



RESEARCH ARTICLE

# Residual impact of arbuscular mycorrhizal fungi and *Rhizobium* on growth and productivity of pigeon pea (*Cajanus cajan* (L.) Huth)

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## Abstract

A two-year field trial was conducted to examine the residual effects of arbuscular mycorrhizal fungi (AMF) and *Rhizobium* on the growth and productivity of pigeon pea. The study aimed to clarify how these two biological agents affect plant growth and yield metrics differently. The study was conducted at Lovely Professional University, Phagwara, Kapurthala district, Punjab, during the kharif season 2023–24. The trial tested different doses of recommended dose of fertiliser (RDF), combined with AMF and *Rhizobium* residues, on pigeon pea. The treatment includes T1 (100 % RDF), T2 (AMF + 100 % RDF), T3 (*Rhizobium* + 100 % RDF), T4 (AMF + *Rhizobium* + 100 % RDF), T5 (75 % RDF), T6 Maize (AMF + 75 % RDF), T7 (*Rhizobium* + 75 % RDF), T8 (AMF + *Rhizobium* + 75 % RDF), T9 (50 % RDF), T10 (AMF + 50 % RDF), T11 (*Rhizobium* + 50 % RDF) and T12 (AMF + *Rhizobium* + 50 % RDF). Plant growth and yield attributes were analyzed using standard methods. A significant residual impact of AMF and *Rhizobium* on plant growth and yield was observed. Compared to the T1, T8 (AMF + *Rhizobium* + 75 % RDF) increased the chlorophyll index (17.4 %), dry biomass (30.7 %), biological yield (17.5 %) and harvest index (17.7 %). This study demonstrates the substantial residual effects of AMF and *Rhizobium* inoculation on subsequent pigeon pea crops. The enhanced nutrient availability caused by these beneficial microorganisms' residual effects leads to increased plant growth and healthy biomass accumulation, ultimately improving grain yields in pigeon peas.

**Keywords:** arbuscular mycorrhizal fungi; pigeon pea; residual impact; *Rhizobium*

## Introduction

Pigeon pea (*Cajanus cajan* (L.) Huth) is a major legume crop in semi-arid regions, playing a crucial role in sustaining food security and enhancing soil fertility. It is a primary protein source for many developing nations, particularly for populations with limited access to animal-based protein (1). Globally, pigeon pea is cultivated on approximately 4.97 million hectares, yielding an annual production of around 4.18 million tons. India is the largest producer, accounting for approximately 82 % of the world's total production, followed by Myanmar and Malawi (2). The average global yield of pigeon pea is approximately 840 kg ha<sup>-1</sup>, which is typically low compared to other legume crops. These limitations hinder the crop's ability to meet the growing demand for protein-rich foods, particularly in regions where it is a staple. To address these challenges, sustainable agricultural practices are necessary to enhance pigeon pea yields and enhance grain quality while minimising environmental impacts (3).

One promising approach to increasing pigeon pea production is the use of beneficial soil microorganisms, such as arbuscular mycorrhizal fungi (AMF) and *Rhizobium* bacteria. By forming symbiotic relationships with plant root systems, AMF enhance the absorption of essential nutrients, including phosphorus pentoxide, which is often limited in many soils (4).

The combined use of AMF and *Rhizobium* can create a synergistic effect, enhancing nutrient availability and uptake, ultimately improving crop performance. Co-inoculation with AMF and *Rhizobium* can significantly enhance plant growth, nutrient absorption and yield in various legume crops. For instance, pigeon pea yields have been shown to increase by 20–30 % under field conditions following co-inoculation (5).

The use of AMF and *Rhizobium* as bio-inoculants is a promising method to enhance pigeon pea productivity and grain quality. Initiating these helpful microorganisms into the soil can enhance nutrient availability, improve plant growth and promote nitrogen fixation (6). Additionally, the residual effects of these bio-inoculants from previous cropping systems can persist and affect subsequent crops, such as pigeon pea (7). Intercropping systems, in which multiple crops are grown in the same field, are standard in many agricultural regions (8). These systems can provide additional benefits such as increased resource utilisation, reduced pest and disease pressure and improved soil health. When AMF and *Rhizobium* are integrated into an intercropping system, their benefits can extend beyond the primary crop to influence the growth and productivity of subsequent crops grown in rotation (9). Sustainable cropping systems increasingly rely on AMF and *Rhizobium*, to boost crop

yields and reduce dependence on synthetic inputs (4).

