to $p \leq 0.05$ to determine statistically meaningful differences.

RESULTS

Growth and Yield Performance of Sunflower at the Mpwapwa Site

Sunflower varieties did not differ significantly ($p > 0.05$) for plant height, stem diameter, number of leaves, head diameter, or seed yield at Mpwapwa (Table 2). Plant height at 56 days averaged 76.1 cm for Hysun 33, 74.4 cm for Records, and 62.9 cm for the local variety. Stem diameter ranged from 8.2 cm (Hysun 33) to 8.9 cm (local), while leaf number and head diameter showed minor variation. Seed yields were 1,036–1,079 kg ha⁻¹ across varieties. These results indicate similar performance of all genotypes under Mpwapwa conditions.

Fertiliser application significantly affected most growth parameters. Plant height and stem diameter increased consistently with higher fertiliser rates, with the tallest plants (84.3 cm) at 75% and the largest stems (9.7 cm) at 75%. Head diameter also responded to fertiliser ($p = 0.003$), reaching 21.5 cm at 100%. The number of leaves peaked at 50% and 75% rates (32 leaves). Seed yield, however, did not differ significantly ($p = 0.076$) across fertiliser levels, ranging from 994 to 1,158 kg ha⁻¹.

Interactions between variety and fertiliser rate were largely non-significant, except for stem diameter at certain early stages ($p < 0.001$), as shown in Table 3. Numerical trends suggest that higher fertiliser levels increased vegetative growth, particularly for Records and Hysun 33, but these gains did not translate into proportional yield improvements under Mpwapwa conditions.

Table 2: Main Effects of Sunflower Varieties and Fertiliser Application Rates on Growth and Yield Parameters at Different Days After Planting

Factor	Factor levels	Plant height before top dressing	Plant height 14 days	Plant height 28 days	Plant height 42 days	Plant height 56 days	Stem diameter before	Stem diameter 14 days	Stem diameter 28 days	Stem diameter 42 days	Stem diameter 56 days	Number of leaves	Head diameter 50 days	Head diameter 60 days	Head diameter 70 days	Yield (kg ha ⁻¹)
Varieties	Hysun 33	28.5a	57.1a	57.8a	58.6a	76.1a	3.5a	4a	7a	8a	8.2a	31a	16.2a	17a	21.6a	1036a
	Local variety	23.6a	47.2a	47.9a	48.7a	62.9a	3.9a	4.3a	7.7a	8.6a	8.9a	29.1a	13.3a	14a	17.7a	1079a
	Record	27.9a	55.8a	56.5a	57.3a	74.4a	3.7a	4.2a	7.4a	8.6a	8.8a	30.4a	14a	14.7a	18.6a	1039a
	LS D	5.2	10.5	10.5	10.5	14.0	0.3	0.3	0.7	1.0	1.0	3.7	3.1	3.1	4.1	143.1
	P value	0.115	0.115	0.116	0.115	0.116	0.075	0.075	0.087	0.286	0.268	0.522	0.127	0.129	0.127	0.73
Fertiliser (%)	0	18.2b	35.4b	37.2b	37.9b	48.5b	3.1d	3.6d	6.2c	7.4b	7.7b	27.5a	13.1b	14b	17.5b	1035a
	25	26.6a	23.2a	53.9a	54.7a	70.9a	3.6bc	4.1bc	7.2b	8.3ab	8.6ab	31a	13.76b	14.5b	18.4b	1158a
	50	27a	54a	54.7a	55.5a	72a	3.4cd	4cd	68.bc	8.1ab	8.4ab	31.5a	14.3ab	15.ab	19ab	1048a
	75	31.6a	63.2a	63.9a	64.7a	84.3a	4.1ab	4.6ab	8.2a	9.4a	9.7a	31.5a	15.2ab	16ab	20.2ab	994a
	100	30a	59.9a	60.7a	61.4a	79.9a	4.2a	4.7a	8.4a	8.6ab	9ab	29.3a	16.1a	16ab	21.5a	1021a
	LS D	4.6	9.3	9.3	9.3	12.4	0.3	0.3	0.7	1.2	1.2	2.9	1.5	1.5	2.0	119.1
	P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.024	0.02	0.031	0.003	0.003	0.003	0.076

Means along the same column bearing different letter(s) differ significantly at 5% level of probability.

