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Synergistic effect of nutrient fertilizer and arbuscular mycorrhizal fungi on maize growth and grain yield in central northern Tanzania

Hussein Ninga Qwaray*[1,2], Mashamba Philipo[1], Akida Meya[1]

[1]*Department of Sustainable Agriculture and Biodiversity Ecosystem Management, Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania*

[2]*St. Joseph Sustainable Organic Farm, Kituru, Mwanga, Tanzania*

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Abstract

This study explored the synergistic effects of Arbuscular Mycorrhizal Fungi (AMF) and nutrient fertilizer resources (organic fertilizer (cattle manure) and inorganic fertilizer (NPK) on maize plant growth and grain yield in central-northern Tanzania, emphasizing their potential in nutrient-limited environments. The AMF on the Tanzania maize variety (TMV1) in two experiments. The first experiment was conducted in a screen house to identify the most effective AMF formulation, using 81 pots with two seeds sown per pot and three AMF treatments, with cattle manure applied at the rate of 0.04375 kg per pot and 0.5 kg per hole in open field. The second experiment occurred in the field setting in a randomized complete block design with AMF, NPK, and cattle manure combinations as treatments. Each treatment plot measured 3 × 3 m, with appropriate spacing and weekly irrigation maintained throughout the season. Data on plant height, stem girth, and leaf length were collected during the second and third months to assess treatment impacts. Over four weeks, treatments that combined AMF with cattle manure significantly enhanced key maize growth parameters, including plant height, stem girth, and leaf length. Treatment T5 (mycorrhiza 2 with cattle manure) exhibited the most substantial increases among the treatments. Monthly evaluations revealed that treatment T2 (AMF 2 combined with NPK) resulted in maize plants with remarkable heights of 188.44 cm, while T1 (AMF 1 with NPK) enhanced leaf length. Additionally, treatment T4 showed significant dry matter retention, highlighting the effectiveness of these combined nutrient strategies. The findings suggest that integrating AMF with organic and inorganic fertilizers can optimize maize yield, and offer a sustainable strategy for smallholder farmers in Tanzania to enhance productivity in the face of nutrient challenges.

* **Corresponding Author:** Hussein Ninga Qwaray ✉ husseinq@nm-aist.ac.tz

Introduction

Maize (*Zea mays* L.) is a staple cereal crop that is crucial for food security and nutrition for millions of people in developing countries (Hossain *et al*., 2019). It is one of the staple foods in the world after rice, wheat, and sorghum (De Groote *et al*., 2020). In developing countries, its widespread cultivation and use as a staple food underline its vital role in food security and dietary energy supply Sasson, 2012. In sub-Saharan Africa (SSA), maize is a key crop for smallholder farmers who rely on it as a source of food and household income (Santpoort, 2020; Wahab *et al*., 2022). In Tanzania, maize is a primary food staple, consumed by millions annually (Utonga, 2022; Tanumihardjo *et al*., 2020). Despite its importance, maize yields remain low, hardly reach 1.5 tonnes per hectare (t ha^{-1}), and are significantly lower than the potential yields of over 4 t ha^{-1} under optimal crop management (Mkonda *and* He, 2016). Such a vast yield gap is primarily attributed to declining soil fertility, recurrent droughts, and suboptimal agronomic practices (Begna, 2020; Getnet *et al*., 2022). Maize productivity is constrained by various challenges, including declining soil fertility, climate-related stress, and limited access to improved agricultural inputs.

Using inorganic fertilizers has become widespread in the country to enhance maize production (Cassim *et al.,* 2024). However, overreliance on inorganic fertilizers negatively affects natural soil health by impacting biodiversity and diminishing returns. Therefore, more sustainable and long-term solutions are required restore soil health while increasing land productivity.

Earlier studies report that Arbuscular Mycorrhizal Fungi (AMF) present a promising solution to these challenges. For instance, AMF form symbiotic relationships with plant roots and enhance nutrient uptake, water absorption, and plant resilience to stress (Mitra *et al*., 2021). Additionally, cattle manure applications strengthen soil structure, promote microbial activity, and increase soil organic matter, leading to healthier and more productive soils (Iqbal *et al*., 2019).

