



Seasonal Consistency and Agronomic-Economic Trade-offs of Arbuscular Mycorrhizal Fungi, Organic Manure and NPK Nutrient Management for Maize in Semi-Arid Taveta, Kenya

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Authors' contributions

This work was carried out in collaboration among all authors. Author PM contributed to conceptualization, investigation, field data collection, data curation, and preparation of the original draft. Author JGW contributed to supervision, methodology, interpretation, and manuscript review. Author MM contributed to methodology, agronomic interpretation, and manuscript review. Author BM contributed to field methodology, technical support, and manuscript review. Author AKK contributed to supervision, methodology, statistical interpretation, manuscript restructuring, and critical review. All authors read and approved the final manuscript.

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Abstract

Sustainable maize production in semi-arid environments requires nutrient-management strategies that account for seasonal variability in crop responses to biological, organic and mineral inputs. This study evaluated the agronomic and economic responses of maize to arbuscular mycorrhizal fungi (AMF), organic manure (OM), NPK fertiliser and their pairwise combinations in Taveta, Kenya. A two-season randomised complete block experiment comprised seven treatments replicated three times per season. Maize (*Zea mays* L.) cv. DK 777 received AMF, OM, NPK 17:17:17, AMF+OM, AMF+NPK, OM+NPK or no amendment. Plot-level analyses tested treatment, season and treatment $\times$ season effects, with Tukey HSD used for mean separation. Treatment significantly affected grain yield and biomass ($P < .001$), whereas treatment $\times$ season interactions were not significant ($P = .772$ and $.408$, respectively). Pooled grain yield was highest under NPK ($148.23 \text{ g plant}^{-1}$), OM+NPK ($147.77 \text{ g plant}^{-1}$) and AMF+NPK ($146.17 \text{ g plant}^{-1}$), compared with $92.03 \text{ g plant}^{-1}$ in the control. Root length showed a significant treatment $\times$ season interaction ($P = .011$), indicating greater seasonal sensitivity of below-ground responses. Week-6 plant height, leaf area and stem diameter were strongly associated with grain yield in both seasons. NPK generated the highest two-season mean net benefit (KSh 1,401.08) and benefit-cost ratio (4.00). Overall, NPK and NPK-containing pairwise treatments produced strong productivity responses, although pairwise combinations did not significantly outperform NPK alone for pooled grain yield. These findings support context-specific nutrient management that integrates agronomic performance, seasonal variability and short-term economic returns.

Keywords: Arbuscular mycorrhizal fungi; maize; nutrient management; organic manure; semi-arid agriculture.

1. Introduction

Maize (*Zea mays* L.) remains a strategic staple and income crop across sub-Saharan Africa, but yield improvement in many smallholder systems is constrained by nutrient depletion, low soil organic matter, rainfall variability and the rising cost of external inputs. These constraints interact particularly strongly in semi-arid environments, where soil-water availability regulates nutrient diffusion, mineralisation, root activity and ultimately the crop response to fertiliser. Consequently, nutrient-management recommendations developed under more favourable environments may not transfer directly to water-limited production zones.

Integrated soil fertility management (ISFM) seeks to improve the efficiency and resilience of nutrient supply by combining mineral fertilisers with organic resources and other locally appropriate practices (Vanlauwe *et al.*, 2015). The principle is attractive because mineral fertilisers can rapidly correct nutrient deficiencies, whereas organic amendments contribute carbon and a broader nutrient spectrum and may improve soil physical and chemical conditions (Chivenge *et al.*, 2011). Evidence from long-term Kenyan experiments shows that manure combined with mineral N can sustain maize productivity over many seasons, but the magnitude of response remains strongly site- and climate-dependent (Laub *et al.*, 2023). A more recent synthesis across African smallholder systems similarly emphasises that the benefits of organic inputs are highly localised; manure and manure-plus-mineral fertiliser generally improve maize yield and several soil indicators, but outcomes vary with rainfall, soil texture, acidity, initial soil organic carbon and resource quality (Sileshi *et al.*, 2025). Recent field evidence shows that integrated organic-mineral nutrient management can improve maize growth and yield, although responses vary among nutrient combinations (Yadav *et al.*, 2024).

This context dependence is especially important in dry environments. Long-term Kenyan evidence indicates that seasonal rainfall and temperature can override soil-fertility effects in determining maize yield in a given season, even where soil organic carbon is being maintained (Laub *et al.*, 2025). Simulation analyses across Kenya likewise indicate that the yield benefits of manure-mineral fertiliser strategies depend strongly on adequate rainfall (Laub *et al.*, 2026). Thus, a useful nutrient-management experiment should evaluate not only mean treatment performance but also whether treatment responses are stable across contrasting seasons. A two-season study in central Myanmar also found that maize responses to integrated organic and inorganic inputs varied between monsoon and post-monsoon conditions (Htun *et al.*, 2025).

Arbuscular mycorrhizal fungi (AMF) provide a biological pathway for improving resource acquisition. Their extraradical hyphae extend the effective soil volume explored by roots and can enhance phosphorus acquisition and plant performance, although the magnitude of benefit varies with host genotype, soil fertility, indigenous microbial communities and environmental conditions (Berruti *et al.*, 2016; Smith & Smith, 2011; Zhang *et al.*, 2019). A global meta-analysis of cereal studies reported a positive field-inoculation effect on grain yield, but with substantial variability among trials (Zhang *et al.*, 2019). Under drought stress, more recent meta-analytic evidence indicates that mycorrhizal inoculation can improve plant biomass and nutrient acquisition, while again showing strong modulation by soil and biological context (Zaman *et al.*, 2024). These findings argue against treating AMF inoculation as a universally effective substitute for adequate nutrient supply.