Table 3: Interaction Effects of Sunflower Variety and Fertiliser Rate on Growth and Yield at Different Days After Planting

Factor levels	Plant height before dressing	Plant height top 14 days	Plant height 28 days	Plant height 42 days	Plant height 56 days	Stem diameter before	Stem diameter 14 days	Stem diameter 28 days	Stem diameter 42 days	Stem diameter 56 days	Number of leaves	Head diameter 50 days	Head diameter 60 days	Head diameter 70 days
Hysun 33 0	22.3bcd	44.6bcd	45.3bd	46.1bcd	59.4bcd	3.3cde	3.8cd	6.6c-f	8.1a	8.3a	34a	15.8a	16.5a	21a
Hysun 33 100	33.1ab	66.2ab	67ab	67.7ab	88.3ab	4abc	4.5abc	8.1a-d	8.4a	8.6a	33a	17.2a	17.9a	22.9a
Hysun 33 25	29.1a-d	58.1a-d	58.8a-d	59.6a-d	77.5a-d	3.3cde	3.8cde	6.5c-f	7.4a	7.6a	33a	15.4a	16.1a	20.5a
Hysun 33 50	30.2abc	60.4abc	61.1abc	61.9abc	80.5abc	3.2cde	3.7cde	def	7.7a	8a	32a	16.5a	17.2a	22a
Hysun 33 75	28.1a-d	56.2a-d	57a-d	57.7a-d	75a-d	3.7a-d	4.2a-d	7.4a-e	8.5a	8.7a	32a	16.3a	17.1a	21.8a
Local variety 0%	15.4d	30.7d	31.5d	32.2d	41d	3.5bcde	4b-d	6.9b-f	7.4a	7.7a	32a	11.9a	12.7a	15.9a
Local variety 100%	25a-d	50a-d	50.7a-d	51.5a-d	66.7a-d	4.1abc	4.6abc	8.1a-d	8.6a	8.9a	31a	15.4a	16.1a	20.5a
Local variety 25%	24.2bcd	48.4bcd	49.1bcd	49.9bcd	64.5bcd	3.4b-e	3.9b-d	6.8b-f	8.2a	8.4a	30a	13.1a	13.9a	17.4a
Local variety 50%	26.3a-d	52.5a-d	53.3a-d	54a-d	70a-d	4.4ab	4.9ab	8.8ab	9.3a	9.5a	30a	12.8a	13.5a	17a
Local variety 75%	27.1a-d	54.2a-d	54.9a-d	55.7a-d	72.2a-d	4abc	4.5abc	8a-d	9.6a	9.9a	30a	13.3a	14a	17.7a
Record 0%	17cd	34cd	34.7cd	35.5cd	45.3cd	2.5e	3e	5f	6.8a	7a	29a	11.7a	12.4a	15.5a
Record 100%	31.8ab	63.5ab	64.3ab	65bd	84.6ab	4.6a	5.1aa	9.2a	9.3a	9.6a	29a	15.8a	16.6a	21.1a
Record 25%	26.5a-d	53.1a-d	53.8a-d	54.6a-d	70.8a-d	4.2abc	4.7abc	8.4abc	9.5a	9.7a	28a	12.9a	13.7a	17.2a
Record 50%	24.6bcd	49.2bcd	49.9bcd	50.7bcd	65.5bcd	2.7de	3.2de	5.4ef	7.3a	7.6a	27a	13.6a	14.4a	18.1a
Record 75%	39.6a	79.3a	80a	80.8a	105.7a	4.6a	5.1aa	9.2a	10.1a	10.4a	25a	16a	16.7a	21.3a
Grand mean	26.67	53.3	54.1	54.8	71.1	3.693	4.193	7.36	8.4	8.66	30.17	14.49	15.25	19.31
S.E.D.	4.091	8.19	8.19	8.19	10.92	0.2857	0.2857	0.569	0.988	0.987	2.618	1.608	1.61	2.144
p value	0.119	0.118	0.119	0.118	0.119	<0.001	<0.001	<0.001	0.196	0.198	0.349	0.81	0.805	0.808

Means along the same column bearing different letter(s) differ significantly at 5% level of probability.