Combined applications of AMF and nutrient sources such as organic and inorganic fertilizers offer a sustainable approach to improving maize yields addressing nutrient deficiencies and soil health issues (Gao *et al*., 2020). This practice aligns with efforts to reduce reliance on inorganic fertilizers and promote environmentally friendly agricultural systems. Despite the known benefits of AMF and organic fertilizers such as cattle manure, little research has been done on their combined use in maize production in Tanzania. Understanding the interactions between these two components could provide critical insights for improving maize production in smallholder maize fields which are characterized by low nutrient inputs. This study evaluated the effects of combined AMF and nutrient fertilizer resources (cattle manure and NPK) on maize plant growth and grain yield. By assessing plant growth and yield parameters such as plant height, stem girth, leaf size, 100-grain yield, number of cobs per plant, and cob weight, the aim of this research was to demonstrate how these practices can contribute to more sustainable maize production systems in Tanzania.

Materials and methods

Description of the study site

The study was conducted at Tanzania Agricultural Research Institute Seliani (TARI Seliani) which is in Arusha, Tanzania (Fig. 1), from March to October 2024. TARI-Seliani is situated at 3°22′00″S and 36°37′19″E, at an altitude of 1,387 meters above sea level (m.a.s.l.), approximately 16 km east of the Arusha city center.

The study site experiences a bimodal rainfall pattern, with an average annual precipitation of 760 mm, although with uneven rainfall distribution. The long-term mean temperatures range between 18 and 27°C. The soil at the experimental site has a pH of 7.2, which is classified as fine-textured clay. The soil is rich in organic matter and contains high levels of essential nutrients, including nitrogen (N), phosphorus (P), and potassium (K), along with an adequate cation exchange capacity (CEC), which supports optimal crop growth.