Combining AMF or organic resources with mineral fertiliser could therefore produce complementary responses (Fall *et al.*, 2023): fertiliser supplies immediately available nutrients, manure contributes organic matter and gradually available nutrients, and AMF may enhance soil exploration. Field studies in Africa increasingly support the value of integrated nutrient management, although the identity of the best treatment varies by environment. For example, combined manure and mineral fertiliser increased maize growth and yield in contrasting Ghanaian agroecologies, but sole NPK remained competitive for several vegetative and yield responses (Essilfie *et al.*, 2024). This distinction is agronomically important because a numerically larger response from an integrated treatment does not necessarily constitute statistical synergy, nor does it automatically translate into greater economic return. In a semi-arid maize system, integrated fertilisation improved yield and resource-use performance under contrasting water supplies (Wang *et al.*, 2025). Long-term semi-arid research likewise reported improved maize growth, nutrient accumulation and productivity under integrated crop management (Barman *et al.*, 2025).

Taveta in Taita Taveta County, southeastern Kenya, is a semi-arid production environment where maize growers face both seasonal water variability and the practical need to use nutrient inputs efficiently. Field evidence comparing AMF, organic manure and mineral fertiliser in this environment remains limited. Moreover, many nutrient-management studies emphasise end-of-season yield while giving less attention to when growth trajectories diverge, whether root responses are season-sensitive, and how vegetative development relates to final grain production.

This study therefore evaluated AMF, organic manure and NPK fertiliser applied singly and in pairwise combinations over two maize cropping seasons. Specifically, it examined (i) temporal vegetative growth, phenology and root development; (ii) yield formation, biomass production and harvest index; (iii) the stability of treatment responses across seasons; (iv) associations between final vegetative traits and grain yield; and (v) indicative treatment-level economic performance. Because the AMF+OM+NPK treatment was not included, the experiment is interpreted as a comparison of seven predefined nutrient-management treatments rather than a complete 2³ factorial experiment. We hypothesised that NPK-containing and integrated treatments would improve crop growth and yield relative to the unamended control, but that the magnitude of response would vary with season.

2. Materials and Methods

2.1 Study Site and Baseline Soil

The field experiment was conducted at Timbila in Taveta Sub-County, Taita Taveta County, Kenya (3°22'26.65" S, 37°42'39.48" E; 744.5 m above sea level) during two maize cropping seasons in 2025–2026. The area is semi-arid, with bimodal rainfall and temperatures generally ranging from 17 to 27 °C. The experimental soil was loamy and moderately well drained. Before treatment application, composite soil sampled from 0–20 cm had pH 6.31, total N 3.3 g kg⁻¹, organic C 33.9 g kg⁻¹, C:N ratio 10.3:1, available P 63.62 mg kg⁻¹ and K 1033.5 mg kg⁻¹.

2.2 Experimental Design and Treatments

The experiment was arranged as a randomised complete block design (RCBD) with seven nutrient-management treatments replicated three times, resulting in 21 plots per season. Treatments were AMF, organic manure (OM), NPK 17:17:17, AMF+OM, AMF+NPK, OM+NPK and an unamended control. The AMF+OM+NPK combination was not included; consequently, the design compared predefined sole and pairwise treatments and did not permit estimation of the full three-factor interaction structure.

Each plot measured 4 × 4 m (16 m²) and contained 84 planting positions. Plots were separated by 1.0-m alleys, blocks by 1.5-m alleys, and a 1.0-m border surrounded the experiment. Maize cv. DK 777 was planted at 75 × 25 cm spacing, one seed per planting position. NPK 17:17:17 was applied at 706 kg ha⁻¹ (approximately 120 kg N ha⁻¹; 1.13 kg product plot⁻¹). Granular AMF inoculum containing *Glomus spp.* was applied at 500 kg ha⁻¹ (0.8 kg plot⁻¹; approximately 9.5 g planting position⁻¹). Well-decomposed farmyard manure was applied at 10 t ha⁻¹ (16 kg plot⁻¹; approximately 190 g planting position⁻¹). In pairwise treatments, each component was applied at its sole-treatment rate.

2.3 Crop Measurements

Five plants were tagged within each plot and treated as subsamples, not independent experimental replicates. Plant height, leaf dimensions, stem diameter and leaf number were measured repeatedly during vegetative development. Leaf area was estimated from measured leaf dimensions using the procedure adopted in the field datasheet. Primary root length was measured at final sampling after excavation and cleaning. Days to 50% tasseling and 50% silking were recorded at plot level.

At harvest, cob length, cob diameter, cob weight, kernels per cob and 100-grain weight were determined. Grain, stover and total above-ground biomass were recorded. Harvest index was calculated at plot level as total grain mass divided by total above-ground biomass ×100. Grain values are reported on the same per-plant basis used in the raw field dataset.

2.4 Plant and Soil Nutrient Measurements

Leaf and post-harvest soil samples were analysed for N, P and K using standard laboratory procedures based on micro-Kjeldahl N determination, spectrophotometric P determination and flame-emission K determination (Okalebo *et al.*, 2002). Samples from replicate plots were bulked into a single treatment-level composite before laboratory determination. Consequently, the nutrient measurements did not retain independent treatment replication and were not used for inferential treatment comparisons in the present manuscript. This decision avoids pseudoreplication and confines the main paper to statistically supported agronomic outcomes.