Growth and Yield Performance of Sunflower at the Bahi Site

At Bahi, sunflower varieties differed significantly only in stem diameter ($p = 0.006$), with the local variety producing the widest stems (9.4 cm at 56 days), as shown in Table 4. Plant height, leaf number, head diameter, and grain yield were similar among varieties ($p > 0.05$), with yields ranging from 757 to 794 kg ha⁻¹.

Fertiliser application significantly enhanced plant height, stem diameter, and head diameter ($p < 0.001$). Heights at 56 days increased from 54.7 cm in the control to 84.2 cm at 75% fertiliser. Stem diameter ranged from 7.5 cm (control) to 9.9 cm (75–100%). Head diameter at 70 days increased from 17.8 cm (control) to 25.2 cm (100%). Seed yield did not differ significantly ($p = 0.203$) across fertiliser rates, ranging from 721 to 846 kg ha⁻¹.

Variety $\times$ fertiliser interactions significantly ($p < 0.001$) influenced stem diameter but not plant height, leaf number, head diameter, or yield (Table 5). Records with 75% fertiliser achieved the largest stems, while the local variety at 25% yielded the highest numerically. These results indicate that moderate fertiliser levels can improve vegetative growth without necessarily increasing seed yield.

Table 4: Main Effects of Sunflower Varieties and Fertiliser Application Rates on Agronomic and Seed Yield at the Bahi Site

F ac to r	Fac tor leve ls	Plant height before top dressing	Plant height 14 days	Plant height 28 days	Plant height 42 days	Plant height 56 days	Stem diameter before top dressing	Stem diamet er 14 days	Stem diamet er 28 days	Stem diamet er 42 days	Stem diamet er 56 days	Num ber of leave s	Head diamet er 50 days	Head diamet er 60 days	Head diamet er 70 days	Yiel d (kg ha ⁻¹)
Variety	Hys un 33	27.4a	54.9a	55.6a	56.4a	73.2a	3.3b	3.8b	6.6b	8.1b	8.4b	31.6a	16.1a	16.9a	21.5a	758. 8a
	Loc al vari ety	25.3a	50.7a	51.4a	52.2a	67.6a	3.9a	4.4a	7.7a	9.1a	9.4a	32.1a	16a	16.7a	21.3a	793. 8a
	Rec ord	27.8a	55.6a	56.4a	57.1a	74.2a	3.7a	4.2a	7.4a	8.8ab	9ab	32.1a	16.2a	17a	21.6a	757. 5a
	L.S. D.	5.123	10.24	10.23	10.24	13.68	0.2625	0.2625	0.5507	0.766	0.778	1.16	2.704	2.724	3.62	164. 7
	p valu e	0.492	0.487	0.488	0.487	0.488	0.005	0.005	0.006	0.054	0.055	0.458	0.977	0.972	0.976	0.83 4
Fertilizers	0%	20.5b	41b	41.8b	42.5b	54.7b	3c	3.5c	6c	7.3c	7.5c	30.8a	13.4c	14.1c	17.8c	768. 8a
	25 %	25.9ab	51.9ab	52.6ab	53.4ab	69.2ab	3.5b	4b	7b	8.5b	8.8b	32.1a	15.9b	16.6b	21.1b	845. 8a
	50 %	27.2a	54.4a	55.1a	55.9a	72.5a	3.5b	4b	7b	8.3bc	8.5b	31.8a	15.5bc	16.2bc	20.7bc	775a
	75 %	31.5a	63.2a	63.9a	64.7a	84.2a	4a	4.5a	8a	9.7a	9.9a	32.7a	16.8ab	17.5ab	22.4ab	720. 8a
	100 %	29.1a	58.2a	59a	59.7a	77.6a	4.1a	4.6a	8.2a	9.7a	9.9a	32.2a	18.9a	19.7a	25.2a	739. 6a
	L.S. D.	4.165	8.33	8.33	8.33	11.11	0.2911	0.2911	0.5812	0.725	0.723	2.61	1.603	1.61	2.142	109. 3
	p valu e	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.699	<0.001	<0.001	<0.001	0.20 3

Means along the same column bearing different letter(s) differ significantly at 5% level of probability.