Additionally, there is a lack of understanding of how the combination of AMF and *Rhizobium*, used in an intercropping system, affects pigeon pea growth, productivity and grain quality in the following season (10). This research gap is crucial for developing sustainable cropping strategies that enhance long-term resource utilisation and crop yields (11). The objective of this study is to evaluate the influence of AMF and *Rhizobium* on the growth, yield and overall crop output of pigeon pea, with emphasis on their combined effects on crop performance.

## Materials and Methods

A two-year field experiment involving the pigeon pea variety PAU 881 was conducted at Lovely Professional University's agricultural research farm in Jalandhar, Punjab, from 2023 to 2024. The location coordinates are 31°14'30.5" N latitude and 75°41'52.1" E longitude. A total of 12 treatments were implemented using a randomized complete block design with three replications. The AMF and *Rhizobium* inoculants used in this study were obtained from certified commercial suppliers. The AMF inoculum was acquired as a commercial biofertiliser (A to Z Mycorrhiza Biofertilizer, Sunshine Agri Pvt. Ltd., India). Conversely, the *Rhizobium* inoculant specific for moong bean (*Vigna radiata* (L.) R.Wilczek) was sourced as Premium Rhizo (IPL Biologicals Ltd., India). Both inoculants were purchased from an authorised agricultural input dealer and applied according to the recommended dosage. The treatment includes T<sub>1</sub> (100 % RDF), T<sub>2</sub> (AMF + 100 % RDF), T<sub>3</sub> (*Rhizobium* + 100 % RDF), T<sub>4</sub> (AMF + *Rhizobium* + 100 % RDF), T<sub>5</sub> (75 % RDF), T<sub>6</sub> Maize (AMF + 75 % RDF), T<sub>7</sub> (*Rhizobium* + 75 % RDF), T<sub>8</sub> (AMF + *Rhizobium* + 75 % RDF), T<sub>9</sub> (50 % RDF), T<sub>10</sub> (AMF + 50 % RDF), T<sub>11</sub> (*Rhizobium* + 50 % RDF) and T<sub>12</sub> (AMF + *Rhizobium* + 50 % RDF). The plot size was 4 × 7.5 m (30 m<sup>2</sup>), with a row spacing of 50 × 30 cm. The experiment was conducted between 2022 and 2023. Meteorological data during the experiment indicate monthly trends from May to October for maximum and minimum temperature, relative humidity (RH) and rainfall (Fig. 1). The study area experienced peak temperatures and rainfall in July, while RH was highest in August and September. All parameters declined sharply after September, indicating the transition from the monsoon to post-monsoon season.

To evaluate the growth response of pigeon pea to the residual impact of AMF and *Rhizobium* application, a series of systematic measurements was conducted. Plant heights were measured from the base to the apex using a calibrated measuring tape. The chlorophyll index was estimated using a SPAD (Soil Plant Analysis Development) meter (model SPAD-502). The number of primary branches was quantified through manual counting. Dry biomass was measured with an analytical balance. The fresh biomass samples were dried in an oven at 55 °C until they reached a constant weight, showing that all moisture had been removed. The dry biomass was determined by weighing the oven-dried samples using an analytical balance.

Crop growth rate (CGR) was estimated using the formula (12):

$$\text{CGR} = \frac{W_2 - W_1}{A \times (T_2 - T_1)}$$

Relative growth rate (RGR) was estimated using the formula (12):

$$\text{RGR} = \frac{\{\text{Log}(W_2) - \text{Log}(W_1)\}}{A \times (T_2 - T_1)}$$

Where W<sub>1</sub> and W<sub>2</sub> are the dry matter (g m<sup>-2</sup>) at successive sampling intervals T<sub>1</sub> and T<sub>2</sub> (days) and A is the ground area (m<sup>2</sup>). CGR indicates the rate of dry matter accumulation per unit area per day (g m<sup>-2</sup> day<sup>-1</sup>).

The seed index of pigeon pea was determined by counting and weighing 100 grains. Additionally, plants were manually harvested and threshed from a 1 m<sup>2</sup> area at maturity, allowing calculation of biological yield and grain yield.