2.5 Economic Analysis

A treatment-level partial budget was used to compare short-run economic performance. Grain was valued at KSh 50 kg⁻¹. Treatment-specific input costs were AMF KSh 440 plot⁻¹, OM KSh 416.67 plot⁻¹, NPK KSh 466.67 plot⁻¹, AMF+OM KSh 856.67 plot⁻¹, AMF+NPK KSh 906.67 plot⁻¹ and OM+NPK KSh 883.34 plot⁻¹. Common production costs were excluded because they did not differ among treatments. Net benefit was calculated as gross grain benefit minus treatment-specific input cost. Benefit-cost ratio (BCR) was calculated for treatments with non-zero treatment cost; a conventional treatment BCR was therefore not assigned to the unamended control.

2.6 Statistical Analysis

The plot was the experimental unit. For traits measured on five plants within a plot, plant observations were first averaged to a plot mean before inferential analysis. For 100-grain weight, the available plot-level measurement was used directly. Weekly plant-height responses were analysed separately by season and sampling week using RCBD models with treatment and block effects; Tukey's honestly significant difference (HSD) test was applied after a significant omnibus treatment test.

For final agronomic traits, the two seasons were analysed jointly using the model $Y = \text{season} + \text{treatment} + \text{season} \times \text{treatment} + \text{block}(\text{season}) + \text{error}$. Season and treatment were treated as fixed effects and block was accounted for within season. Where the season $\times$ treatment interaction was not significant, pooled treatment means across seasons were compared using Tukey HSD. Where the interaction was significant, treatment means were examined within season. Pearson correlations between Week-6 vegetative traits and final grain yield were calculated from plot means separately for each season ($n=21$ plots season⁻¹). These relationships were interpreted as exploratory associations rather than causal effects. Statistical significance was assessed at $P = .05$.

3. Results

3.1 Treatment Effects Emerged Progressively during Vegetative Growth

Plant-height trajectories showed that treatment differences were small during crop establishment but became increasingly evident as vegetative growth progressed (Fig. 1). In Season 1, the treatment effect was not significant at Week 1 ($P = .095$), became significant at Week 2 ($P = .014$), and remained significant through Weeks 3-6 ($P = .013$, .003, .004 and .005, respectively). In Season 2, treatment effects were not significant during Weeks 1-2 ($P = .246$ and .086) but became significant from Week 3 onward ($P = .032$, .002, < .001 and < .001 for Weeks 3-6). NPK, AMF+NPK and OM+NPK increasingly occupied the upper Tukey groups during late vegetative development, whereas the control and AMF alone generally remained lower. Thus, nutrient management altered the trajectory of canopy development rather than producing an immediate uniform separation after establishment.

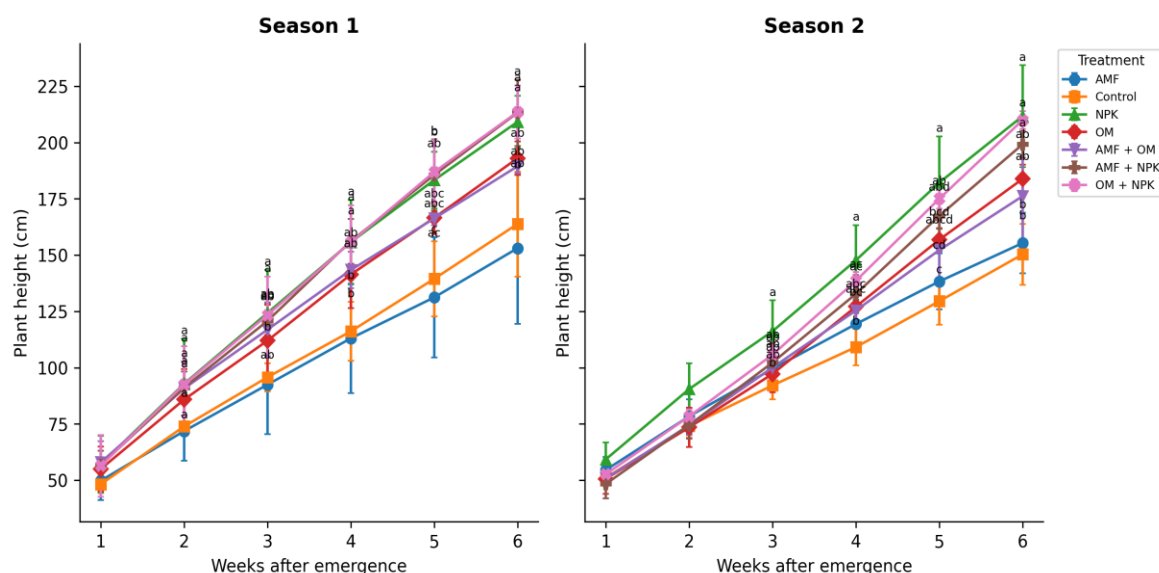


Fig. 1. Temporal changes in maize plant height under nutrient-management treatments during two cropping seasons. Points are plot-level means $\pm$ SD ($n = 3$ blocks). Different lowercase letters indicate Tukey HSD groups within a week following a significant RCBD treatment effect ($P < .05$); letters are omitted when the omnibus treatment effect was not significant

3.2 Phenology and Yield Formation

Across seasons, treatment significantly affected both tasseling ($P < .001$) and silking ($P < .001$), while treatment $\times$ season interactions were not significant ($P = .829$ and .440, respectively). The control reached the silking stage latest (73.30 ± 2.39 d), whereas NPK (68.57 ± 1.09 d), OM+NPK (69.20 ± 1.50 d) and AMF+NPK (69.50 ± 1.12 d) reached silking earlier (Table 1). Season affected tasseling ($P < .001$) and silking ($P < .001$), indicating a shift in developmental timing between the two cropping periods.