Table 5: Interaction Effects of Variety and Fertiliser Rates on Sunflower Performance at the Bahi Site

Factor levels	Plant height before top dressing	Plant height 14 days	Plant height 28 days	Plant height 42 days	Plant height 56 days	Stem diameter before top dressing	Stem diameter 14 days	Stem diameter 28 days	Stem diameter 42 days	Stem diameter 56 days	Number of leaves	Head diameter 50 days	Head diameter 60 days	Head diameter 70 days	Yield (kg ha ⁻¹)
Hysun 330	20.8b	41.6b	42.3b	43.1b	55.4b	3efg	3.5efg	6efg	7.8cde	8.1cde	31.3a	15ab	15.8ab	20ab	806.2a
Hysun 33100	30.2ab	60.4ab	61.2ab	61.9ab	80.6ab	3.9a-e	4.4a-e	7.7a-e	9.2a-d	9.4a-d	30.8a	16.8ab	17.6ab	22.5ab	712.5a
Hysun 3325	27.3ab	54.5ab	55.3ab	56ab	72.7ab	2.9fg	3.4fg	5.8fg	7.6cde	7.9cde	31.5a	16.5ab	17.2ab	22ab	825a
Hysun 3350	30.2ab	60.4ab	61.1ab	61.9ab	80.5ab	3.4c-g	3.9c-g	6.8c-g	8.2b-e	8.5b-e	33.3a	16ab	16.8ab	21.4ab	750a
Hysun 3375	28.7ab	57.6ab	58.3ab	59.1ab	76.7ab	3.4c-g	3.9c-g	6.8c-g	7.9b-e	8.2b-e	31a	16.1ab	16.9ab	21.5ab	700a
Local variety 0	20.2b	40.3b	41.1b	41.8b	53.7b	3.3d-g	3.8d-g	6.7d-g	7.7cde	7.9cde	33a	12.5b	13.2b	16.7b	725a
Local variety 100	27.1ab	54.1ab	54.9ab	55.6ab	72.2ab	4a-d	4.5a-d	8a-d	9.3a-d	9.6a-d	32.3a	19.8a	20.5a	26.3a	806.2a
Local variety 25	25.4ab	50.8ab	51.6ab	52.3ab	67.8ab	3.6b-f	4.1b-f	7.2b-f	8.9a-d	9.2a-d	31.3a	15.4ab	16.1ab	20.4ab	937.5a
Local variety 50	26.8ab	53.7ab	54.4ab	55.2ab	71.5ab	4.3abc	4.8abc	8.5abc	9.5abc	9.8abc	31.5a	14.7ab	15.4ab	19.5ab	825a
Local variety 75	27.3ab	54.6ab	55.3ab	56.1ab	72.7ab	4.2a-d	4.7a-d	8.3a-d	10.1ab	10.4ab	32.5a	17.6ab	18.3ab	23.4ab	675a
Record 0	20.6b	41.3b	42b	42.8b	55b	2.7g	3.2g	5.3g	6.3e	6.5e	28.3a	12.6b	13.4b	16.8b	775a
Record 100	30.1ab	60.1ab	60.9ab	61.6ab	80.1ab	4.4ab	4.9ab	8.9ab	10.6a	10.8a	33.5a	20.2a	20.9a	26.8a	700a
Record 25	25.1b	50.3b	51b	51.8b	67.1b	4.1a-d	4.6a-d	8.1a-d	9a-d	9.2a-d	33.5a	15.7ab	16.5ab	20.9ab	775a
Record 50	24.6b	49.2b	49.9b	50.7b	65.5b	2.9fg	3.4fg	5.8fg	7.1de	7.4de	30.8a	15.9ab	16.6ab	21.2ab	750a
Record 75	38.7a	77.4a	78.1a	78.9a	103.2a	4.5a	5a	9.1a	11a	11.3a	34.5a	16.7ab	17.4ab	22.2ab	787.5a
Grand mean	26.86	53.7	54.5	55.2	71.6	3.628	4.128	7.24	8.66	8.93	31.9	16.09	16.83	21.44	770
S.E.D.	3.809	7.62	7.62	7.62	10.16	0.2469	0.2469	0.4978	0.636	0.637	2.05	1.574	1.583	2.206	107.2
p value	0.139	0.141	0.141	0.141	0.142	<0.001	<0.001	<0.001	<0.001	<0.001	0.254	0.252	0.263	0.122	0.547