Harvest index (HI) was calculated using the following formula (12):

$$\text{HI (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

The data in this study were analyzed using R-Studio (version 4.2.2), employing one-way analysis of variance (ANOVA) at a significance level of  $p < 0.05$  to identify significant differences between group means. Following ANOVA, Duncan's Multiple Range Test (DMRT) was performed as a post hoc test to identify specific group differences. Additionally, OriginPro software (Origin 2024b) was used to create graphical visualisations of the data and to perform Principal component analysis (PCA), facilitating a clear and practical assessment of the results. This comprehensive approach ensured robust statistical analysis and enhanced the interpretability of our findings.

## Results and Discussion

### Plant growth attributes

Arbuscular mycorrhizal fungi and *Rhizobium* had a significant residual impact on the plant height of pigeon pea at 30, 60 and 90 days after sowing (DAS) (Fig. 2, Table 1). ANOVA at  $p \leq 0.05$  indicated that plant height at 90 DAS was significantly influenced by treatments, with the maximum increase observed under T<sub>12</sub> (16 %), followed by T<sub>4</sub> (14 %) and T<sub>8</sub> (13 %), compared to the control (T<sub>1</sub>). The increase in plant height may be due to AMF, which increases plant efficiency in the uptake of vital nutrients, particularly phosphorus (P) and macronutrients, by enhancing root surface area through the mycelial network (13). The improved nutrient acquisition supports vigorous vegetative growth, resulting in increased plant height (14). The chlorophyll index was significantly affected by the residual impact of AMF and *Rhizobium* at different growth stages. The highest chlorophyll index at 90 DAS was recorded in treatment T<sub>8</sub> (AMF + *Rhizobium* + 75 % RDF), registering an increase of 17.4 % over the control. This was followed by treatments T<sub>7</sub> and T<sub>4</sub>, which showed improvements of 12.8 % and 11.7 %, respectively as compared to the control (Fig. 2, Table 2). The improved chlorophyll index observed in pigeon pea trifoliolate leaves, resulting from the residual effects of AMF and *Rhizobium*, can be attributed to their combined effects on nutrition and plant health. Arbuscular mycorrhizal fungi enhance the uptake of essential nutrients, such as P, magnesium (Mg) and micronutrients, which are crucial for chlorophyll synthesis and function (4). Phosphorus, for example, is a fundamental element of ATP and other energy-transferring molecules needed for photosynthesis. Magnesium is a central atom in the chlorophyll molecule and its increased availability directly enhances

**Table 1.** Impact of co-inoculation of AMF and *Rhizobium* on plant height of pigeon pea crop at 30, 60, 90 and 120 DAS during 2022 and 2023 seasons