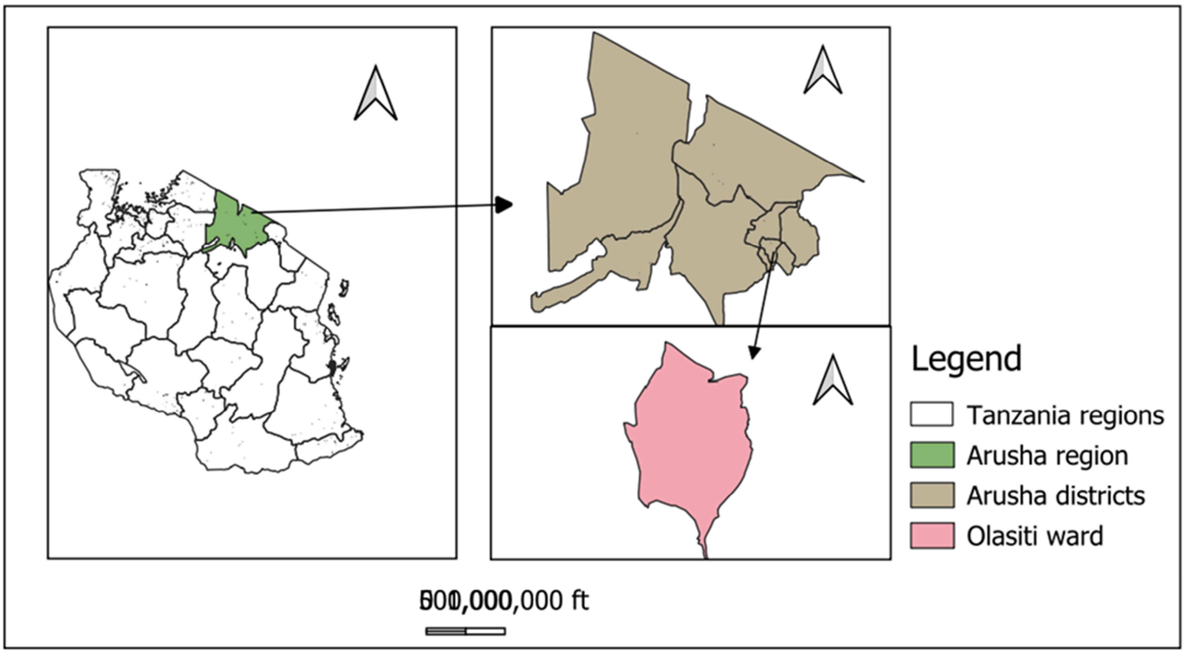

Fig. 1. Map of the study site

Collection/preparation of AMF

Three AMF strains were used in this research and were collected from two different sources. Two commercial strains (AMF 1 and AMF 2) were outsourced from Good Crop Tanzania Limited, based in Arusha. The third AMF strain (referred to herein as AMF 3) was isolated from maize roots following a methodology proposed by Willis *et al.* (2013) Hayman (1982), Berruti *et al.* (2017), and Estrada *et al.* (2013) with minor modifications.

Research design and experimental treatments

The research comprised of two experiments. The first experiment was conducted under screen house conditions to identify the most effective AMF formulation in promoting maize plant growth. The second experiment was conducted under field conditions to validate the performance of the selected AMF formulation from the screen house experiment at enhancing maize plant growth and the overall grain yield. The screen house experiment consisted of 9 treatments which included (i) mycorrhiza 1 and NPK, (ii) mycorrhiza 2 and NPK, (iii) mycorrhiza 3 and NPK, (iv) mycorrhiza 1 and cattle manure, (v) mycorrhiza 2 and cattle manure, (vi) mycorrhiza 3 and cattle manure (vii) NPK only (viii) cattle manure only (ix) control. On the other hand, the field experiment consisted of 7 treatments and included (i) mycorrhiza 1 and NPK, (ii) mycorrhiza 2 and NPK, (iv) mycorrhiza 1 and cattle manure, (v) mycorrhiza 2 and cattle manure (vii) NPK only (viii) Cattle manure only (ix) Negative control. The treatments in the screen house and the field experiments were arranged in a Completely Randomized Design (CRD) with three replications. While the first experiment thus included nine treatments with three replicates, giving a total of 27 samples, the second experiment involved the top-performing treatments from the first experiment, excluding T3 and T6, resulting in seven treatments with three replicates which form a total of 21 samples.

Tanzania Maize Variety (TMV1) was used as a test crop for both experiments. Eighty-one pots were utilized in the screen house, with two seeds sown in each pot. The spacing between pots was 15 cm, while the treatment units were spaced by 30 cm. Cattle manure was applied at the rate of 0.04 kg per pot. In the planting holes, AMF strains were used at 10 g per pot for AMF1 and AMF2 and 20 g per pot for AMF3. Data on plant height, leaf size, and stem girth was collected from the screen house experiment from the 4th to 6th weeks after planting (WAP). The field experiment was established on April 29, 2024 with maize seeds planted at a spacing of 0.3 m between plants and 0.7 m between rows on land prepared using a disc plough. Each treatment plot measured 3 m by 3 m (9 m^2). Three maize seeds were sown per hole and later thinned to 1 seedling. The tested AMF strains were applied at 10 g per planting hole for AMF1 and AMF2 and 20 g for AMF3. NPK was applied at 30 g per planting hole (equivalent to 660 kg ha^{-1}), while cattle manure was applied at 0.5 kg per planting hole (equivalent to 11,000 kg ha^{-1}). The maize was irrigated weekly until physiological maturity. Data from the field experiment was collected from the central maize rows to minimize edge/border effects. Data on days to tasseling were collected over three-day intervals from the initial induction until all 40 plants per treatment plot completed tasseling. The experiment covered one cropping season, with data on maize plant growth parameters (plant height, stem girth, leaf size) and yield parameters (77 days were used for tasselling).

Results and discussion

Effectiveness of AMF on promoting maize plant growth under screen house conditions

The ANOVA results demonstrated statistically significant differences among treatments for each maize growth parameter: plant height ($F = 12.0$, $p < 0.0008$), plant girth ($F = 22.94$, $p < 0.0001$), and leaf length ($F = 16.7$, $p = 0.0$), confirming that specific treatments had markedly different impacts on early growth stages. T6, T2, and T1 emerged as the most effective treatments, potentially ideal for promoting robust early growth, particularly in smallholder or experimental settings (Table 1). T9 consistently show low performance highlighting its limited utility in promoting height, girth, or leaf length, suggesting it may not be suitable for growth optimization. These results provide key insights into treatment effectiveness of maize plant, emphasizing that targeted selections can significantly enhance growth metrics in the early stages of the plant.