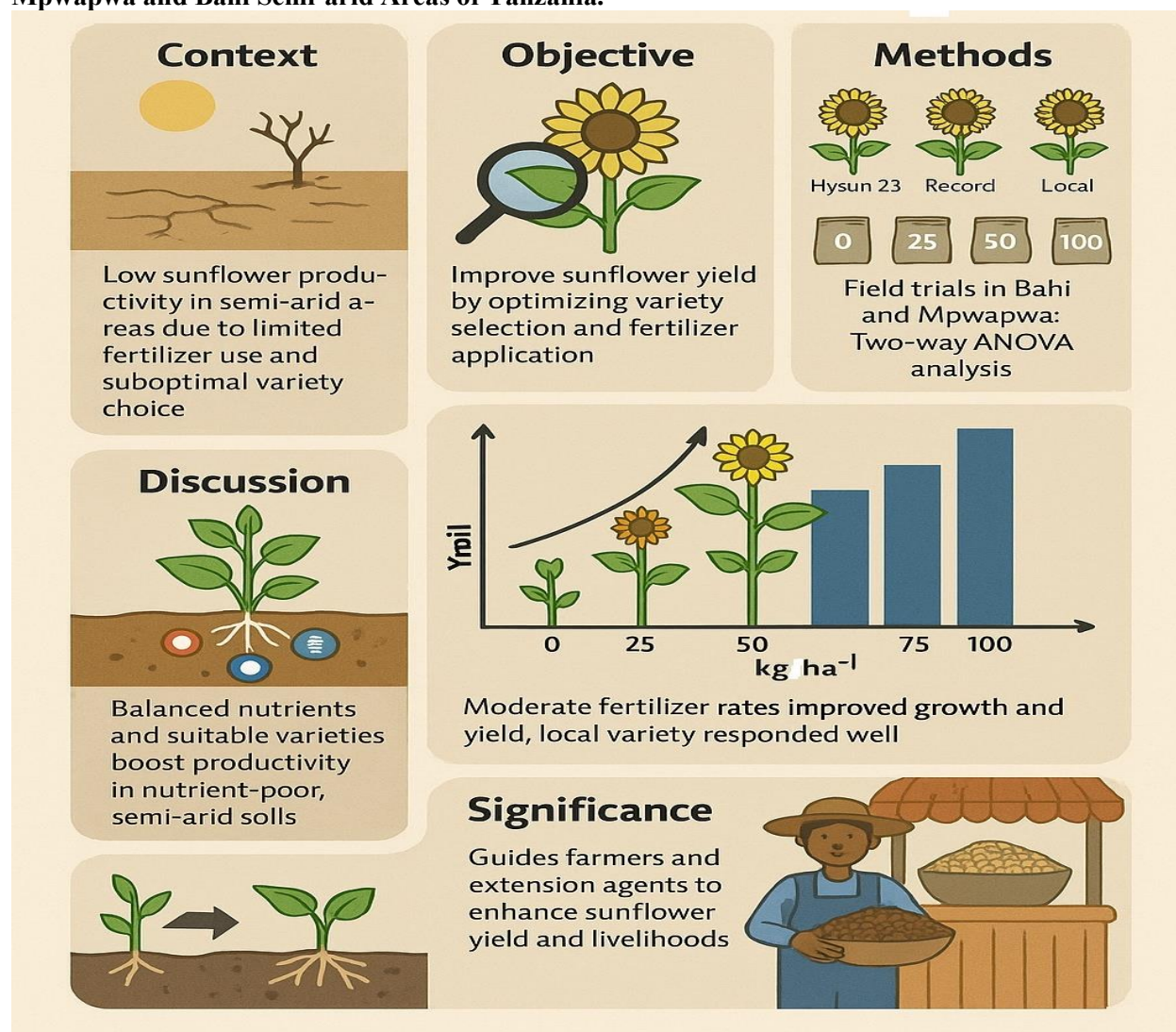
Means along the same column bearing different letter(s) differ significantly at 5% level of probability.