Yield formation responded strongly to nutrient management. Treatment effects were significant for cob length ($P < .001$), cob diameter ($P < .001$), kernels cob⁻¹ ($P < .001$) and 100-grain weight ($P = .018$), with no significant treatment $\times$ season interaction for these traits. Pooled cob length was greatest under AMF+NPK (19.08 cm) and OM+NPK (18.82 cm), compared with 14.07 cm in the control. Kernel number increased from 389.9 kernels cob⁻¹ in the control to 559.1 under NPK and 577.4 under OM+NPK. NPK had the highest pooled 100-grain weight (28.17 g), although several treatments overlapped statistically after Tukey adjustment (Fig. 2).

These responses show that the productivity effect was expressed through multiple components of reproductive development rather than grain mass alone.

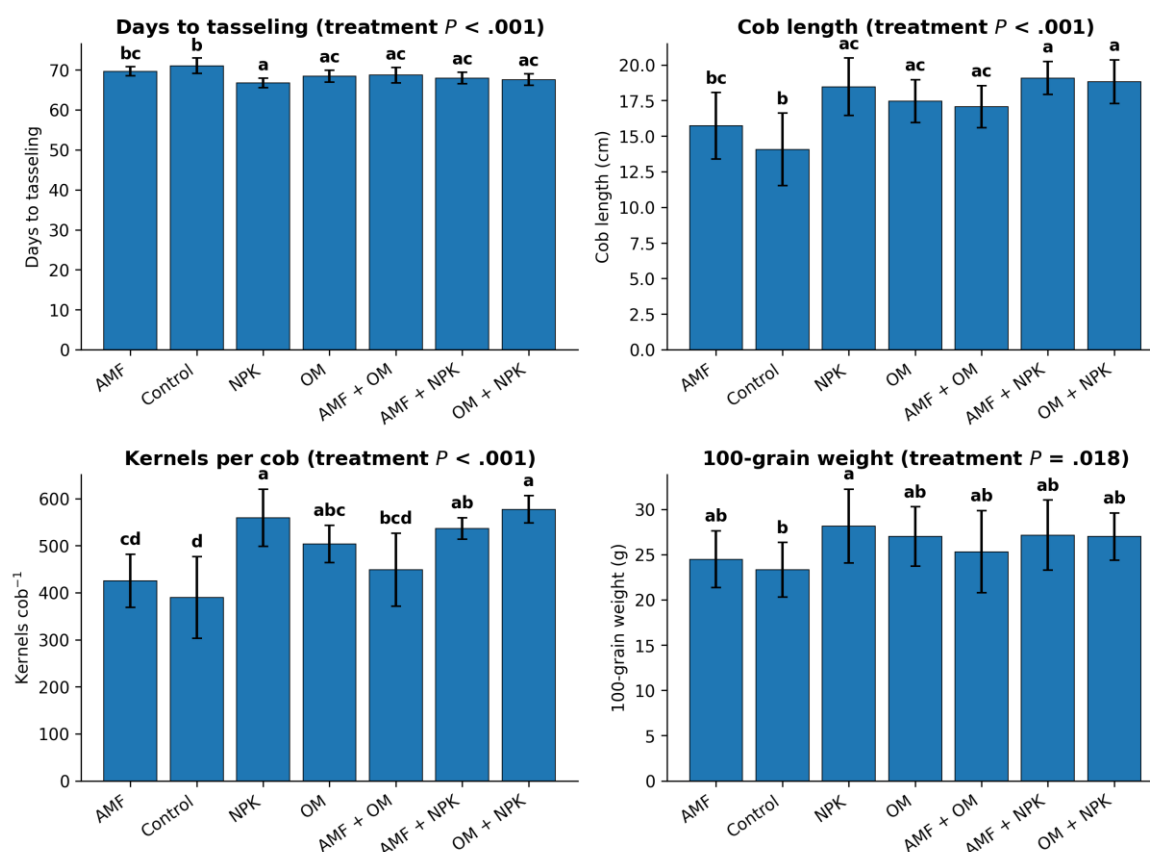


Fig. 2. Pooled phenological and yield-component responses of maize to nutrient-management treatments across two seasons: (A) days to tasseling, (B) cob length, (C) kernels per cob and (D) 100-grain weight. Bars are means $\pm$ SD of plot means ($n = 6$; three blocks per season). Different lowercase letters indicate Tukey HSD groups at $P < .05$. Treatment $\times$ season interactions were not significant for these traits

Table 1. Selected agronomic responses of maize to nutrient-management treatments across two cropping seasons

Treatment	Days to silking	Cob diameter (mm)	Harvest index (%)
AMF	72.07 $\pm$ 1.84 bc	48.19 $\pm$ 2.45 bc	29.53 $\pm$ 4.24 a
Control	73.30 $\pm$ 2.39 b	46.90 $\pm$ 1.89 b	29.27 $\pm$ 4.88 a
NPK	68.57 $\pm$ 1.09 a	50.96 $\pm$ 1.55 ac	25.48 $\pm$ 1.80 a
OM	70.00 $\pm$ 1.97 ac	50.12 $\pm$ 1.23 ac	27.88 $\pm$ 3.35 a
AMF + OM	70.40 $\pm$ 2.44 ac	50.44 $\pm$ 2.02 ac	25.84 $\pm$ 4.55 a
AMF + NPK	69.50 $\pm$ 1.12 a	52.40 $\pm$ 0.80 a	25.14 $\pm$ 2.30 a
OM + NPK	69.20 $\pm$ 1.50 a	52.01 $\pm$ 0.46 a	24.30 $\pm$ 3.44 a
Treatment P	< .001	< .001	.021
Season P	< .001	.735	.148
Treatment $\times$ season P	.440	.851	.128