The results from weeks four, five, and six of the study highlighted the significant impact of various treatments on plant development, with AMF treatments and nutrient strategies playing a key role in promoting maize growth (Table 1). Four (WAP), treatments involving AMF3 + cattle manure and AMF2 + NPK showed the highest plant heights, recording 36.93 cm and 36.33 cm, respectively. These combinations proved particularly effective in stimulating vertical growth, as supported by Cozzolino *et al.* (2013), and Fall *et al.* (2023). Additionally, AMF1 + NPK stood out in promoting stem girth, with a notable measurement of 3.60 cm, compared to the control at 2.79 cm, emphasizing the importance of tailored fertilization strategies in enhancing maize growth, as observed by Boyno *et al.* (2023). Regarding leaf length, T2 (AMF2 + NPK) achieved the highest value of 52.27 cm, demonstrating superior leaf development, while T3 (AMF3 + NPK) had the lowest value at 36.90 cm, highlighting that not all treatments yielded similar benefits. These findings indicate the significance of selecting appropriate AMF strains and nutrient combinations to optimize plant growth, as highlighted by (Xu *and* Mou, 2016).

In the fifth week, the trends showed significant growth differences among treatments. T2 (AMF2 + NPK) emerged the best at enhancing plant height at 46.53 cm, followed by T1 (AMF1 + NPK) at 41.77 cm, demonstrating the effectiveness of these treatments in enhancing vertical growth, as noted by Vasant (2021). T5 (AMF2 + cattle manure) also showed substantial height at 41.90 cm. Regarding girth, T5 excelled with a measurement of 3.40 cm, significantly surpassing other treatments, while T1 and T2 showed competitive girth values of 3.03 cm and 2.83 cm, respectively. Leaf length results echoed these trends, with T1 leading at 83.77 cm and T2 at 76.70 cm, indicating their capacity to promote maize leaf growth, as observed by Sabang (2019). However, T3 and T9 lagged in height and leaf length, underscoring the critical importance of effective treatment strategies in optimizing maize performance, as Helmy and Abu-Hussien (2024) highlighted. The analysis using ANOVA confirmed the statistical significance of these differences, with high F-values for each growth parameter: plant height ($F = 44.7$), plant girth ($F = 19.6$), and leaf length ($F = 18.3$), all with p-values <0.0001, validating the effectiveness of the treatments.