Illustrative Effect of Variety Selection and Fertiliser Application on Sunflower

Illustration in Figure 2 shows the effects of three sunflower varieties across five fertiliser levels at Bahi and Mpwapwa. Fertiliser improved plant height, stem diameter, and head size, particularly at moderate rates (25–75%). The Records variety

exhibited strong vegetative growth, while the local variety achieved the highest yield at 25–50%. The figure highlights that site conditions and fertiliser management interact with varietal performance, and moderate nutrient inputs support growth and yield without excessive fertiliser use.

Figure 2: Effects of Variety and Fertiliser Rate (0–100%) on Sunflower Growth and Yield in Mpwapwa and Bahi Semi-arid Areas of Tanzania.



Yield Response to Fertiliser and Genotypic Variation

Seed yields were higher at Mpwapwa ($\approx 1,036$ – $1,079$ kg ha⁻¹) than at Bahi (≈ 757 – 794 kg ha⁻¹), indicating site-specific influences on productivity (Fig. 3). The local variety recorded the highest average yield across sites, followed closely by Records and Hysun 33. Differences among improved varieties were minor, suggesting that

variety selection is less influential than site conditions under the tested management regimes.

Regression analysis showed a negative but non-significant relationship between fertiliser rate and seed yield at both sites ($p > 0.05$). Slopes of 0.73 (Bahi) and 0.77 (Mpwapwa) with low R^2 values (0.37 and 0.23) indicate that higher fertiliser rates consistently increase yields (Table 6). Yields

tended to decline numerically beyond 75% fertiliser, though these trends were not statistically supported. These results indicate that moderate fertiliser application is sufficient, while excessive input does not improve yield and may be unnecessary. Site conditions and varietal choice remain key determinants of sunflower productivity.

Figure 3: Sunflower Seed Yield (kg/ha) Across Two Sites (Bahi and Mpwapwa) and among Three Varieties (Hysun 33, Local variety, and Record).