Values are means $\pm$ SD of plot means pooled across two seasons ($n = 6$ per treatment). Within a column, means sharing a lowercase letter are not significantly different by Tukey HSD ($P < .05$). P values are from the combined RCBD model with block accounted for within season. Harvest index was recalculated at plot level from total grain/total above-ground biomass $\times 100$; the significant omnibus treatment effect did not resolve into significant Tukey pairwise contrasts

3.3 Grain Yield and Biomass Responses were Strong and Broadly Consistent across Seasons

The combined analysis showed significant season and treatment effects on grain yield, but no treatment $\times$ season interaction (season: $F = 8.08$, $P = .009$; treatment: $F = 6.49$, $P < .001$; interaction: $F = 0.54$, $P = .772$). Pooled grain yield was highest under NPK (148.23 ± 13.86 g plant⁻¹), OM+NPK (147.77 ± 13.39 g plant⁻¹) and AMF+NPK (146.17 ± 11.94 g plant⁻¹), all of which were in the upper Tukey group, compared with 92.03 ± 25.91 g plant⁻¹ in the control (Fig. 3A). OM and AMF+OM were intermediate. Importantly, the pairwise integrated treatments did not statistically exceed NPK alone for pooled grain yield.

Biomass showed an even stronger treatment response ($F = 32.63$, $P < .001$), together with a significant season effect ($F = 15.50$, $P < .001$) and a non-significant treatment $\times$ season interaction ($F = 1.07$, $P = .408$). OM+NPK produced the greatest pooled biomass numerically (614.33 ± 68.98 g plant⁻¹), followed by AMF+NPK (584.60 ± 62.29 g plant⁻¹) and NPK (582.07 ± 44.51 g plant⁻¹); these three treatments were statistically comparable and clearly above the control (316.97 ± 78.44 g plant⁻¹) (Fig. 3B).

Harvest index showed a significant overall treatment effect ($P = .021$), but Tukey-adjusted pairwise comparisons did not separate individual treatment means (Table 1). Numerically, the control and AMF treatments had higher harvest indices than the most biomass-productive NPK-containing treatments. This indicates that the strongest nutrient treatments increased total biomass more markedly than the proportion of biomass partitioned to grain.

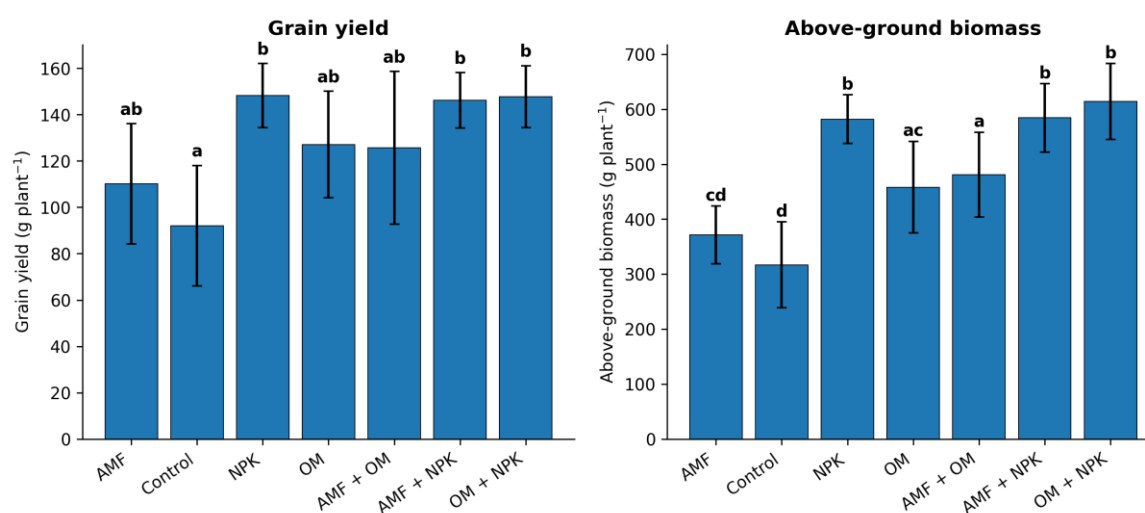


Fig. 3. Grain yield and above-ground biomass of maize under nutrient-management treatments pooled across two cropping seasons. Bars are means $\pm$ SD of plot means ($n = 6$; three blocks per season). Different lowercase letters indicate Tukey HSD groups at $P < .05$. Treatment $\times$ season interactions were not significant for grain yield or biomass

3.4 Root Length was More Season-sensitive than Above-ground Yield Formation

Root length differed strongly among treatments and, unlike most reproductive traits, showed a significant treatment $\times$ season interaction ($P = .011$). In Season 1, AMF+OM produced the greatest mean root length (40.54 cm), whereas the control averaged 30.02 cm. In Season 2, AMF+NPK produced the longest roots (42.83 cm), followed by OM+NPK (41.35 cm), while the control remained lowest at 29.34 cm (Fig. 4). The changing identity of the leading treatment indicates that below-ground response was more environmentally contingent than grain yield, biomass and most yield components.