Table 1. Maize growth parameters over 4–6 weeks under varying treatments

Treat.	Week 4			Week 5			week 6		
	Plant height (cm)	Plant girth (cm)	Leaf length (cm)	Plant height (cm)	Plant girth (cm)	Leaf length (cm)	Plant height (cm)	Plant girth (cm)	Leaf length (cm)
T1	34.17 ± 1.41ab	3.60 ± 0.06a	41.67 ± 0.48a	41.77 ± 1.38b	3.03 ± 0.09b	83.77 ± 2.57a	54.93 ± 1.48a	3.43 ± 0.13bc	99.30 ± 0.70a
T2	36.33 ± 0.55a	2.43 ± 0.18d	52.27 ± 1.27bc	46.53 ± 1.07a	2.83 ± 0.18b	76.70 ± 2.80b	57.13 ± 0.92a	3.63 ±0.09ab	90.83 ± 0.98b
T3	33.27 ± 1.49b	2.13 ± 0.03e	36.90 ± 0.18e	39.43 ± 0.49bc	2.27 ± 0.12c	67.63 ± 0.53cd	49.80 ± 0.49c	2.40 ± 0.06f	65.10 ± 0.95de
T4	32.63 ± 1.24b	2.47 ± 0.09d	42.27 ± 0.78ab	41.50 ± 0.75b	2.77 ± 0.09b	74.53 ± 3.43b	55.27 ± 1.39a	3.23 ±0.09cd	94.90 ± 2.57ab
T5	36.30. ± 1.096a	3.03 ± 0.13b	42.33 ± 0.33b	41.9. ± 0.95b	3.40 ± 0.10a	69.10 ± 0.85c	54.03. ± 2.49ab	3.73 ± 0.09a	77.03 ± 0.43c
T6	36.93 ± 0.78a	2.47± 0.13d	39.37 ± 0.47a	38.70 ± 0.31c	2.23± 0.03c	62.87 ± 0.62de	50.67 ± 0.49bc	2.77± 0.07e	64.57 ± 1.76de
T7	29.60 ± 0.40c	2.30 ± 0.06de	42.27± 0.66d	32.27 ± 0.29d	2.43 ± 0.07c	64.60± 0.53cde	48.43 ± 0.68cd	3.00 ±0.06de	75.33± 2.67c
T8	29.47 ± 0.52c	2.50 ± 0.06d	40.93 ± 0.64de	31.30 ± 0.35de	2.33 ± 0.33c	63.63 ± 0.68de	45.45 ± 1.72de	3.30 ± 0.10c	68.03 ± 0.97d
T9	27.90 ± 0.21c	2.40 ± 0.06de	32.80 ± 91d	29.60 ± 0.25e	2.20 ± 0.06c	60.93 ± 0.14e	43.47± 0.67e	2.83 ± 0.03f	62.40 ± 2.11e
F- value	12.0	22.94	16.7	44.7	19.6	18.3	12.7	36.45	72.7
P-value	<0.0008	<0.0000	0.0001	<0.0001	<0.0001	<0.0001	0.0	<0.0000	<0.001
CV	2.55%	3.47%	1.38%	1.62%	4.5%	1.71%	2.35%	2.51%	1.84%

Note T1= AMF1 + NPK, T2 = AMF2 + NPK, T3= AMF3 + NPK, T4= AMF1 + Cattle manure, T5 = AMF2 + cattle manure, T6 = AMF3 + cattle manure, T7 = NPK only, T8 = Cattle manure only, T9 = No fertilization.

By the sixth week, the impact of AMF treatments was even more pronounced, with statistically significant P-values for plant height, girth, and leaf length at (P <0.0001) further emphasizing their role in enhancing maize growth. T2 (AMF2 + NPK) led in height at 57.13 cm, followed closely by T1 (AMF1 + NPK) at 54.93 cm and T4 (AMF1 + cattle manure) at 55.27 cm, demonstrating the superior vertical growth promoted by these treatments, as supported by Bello *and* Yusuf (2021), and Zhu *et al.*, (2016). The T5 (AMF2 + cattle manure) outperformed other treatments at enhancing stem girth at 3.73 cm, while T2 and T1 followed closely at 3.63 cm and 3.43 cm, respectively. In terms of leaf length, the best treatment was T1 at 99.30 cm, with T2 at 90.83 cm and T4 at 94.90 cm, while T3 and T9 showed significantly lower values of 65.10 cm and 62.40 cm, respectively. Similar results have been obtained by Lino *et al.* (2019) and Saboor *at al.* (2021). This underscores the effectiveness of mycorrhizal treatments in promoting plant growth, particularly when combined with appropriate nutrient strategies. The overall findings confirmed that integrating AMF treatments with nutrient management significantly enhanced maize growth, confirming the potential of these interventions for improving maize crop productivity and health.

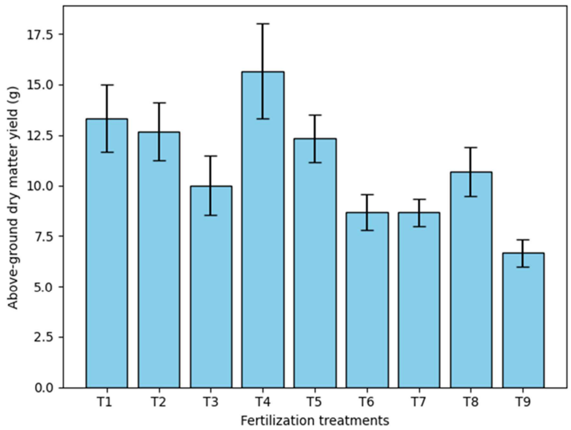

Fig. 2. Maize plant above-ground dry biomass yield Note T1= mycorrhiza 1 &NPK, T2 = Mycorrhiza 2 & NPK, T3= Mycorrhiza 3 & NPK, T4= Mycorrhiza 1 & Cattle manure, T5Mycorrhiza 2 & cattle manure, T6= Mycorrhiza 3 & cattle manure, T7= NPK only, T8 = Cattle manure only, T9= zero treatment