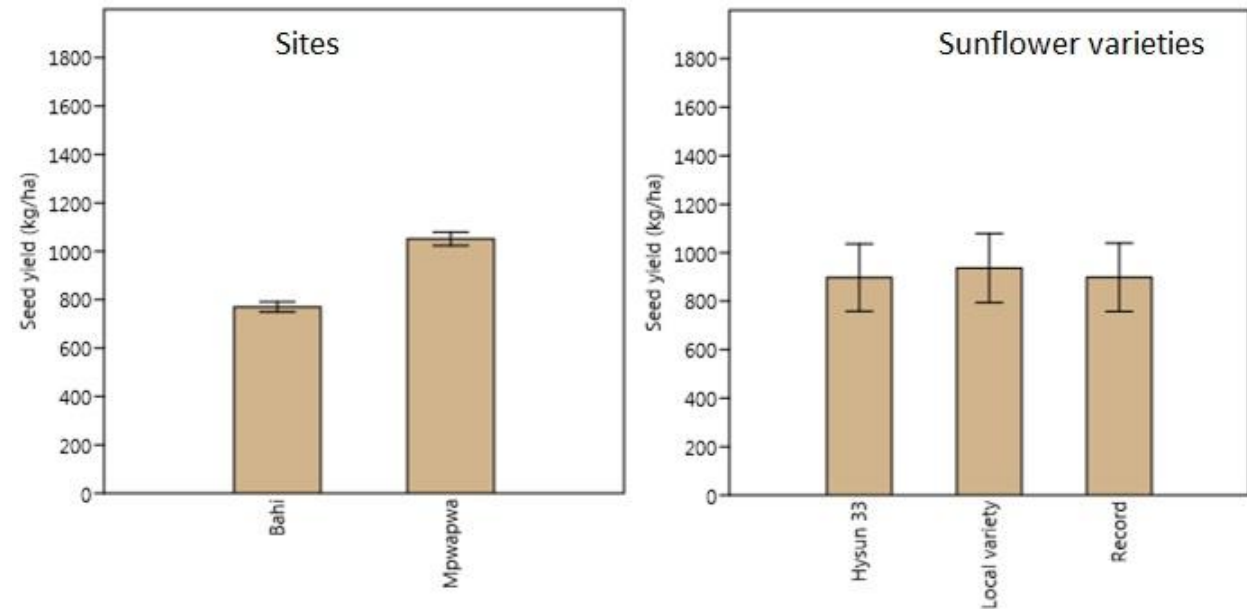


Table 6: Regression between Fertiliser and Sunflower Seed Yield Across Bahi and Mpwapwa Sites

	Variable							
Site	Slope	Error	Intercept	Error	r	p		
Bahi	0.73	0.55	806.68	33.92	-0.61	0.27724		
Mpwapwa	0.77	0.81	1089.60	49.35	-0.48	0.41089		
	Overall statistics:			MANOVA				
Site	R ² :	MSE:		Wilks' lambda:	F:	df1:	df1:	p(regr):
Bahi	0.37	1918		0.63	1.75	1	3	0.2772
Mpwapwa	0.23	4059		0.77	0.91	1	3	0.4109

DISCUSSION

Sunflower Performance with Varietal Differences and Fertiliser Application

The tested sunflower varieties, Hysun 33, Records, and the local genotype, showed no statistically significant differences in seed yield at Mpwapwa and Bahi. Despite genetic differences, these varieties appear to share comparable adaptive capacity to semi-arid conditions (Hladni et al., 2022a; Lamichhane et al., 2022). Similar observations of yield stability among sunflower

genotypes in drought-prone areas indicate that environmental factors, particularly soil fertility and water availability, exert a stronger influence on final yield than varietal growth potential (Jocković et al., 2024). Selection of varieties should therefore consider resource use efficiency under stress rather than potential maximum growth alone (Dar et al., 2021; Meena & Sujatha, 2022).

Fertiliser application increased vegetative growth parameters, including plant height, stem diameter,

and head size. These responses reflect the influence of nutrient availability, especially nitrogen and phosphorus, on sunflower development in semi-arid contexts (Sahoo et al., 2023; Ren et al., 2024b). At higher fertiliser rates, however, vegetative growth increased without proportional improvements in seed yield. This suggests a threshold beyond which additional nutrients do not enhance yield, consistent with studies showing that excess nutrient supply in water-limited environments may promote vegetative biomass at the expense of reproductive development (Rodriguez et al., 2024; Husband et al., 2025; Chen et al., 2023).

Interaction effects between variety and fertiliser were observed for stem diameter but not for yield (Aboye & Edo, 2024; Dudhe et al., 2025). The local variety maintained comparable yields under moderate fertiliser levels despite smaller vegetative size, which may reflect traits such as improved nutrient use efficiency or drought tolerance (Singhal et al., 2023; Ameen et al., 2024). Locally adapted genotypes often display root architecture and osmotic adjustment mechanisms that enhance stress resilience and maintain yield stability (Hladni et al., 2022b; Renzi et al., 2022).

Site-specific differences in growth and yield responses further illustrate the influence of local environmental conditions. Mpwapwa consistently recorded higher yields than Bahi, likely related to soil nutrient composition, rainfall distribution, and microclimatic variation, in line with studies emphasising spatial heterogeneity in semi-arid agroecosystems (Bueno de Mesquita et al., 2024; Mota et al., 2024; Marcelino et al., 2024; Wang et al., 2025). These differences highlight that fertiliser recommendations must account for site-specific conditions rather than applying uniform rates across semi-arid landscapes (Alwang'a et al., 2025; He & Liu, 2025).