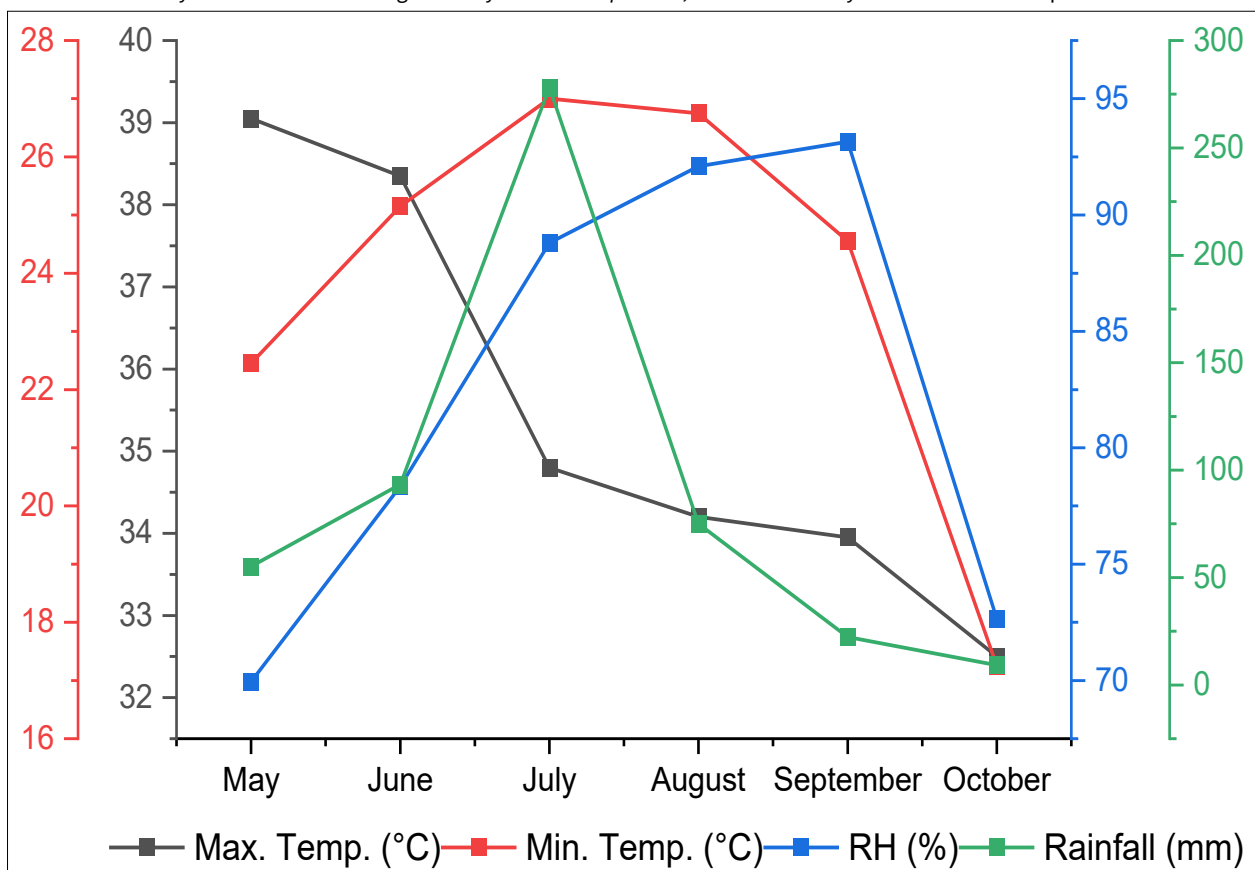
Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	19.4 <sup>cd</sup>	20.5 <sup>e</sup>	19.9 <sup>ef</sup>	81.5 <sup>g</sup>	83.3 <sup>ef</sup>	82.4 <sup>h</sup>	122.4 <sup>e</sup>	128.2 <sup>ef</sup>	125.1 <sup>de</sup>	165.0 <sup>e</sup>	161.5 <sup>g</sup>	163.3 <sup>h</sup>
T2	20.9 <sup>abc</sup>	22.1 <sup>cd</sup>	21.5 <sup>cd</sup>	89.8 <sup>de</sup>	89.9 <sup>d</sup>	89.8 <sup>e</sup>	128.1 <sup>d</sup>	129.5 <sup>e</sup>	128.8 <sup>d</sup>	170.2 <sup>cd</sup>	171.1 <sup>e</sup>	170.7 <sup>f</sup>
T3	21.8 <sup>ab</sup>	25.2 <sup>a</sup>	23.6 <sup>ab</sup>	95.0 <sup>c</sup>	101.4 <sup>ab</sup>	98.3 <sup>bc</sup>	135.0 <sup>c</sup>	140.3 <sup>cd</sup>	137.6 <sup>c</sup>	179.7 <sup>ab</sup>	183.3 <sup>ab</sup>	181.5 <sup>c</sup>
T4	22.8 <sup>a</sup>	25.4 <sup>a</sup>	24.1 <sup>a</sup>	101.7 <sup>a</sup>	104.3 <sup>a</sup>	103.0 <sup>a</sup>	139.0 <sup>bc</sup>	148.5 <sup>ab</sup>	143.5 <sup>b</sup>	186.3 <sup>h</sup>	188.0 <sup>h</sup>	187.2 <sup>b</sup>
T5	19.7 <sup>cb</sup>	18.6 <sup>f</sup>	19.2 <sup>f</sup>	84.7 <sup>fg</sup>	82.6 <sup>f</sup>	83.6 <sup>gh</sup>	111.8 <sup>f</sup>	124.3 <sup>efg</sup>	118.0 <sup>g</sup>	158.9 <sup>g</sup>	157.9 <sup>f</sup>	158.4 <sup>h</sup>
T6	19.9 <sup>bcd</sup>	21.3 <sup>de</sup>	20.6 <sup>de</sup>	87.4 <sup>ef</sup>	87.6 <sup>de</sup>	87.5 <sup>ef</sup>	122.1 <sup>e</sup>	128.9 <sup>ef</sup>	125.5 <sup>de</sup>	164.9 <sup>d</sup>	168.4 <sup>c</sup>	166.7 <sup>g</sup>
T7	21.2 <sup>abc</sup>	22.5 <sup>bc</sup>	22.4 <sup>bc</sup>	95.5 <sup>bc</sup>	100.6 <sup>abc</sup>	98.1 <sup>bc</sup>	137.5 <sup>c</sup>	138.7 <sup>d</sup>	138.1 <sup>c</sup>	178.0 <sup>bc</sup>	181.0 <sup>b</sup>	179.5 <sup>d</sup>
T8	22.2 <sup>a</sup>	24.7 <sup>ab</sup>	23.5 <sup>ab</sup>	99.3 <sup>ab</sup>	100.7 <sup>ab</sup>	100.1 <sup>ab</sup>	143.8 <sup>ab</sup>	150.9 <sup>a</sup>	147.3 <sup>a</sup>	183.0 <sup>h</sup>	187.0 <sup>i</sup>	185.0 <sup>b</sup>
T9	18.5 <sup>d</sup>	18.9 <sup>f</sup>	18.7 <sup>f</sup>	81.6 <sup>g</sup>	87.9 <sup>de</sup>	84.8 <sup>gh</sup>	122.0 <sup>e</sup>	119.6 <sup>g</sup>	120.8 <sup>fg</sup>	155.7 <sup>g</sup>	154.9 <sup>f</sup>	155.3 <sup>j</sup>
T10	18.5 <sup>d</sup>	20.0 <sup>ef</sup>	19.3 <sup>f</sup>	85.1 <sup>fg</sup>	87.7 <sup>de</sup>	86.4 <sup>fg</sup>	122.0 <sup>e</sup>	123.9 <sup>fg</sup>	122.9 <sup>ef</sup>	165.9 <sup>e</sup>	169.7 <sup>d</sup>	167.8 <sup>fg</sup>
T11	21.0 <sup>abc</sup>	22.0 <sup>cd</sup>	21.5 <sup>cd</sup>	93.3 <sup>cd</sup>	95.6 <sup>c</sup>	94.4 <sup>d</sup>	134.8 <sup>c</sup>	136.8 <sup>d</sup>	135.7 <sup>c</sup>	173.9 <sup>e</sup>	176.4 <sup>a</sup>	175.2 <sup>e</sup>
T12	22.2 <sup>a</sup>	22.8 <sup>cd</sup>	22.5 <sup>bc</sup>	95.8 <sup>bc</sup>	96.8 <sup>bc</sup>	96.3 <sup>cd</sup>	144.3 <sup>a</sup>	144.6 <sup>bc</sup>	144.5 <sup>ab</sup>	187.7 <sup>e</sup>	191.1 <sup>a</sup>	189.4 <sup>a</sup>
CD ( $p \leq 0.05$ )	1.065	1.556	1.248	1.276	1.493	3.286	2.051	1.766	3.727	1.997	2.603	2.253
Sd (m)	0.704	0.530	0.425	0.435	0.509	1.120	0.699	0.602	1.270	0.681	0.602	0.768