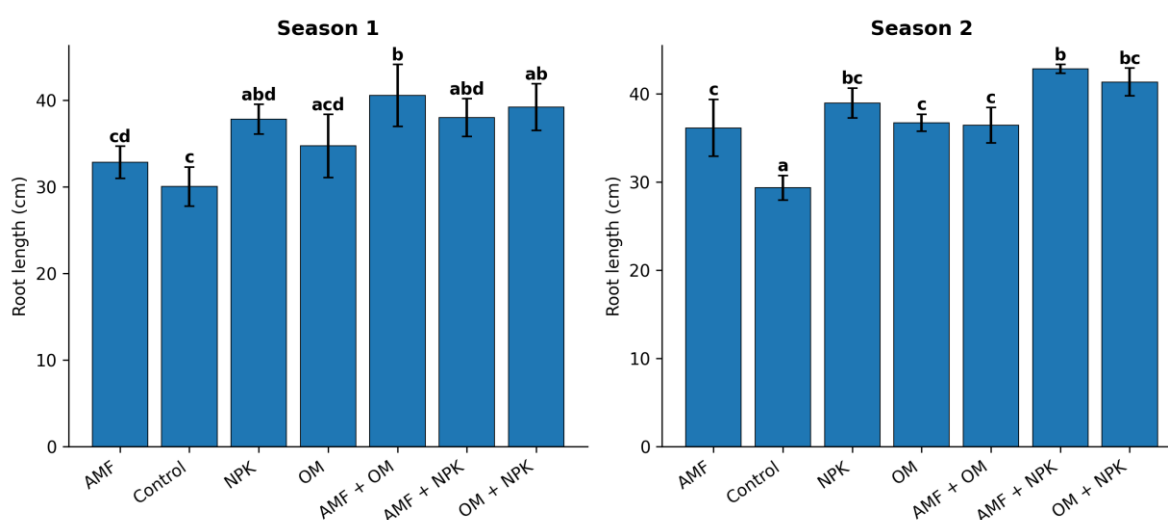


Fig. 4. Root length of maize under nutrient-management treatments in Season 1 and Season 2. Bars are plot means $\pm$ SD ($n = 3$ blocks). Different lowercase letters indicate Tukey HSD groups within a season. The combined analysis detected a significant season $\times$ treatment interaction ($P = .011$)

3.5 Vegetative Vigour was Strongly Associated with Final Grain Yield

At the plot level, final vegetative traits were positively associated with grain yield in both seasons (Table 2). Week-6 plant height was strongly correlated with grain yield in Season 1 ($r = .902$, $P < .001$) and Season 2 ($r = .800$, $P < .001$). Leaf area showed similarly consistent relationships ($r = .857$ and $.863$, respectively), as did stem diameter ($r = .821$ and $.858$). The number of leaves was moderately to strongly associated with grain yield in Season 1 ($r = .708$, $P < .001$) and even more strongly in Season 2 ($r = .878$, $P < .001$). Root length differed from this pattern: its association with grain yield was weak and non-significant in Season 1 ($r = .380$, $P = .089$) but strong in Season 2 ($r = .824$, $P < .001$). This seasonal contrast is consistent with the significant root-length treatment $\times$ season interaction.

Table 2. Pearson correlations between final vegetative traits and grain yield in maize

Vegetative trait	Season 1 r	Season 1 P	Season 2 r	Season 2 P
Plant height	.902	< .001	.800	< .001
Leaf area	.857	< .001	.863	< .001
Stem diameter	.821	< .001	.858	< .001
Number of leaves	.708	< .001	.878	< .001
Root length	.380	.089	.824	< .001

Pearson correlations were calculated from plot-level means ($n = 21$ plots per season). Plant height, leaf area, stem diameter and number of leaves refer to Week-6 measurements. Associations are exploratory and should not be interpreted as causal effects

3.6 Indicative Economic Performance

The partial budget separated agronomic response from short-run economic return. In Season 1, NPK generated the highest net benefit (KSh 1,466.83), followed by OM (KSh 1,395.33). In Season 2, NPK again produced the highest net benefit (KSh 1,335.33), although OM+NPK generated the highest gross return. Across the two seasons, NPK had the highest mean net benefit (KSh 1,401.08) and mean BCR (4.00), followed by OM (mean net benefit KSh 1,185.33; BCR 3.85). The integrated treatments remained agronomically strong, but their additional treatment-specific costs reduced their short-run BCRs relative to NPK alone. Because common production costs and longer-term residual benefits were excluded, these results represent treatment-level partial budgeting rather than whole-farm profitability.

4. Discussion

4.1 Nutrient Management Changed the Trajectory of Crop Development

The temporal analysis provides a more biologically informative picture than a single average across sampling dates. Treatment differences were minimal during establishment but became pronounced as nutrient demand increased, particularly from Week 3 onward. The late-vegetative advantage of NPK, AMF+NPK and OM+NPK indicates that readily available mineral nutrients were important for sustaining rapid canopy expansion. Similar temporal separation between amended and unamended maize has been reported in integrated nutrient-management studies, where sole NPK and manure-mineral combinations frequently produce comparable vegetative responses before differences in reproductive performance become evident (Essilfie *et al.*, 2024).

The strong plot-level associations of plant height, leaf area and stem diameter with final grain yield reinforce the agronomic importance of maintaining vigorous vegetative development. These relationships should not be interpreted as direct causal effects because the same nutrient treatments can simultaneously influence vegetative growth and yield formation. Nevertheless, their consistency across both seasons suggests that canopy development provided a useful integrative signal of treatment performance. The particularly stable leaf-area relationship ($r \approx .86$ in both seasons) is physiologically plausible because leaf-area development determines photosynthetic surface and the potential supply of assimilates to reproductive sinks.