Data on maize plant above-ground dry matter yield showed the significant effects of various experimental treatments (Fig. 2). Treatment T4 recorded the highest value of dry matter (15.67 g), indicating its strong potential to enhance above-ground biomass and overall plant vigour (Macedo *et al.*, 2023; Khan *et al.*, 2024; Singh *et al.*, 2024). Conversely, a declining trend in plant dry matter yield recorded for T1, T2, T3, T5, T6, T7, T8, and T9 showed that these treatments were less effective in promoting maize growth. The p-values of 0.0 recorded for the treatments further showed the observed differences were significant. These results have important implications for agriculture, owing to the necessity of choosing optimal treatments to maximize plant dry matter yield and overall crop performance which is directly linked to sustainable agriculture (German *et al.*, 2017). Favouring treatments that boost above-ground plant growth can help farmers achieve better productivity while advancing sustainable practices.

Table 2. Maize growth parameters over 3 and 4 months under varying treatments

Treatment	2nd month			3rd month		
	Plant height	Plant girth	Leaf length	Plan height	Plant girth	Leaf length
T1	85.54 ± 1.87ab	5.23 ± 0.04ab	85.09 ± 1.20a	175.51 ± 3.18b	12.47 ± 0.27bc	76.69 ± 4.35a
T2	88.54 ± 1.666a	5.34 ± 0.05a	85.48 ± 1.19a	188.44 ± 2.486a	12.58 ± 0.17b	80.52 ± 2.52a
T4	86.79 ± 1.82ab	5.29 ± 0.06ab	84.64 ± 1.06a	155.22 ± 2.61c	12.63 ± 0.17a	77.89 ± 3.15a
T5	88.64 ± 1.73a	5.16 ± 0.08b	84.74 ± 0.93a	169.06 ± 3.69b	12.70 ± 0.19a	72.83 ± 2.94a
T7	84.12 ± 0.965b	5.37 ± 0.06a	80.02± 0.94a	158.69 ± 4.07c	12.57 ± 0.25ab	64.75± 2.99ab
T8	89.24 ± 1.266a	5.27± 0.05ab	83.39 ± 1.19a	153.71 ± 5.05cd	12.07± 0.15d	64.75 ± 3.14b
T9	69.24± 1.296d	4.76 ± 0.07c	74.68 ± 0.56b	145.69± 0.69d	10.57 ± 0.05e	48.09 ± 1.60c
(F-statistics)	20.5	11.85	13.2	19.2	16.7	13.9
P-value	<0.0000	<0.0000	<0.0000	<0.0000	<0.0000	<0.0000
CV	1.79%	1.13%	1.21%	1.90%	1.44%	4.24%

Note T1= mycorrhiza 1 &NPK, T2 = Mycorrhiza 2 & NPK, T4= Mycorrhiza 1 & Cattle manure, T5= Mycorrhiza 2 & cattle manure, T7= NPK only, T8 = Cattle manure only, T9= zero treatment

Effectiveness of the selected AMF formulations in promoting maize plant growth under field conditions

The evaluation of AMF formulations in promoting maize growth showed significant improvements 60 and 90 days after planting (Table 2), (Barazetti *et al.*, 2019; Agbodjato *et al.*, 2022). At 60 DAP, treatments involving AMF2 with cattle manure (T5) or NPK (T2) demonstrated notable significant growth (P <0.0001), with T8 (cattle manure only) producing the tallest plants (89.24 cm). Stem girth and leaf length were also significantly enhanced by these treatments. By 90 days after planting (DAP), T2 (AMF2 + NPK) stood out with the tallest plants (188.44 cm) and longest leaves (80.52 cm), while T5 (AMF2 + cattle manure) achieved the thickest stems (12.70 cm). Single-input treatments like T7 (NPK only) and T8 (cattle manure only) showed moderate growth, while T9 (no treatment) consistently underperformed. These findings highlight the effectiveness of combining mycorrhiza with organic and inorganic fertilizers to boost maize growth (Imran, 2024; Yooyongwech *et al.*, 2022; Moreira *et al.*, 2020. Therefore, integrating these inputs can enhance plant height, stem girth, and leaf length, offering a sustainable strategy for optimizing crop productivity in nutrient-limited soils.