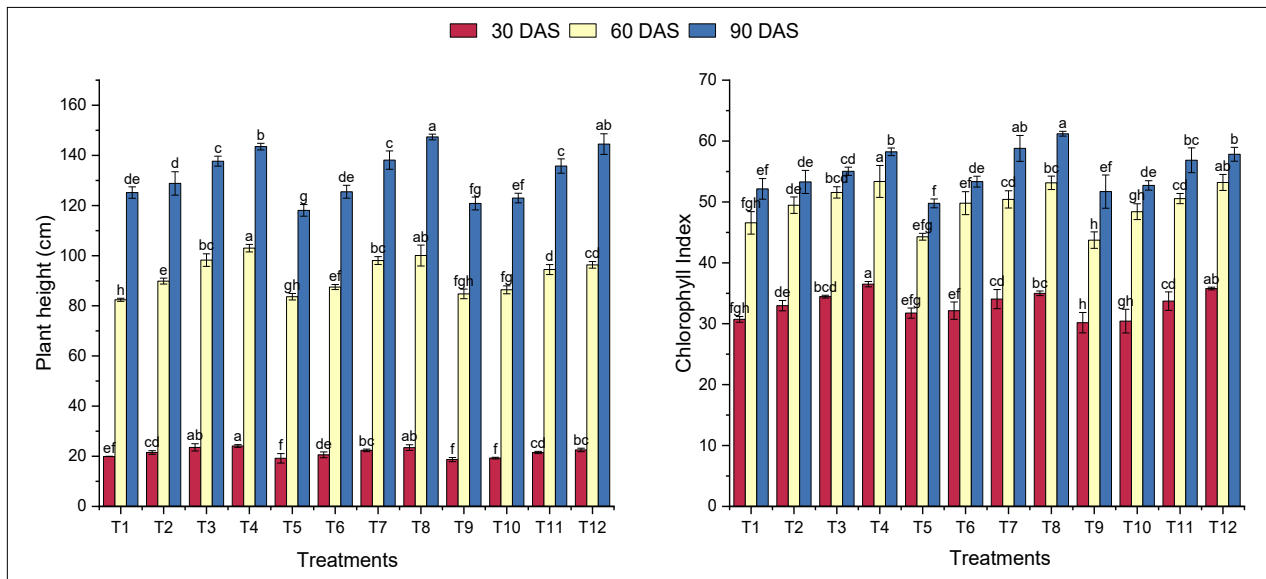
Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by the least significant difference (LSD) for mean separation.