4.2 Earlier Reproductive Development and Stronger Sink Formation under NPK-Containing Treatments

NPK-containing treatments shortened the time to tasseling and silking relative to the control while also increasing cob size and kernel number. Earlier reproductive transition under adequate nutrient supply has been observed in other maize nutrient-management experiments (Essilfie *et al.*, 2024). In the present study, this phenological acceleration was not accompanied by a yield penalty; rather, treatments with earlier silking also tended to occupy the upper groups for cob dimensions, kernels per cob and final grain yield.

Kernel number appeared particularly responsive to nutrient supply, increasing markedly under NPK and OM+NPK relative to the control. This is important because maize grain yield is strongly determined by successful kernel set during the flowering and early grain-filling period. The combined response of cob length, cob diameter and kernel number indicates that treatment effects were expressed through sink establishment as well as vegetative biomass production. However, the absence of significant treatment $\times$ season interactions for these traits suggests that their relative response pattern was more stable than the root response.

4.3 Grain Yield and Biomass: Strong Treatment Effects without Evidence that Pairwise Combinations Surpassed NPK

The most important outcome of the combined analysis is that nutrient management had a highly significant effect on grain yield and biomass, while treatment $\times$ season interactions were not significant. This changes the interpretation from the thesis-style emphasis on

a different numerical 'best treatment' in each season to a more defensible conclusion: NPK, AMF+NPK and OM+NPK formed a statistically similar high-performing group for pooled grain yield, and the same three treatments dominated biomass production. The season effect confirms that absolute productivity shifted between cropping periods, but the non-significant interaction indicates that the relative treatment response for these major productivity variables was broadly conserved across the two observed seasons.

This result aligns with a growing African evidence base showing strong yield benefits from mineral fertiliser and from combinations of mineral fertiliser with organic resources. Long-term experiments in Kenya found that manure plus mineral N was particularly effective for sustaining maize yield, although site and climate strongly modified the magnitude of response (Laub *et al.*, 2023). A 2025 synthesis of African studies reported large maize-yield gains from manure and manure-plus-mineral fertiliser relative to no-input controls, but also emphasised that responses depend on rainfall, soil texture, pH and initial soil carbon (Sileshi *et al.*, 2025). Likewise, field trials in Ghana showed that manure-mineral combinations can increase maize yield while sole NPK remains competitive in some environments (Essilfie *et al.*, 2024).

The present experiment therefore supports integrated nutrient management but does not demonstrate statistical synergy. Because the AMF+OM+NPK treatment was absent, the study was not a complete 2³ factorial experiment. Moreover, AMF+NPK and OM+NPK did not significantly exceed NPK alone for pooled grain yield. The scientifically appropriate conclusion is that the pairwise combinations were effective nutrient-management options under the tested conditions, not that they were universally superior to mineral fertiliser.

4.4 Root Responses Reveal Stronger Seasonal Contingency

Root length was the clearest exception to the otherwise stable treatment pattern. The significant season×treatment interaction, together with the shift from AMF+OM in Season 1 to AMF+NPK in Season 2, indicates that below-ground development was particularly sensitive to seasonal conditions. Root growth responds to both nutrient distribution and soil-water status; therefore, changes in moisture regime can alter the relative value of organic amendments, mineral nutrients and biological symbioses.

AMF biology provides a plausible framework for this variability, but the mechanism cannot be claimed directly because root colonisation was not quantified. Meta-analysis has shown that AMF inoculation can increase cereal grain yield in field studies, but responses are heterogeneous and depend on crop, soil pH and management context (Zhang *et al.*, 2019). Under drought, AMF can enhance biomass and nutrient acquisition, yet the magnitude of response is strongly moderated by soil and host conditions (Zaman *et al.*, 2024). The present root results are therefore consistent with environmentally contingent AMF effects but remain insufficient to attribute the observed response specifically to colonisation or fungal nutrient transfer.

The contrasting root–yield correlations reinforce this interpretation. Root length was not significantly associated with yield in Season 1 but was strongly associated with yield in Season 2. A longer root system is not inherently beneficial if water and nutrient distributions do not reward deeper or greater soil exploration. The functional value of root proliferation is therefore likely to depend on the seasonal resource environment.

4.5 Biomass Accumulation and Harvest Index Indicate a Partitioning Trade-off

OM+NPK produced the greatest numerical biomass, while AMF+NPK and NPK were statistically comparable. Yet the control and AMF-alone treatments had numerically higher harvest indices. This does not imply superior productivity of the control; rather, it indicates that high-input treatments stimulated total biomass more strongly than proportional grain allocation. Harvest index is a ratio, and a particular treatment can therefore increase grain yield while lowering harvest index if vegetative biomass increases even more strongly.

This distinction is useful for interpreting nutrient-management studies because biomass production has agronomic value beyond grain production in systems where stover is used for livestock feed, mulching or soil organic matter return. Conversely, farmers focused primarily on grain may value treatments differently from mixed crop-livestock systems. The lack of significant Tukey pairwise separation for harvest index also cautions against overinterpreting small numerical differences in partitioning.

4.6 Agronomic Performance Must be Separated from Short-run Profitability

NPK produced the highest two-season mean net benefit and BCR in the experimental partial budget even though OM+NPK and AMF+NPK were among the strongest agronomic treatments. The explanation is straightforward: additional inputs increased treatment cost, while the incremental grain return was not large enough to offset those costs under the prices used. This result illustrates why the treatment with the highest biomass or numerical grain yield should not automatically be recommended as the economically preferred option.