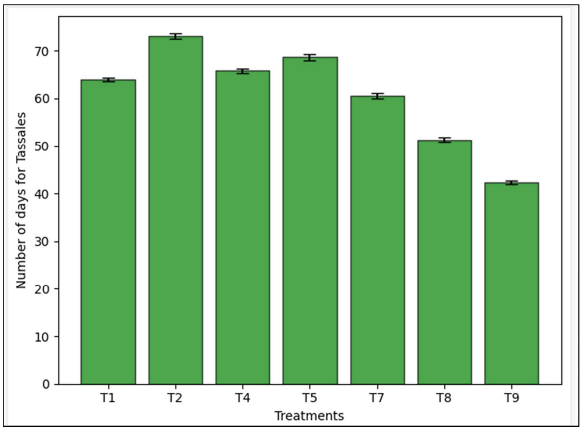

Fig. 3. Effects of fertilization treatments on crop duration reflected on days to tasseling

Note T1= mycorrhiza 1 & NPK, T2 = Mycorrhiza 2 & NPK, T4= Mycorrhiza 1 & Cattle manure, T5 Mycorrhiza 2 & cattle manure, T7= NPK only, T8 = Cattle manure only, T9 = zero treatment

During the tasseling stage (Fig. 3) several treatments significantly influenced plant dry matter accumulation and tasseling timing. However, T2 (AMF2 + NPK) was the most effective, showing the highest dry matter levels ($p<0.000$) and delayed tasseling at an average of 73.03 days. T5 (AMF2 + cattle manure) also performed well, though with slightly higher variability, as previously reported by Habiyaremye *et al.* (2018) and Thangavel *et al.* (2022). Moderate performance was observed for T1 and T4, while T7, T8, and T9 (no treatment) recorded lower dry matter levels. T9 and T8 showed the earliest tasseling at 42.25 and 51.28 days, respectively, indicating faster onset but weaker support for sustained growth. These results suggest that T2 and T5 provided robust growth and delayed tasseling, which could benefit yield, while T7, T8, and T9 required improvement to enhance effectiveness during this critical phase.

Conclusion

This study highlights the significant potential of integrating Arbuscular Mycorrhizal Fungi (AMF) with both organic (cattle manure) and inorganic (NPK) fertilizers to enhance maize growth, dry matter yield, and overall productivity in nutrient-limited environments, such as those commonly found in central-northern Tanzania. The combined application of AMF and fertilizers, particularly the synergy between AMF2 + NPK (T2) and AMF1 + cattle manure (T4), resulted in significant improvements in key maize growth parameters, including plant height, dry matter yield, and days to tasseling. These findings underscore the role of AMF in boosting maize productivity by improving nutrient uptake and root development, leading to more efficient resource utilization. Both controlled screen house experiments and field trials further emphasize the importance of integrating AMF into fertilizer strategies. The treatments combining AMF with either NPK or cattle manure not only promoted faster growth but also reduced the time to tasseling, showing potential for increasing maize yields in a shorter period. Furthermore, the retention of dry matter in some treatments suggests better overall plant health and productivity, which is essential for improving food security in smallholder farming systems. Future research could explore the mechanisms behind the effectiveness of T4, offering deeper insights into sustainable crop improvement. Overall, this research provides strong evidence that integrating AMF with nutrient resources is a sustainable and effective approach to overcoming soil nutrient deficiencies. By optimizing maize production in resource-constrained agricultural systems, this strategy supports both ecological sustainability and the economic prosperity of smallholder farmers in Tanzania. Promoting the adoption of AMF, in combination with organic and inorganic fertilizers, could be a key factor in enhancing maize productivity, improving farm sustainability, and contributing to regional food security.

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