The observed responses suggest that moderate fertiliser application can enhance vegetative growth efficiently without unnecessary input costs or environmental risks (Aghili Nategh et al.,

2021; Chen & Liu, 2023). The local variety's performance under these conditions indicates potential for integrating locally adapted genotypes into site-specific nutrient management strategies to improve productivity and resilience (Friedel & Ardakani, 2021; Zhang et al., 2021). Future research should evaluate complementary strategies such as water management and breeding for nutrient and drought use efficiency to stabilise yields under variable semi-arid conditions (He et al., 2024; Hussain et al., 2025).

Practical Implications and Challenges of Sunflower Production in Semi-arid Areas

The study indicates that moderate fertiliser application improved sunflower vegetative growth without proportional gains in seed yield at the highest rates. This reflects interactions between nutrient supply and environmental limitations, particularly water availability, which influences nutrient uptake and utilisation (Soothar et al., 2021; Ma et al., 2022). The local variety's ability to sustain yields under moderate inputs suggests that genetic adaptation contributes to yield stability in water-limited semi-arid agroecosystems (Saadaoui et al., 2022; Paroda et al., 2024). Integrating genotype characteristics with nutrient management is therefore essential to optimise growth responses under these conditions (Temme et al., 2024; Zalai et al., 2025).

Differences between Mpwapwa and Bahi reflect the heterogeneity of semi-arid farming landscapes, including soil texture, organic matter content, and microclimate, which influence nutrient dynamics and crop growth patterns (Tianjiao et al., 2022; Kaplan et al., 2024). These variations complicate the adoption of uniform agronomic recommendations and reinforce the need for site-specific fertiliser management to maximise nutrient use efficiency (Videgain et al., 2024; Reuter et al., 2025). Increased vegetative growth at higher fertiliser rates without consistent yield gains suggests that excessive nutrient supply may disproportionately favour vegetative development over reproduction under water-limited conditions (Bhattacharya & Bhattacharya, 2021; Gregory et al., 2025).

Challenges for smallholder farmers include limited access to fertilisers and fluctuating market availability, which constrain the practical application of nutrient rates demonstrated to enhance growth (Tomasi et al., 2024; Li & Liu, 2025). Variable and often insufficient rainfall further restricts nutrient uptake, as plant absorption depends on soil moisture, increasing the risk of nutrient losses through leaching or volatilisation (Ali et al., 2024; Agbna & Zaidi, 2025; Sahu et al., 2023; Rai & Sarkar, 2025).

Extension services and knowledge dissemination remain limited, affecting farmers' ability to implement appropriate fertiliser and variety strategies relative to local conditions (Hessel et al., 2022; Tibamanya et al., 2022). Climate variability, including increased frequency of drought, amplifies uncertainty in nutrient and water management, further influencing yield outcomes (Lesk et al., 2022; Rezaei et al., 2023; Shafiq et al., 2021; Waqar et al., 2022).

Sunflower performance in semi-arid areas is determined by interactions among genetic traits, environmental factors, and management practices. Optimal nutrient management in these systems must navigate constraints imposed by variable water availability, heterogeneous soils, and socio-economic limitations, shaping both growth and yield responses (Enahoro-Ofagbe et al., 2024; Nungula et al., 2024b). Understanding these dynamics provides a basis for designing practical, site-adapted strategies to improve productivity under semi-arid conditions.

CONCLUSION AND FUTURE DIRECTIONS

The study evaluated sunflower growth and yield under different varieties and fertiliser rates in semi-arid conditions. Fertiliser application improved vegetative growth and head development, but seed yield did not differ significantly across treatments. The local variety performed similarly to improved varieties under moderate nutrient inputs, suggesting its adaptation to semi-arid environments. Site variability

highlighted the influence of local soil and climate conditions on crop response.

Future research should investigate site-specific nutrient management that accounts for soil fertility, water availability, and varietal characteristics to improve yield stability. Additional studies are needed to clarify factors affecting yield responses at higher fertiliser rates and to evaluate long-term environmental effects. Efforts to increase smallholder access to inputs and agronomic guidance may support the practical application of research findings in these regions.

Data Availability Statement

No publicly available datasets were analysed in this study.

Author Contributions

EWS: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualisation, Writing – original draft, Writing – review & editing. NLK: Supervision, Validation, Visualisation, Writing – review & editing. EKN: Supervision, Validation, Visualisation, Writing – review & editing.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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