At the same time, the partial budget does not capture longer-term benefits of organic inputs, including carbon additions, changes in soil physical properties and residual nutrient effects. Recent African synthesis emphasises both the potential soil-health benefits of manure and the need to localise recommendations because manure quality, labour, transport and opportunity costs vary greatly among farms (Sileshi *et al.*, 2025). Long-term Kenyan studies similarly show that the value of organic-mineral integration becomes clearer when yield sustainability across many seasons is considered (Laub *et al.*, 2023; Laub *et al.*, 2025). Thus, the present economic ranking should be interpreted as a short-run comparison under the tested input and grain prices, not as a universal farm recommendation.

5. Implications, Strengths and Limitations

Three features strengthen the inference from this study. First, reanalysis retained the plot as the experimental unit, preventing pseudoreplication from the five within-plot plant subsamples. Second, the two seasons were analysed jointly, allowing direct tests of season×treatment interaction rather than inferring seasonal consistency from parallel analyses. Third, repeated plant-height observations were retained as temporal trajectories, revealing when treatment differences emerged.

The study nevertheless had important boundaries. It was conducted at one site with one maize cultivar over two seasons. The three-way AMF+OM+NPK treatment was not included, so full factorial interactions and three-way synergy cannot be estimated. AMF colonisation was not measured, preventing mechanistic attribution of responses to fungal establishment. Soil and leaf nutrient samples were composited by treatment, eliminating independent replication for those laboratory measurements; accordingly, nutrient data were not used for inferential claims. Finally, the economic analysis excluded common production costs and longer-term residual effects.

These limitations define a clear next research step: multi-site and multi-season trials retaining independent soil and tissue samples for every plot; direct measurement of AMF root colonisation; treatment structures capable of testing full factorial interactions; nutrient-use-efficiency indices; soil-water monitoring; and farmer-scale partial budgeting that incorporates labour, manure opportunity cost, input accessibility and price uncertainty. Such work is particularly important because recent Kenyan analyses show that ISFM benefits can be strongly conditioned by rainfall and local soil context (Laub *et al.*, 2025; Laub *et al.*, 2026).

6. Conclusion

Across two cropping seasons in semi-arid Taveta, nutrient management altered maize growth trajectories, reproductive development, root growth, biomass accumulation and grain production. The combined analysis identified NPK, AMF+NPK and OM+NPK as a statistically similar high-performing group for pooled grain yield, while the same NPK-containing treatments also dominated biomass production. Most reproductive and yield traits showed no treatment×season interaction, indicating broadly conserved relative treatment responses despite significant seasonal shifts in absolute crop performance. Root length was the major exception, showing a significant treatment×season interaction and a season-specific relationship with grain yield.

The results do not support a claim that pairwise integration universally outperformed mineral fertiliser: NPK alone was statistically comparable with the leading integrated treatments for pooled grain yield and produced the highest short-run net benefit and BCR. The evidence instead supports context-specific nutrient management in which agronomic response, seasonal conditions, locally available organic resources and input costs are considered together. For Taveta, NPK-containing strategies warrant further farmer-scale validation, while the potential longer-term value of manure and AMF should be tested with replicated nutrient measurements, direct AMF-colonisation assessment and longer-duration soil-health monitoring.

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Data Availability

The raw datasets supporting the findings of this study are available from the corresponding author upon reasonable request and subject to Taita Taveta University data-sharing requirements.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

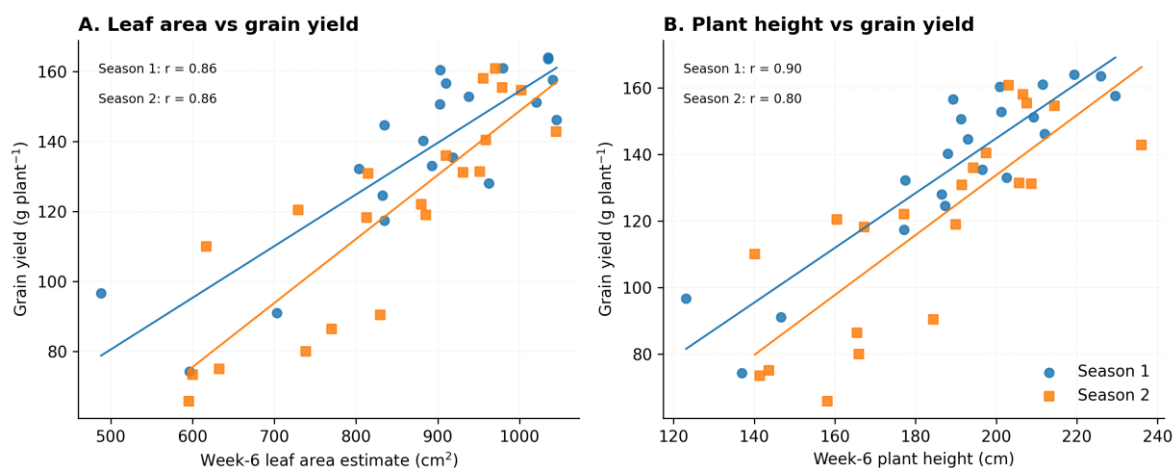
Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Material

Supplementary Fig. S1 provides the exploratory plot-level relationships between Week-6 vegetative traits and final grain yield. The figure is supplementary because Table 2 provides the inferential summary without duplicating a main-text fig.



Relationships are exploratory Pearson associations among plot means ($n = 21$ per season) and should not be interpreted as causal effects.

Supplementary Fig. S1. Relationships between Week-6 leaf area and plant height and final grain yield in two maize cropping seasons. Points represent plot means ($n=21$ per season); fitted lines are descriptive linear trends. Pearson r values are shown by season. Associations should not be interpreted as causal effects

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