**Table 2.** Impact of co-inoculation of AMF and *Rhizobium* on the chlorophyll index of pigeon pea at 30, 60, 90 and 120 DAS during 2022 and 2023 seasons

Treatments	30 DAS			60 DAS			90 DAS		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	30.2 <sup>ef</sup>	31.2 <sup>g</sup>	30.7 <sup>fgh</sup>	48.4 <sup>def</sup>	44.7 <sup>f</sup>	46.6 <sup>fgh</sup>	51.5 <sup>d</sup>	52.8 <sup>e</sup>	52.2 <sup>ef</sup>
T2	31.3 <sup>cde</sup>	34.6 <sup>cde</sup>	33.0 <sup>de</sup>	47.6 <sup>ef</sup>	51.3 <sup>bcd</sup>	49.5 <sup>de</sup>	52.3 <sup>cd</sup>	54.3 <sup>e</sup>	53.3 <sup>de</sup>
T3	33.2 <sup>abc</sup>	35.7 <sup>bc</sup>	34.5 <sup>bcd</sup>	51.3 <sup>abcd</sup>	51.9 <sup>abcd</sup>	51.6 <sup>bcd</sup>	54.5 <sup>bc</sup>	55.6 <sup>de</sup>	55.0 <sup>cd</sup>
T4	34.9 <sup>a</sup>	38.1 <sup>a</sup>	36.5 <sup>a</sup>	52.9 <sup>ab</sup>	53.8 <sup>ab</sup>	53.4 <sup>a</sup>	55.5 <sup>ab</sup>	60.9 <sup>ab</sup>	58.2 <sup>b</sup>
T5	29.6 <sup>ef</sup>	33.9 <sup>de</sup>	31.8 <sup>efg</sup>	46.3 <sup>fg</sup>	42.2 <sup>g</sup>	44.3 <sup>efg</sup>	47.4 <sup>e</sup>	52.1 <sup>e</sup>	49.8 <sup>f</sup>
T6	31.1 <sup>de</sup>	33.2 <sup>ef</sup>	32.1 <sup>ef</sup>	49.1 <sup>def</sup>	50.5 <sup>de</sup>	49.8 <sup>ef</sup>	51.2 <sup>d</sup>	55.5 <sup>de</sup>	53.3 <sup>de</sup>
T7	33.1 <sup>abcd</sup>	35.0 <sup>cd</sup>	34.1 <sup>cd</sup>	49.5 <sup>cde</sup>	51.4 <sup>bcd</sup>	50.4 <sup>cd</sup>	57.1 <sup>ab</sup>	60.5 <sup>ab</sup>	58.8 <sup>ab</sup>
T8	34.5 <sup>ab</sup>	35.5 <sup>c</sup>	35.0 <sup>bc</sup>	52.3 <sup>abc</sup>	53.9 <sup>a</sup>	53.1 <sup>bc</sup>	58.3 <sup>a</sup>	64.1 <sup>a</sup>	61.2 <sup>a</sup>
T9	29.4 <sup>ef</sup>	30.9 <sup>g</sup>	30.2 <sup>h</sup>	44.0 <sup>g</sup>	43.5 <sup>g</sup>	43.7 <sup>h</sup>	47.3 <sup>e</sup>	56.1 <sup>cde</sup>	51.7 <sup>ef</sup>
T10	28.6 <sup>f</sup>	32.3 <sup>fg</sup>	30.4 <sup>gh</sup>	47.7 <sup>ef</sup>	49.1 <sup>e</sup>	48.4 <sup>gh</sup>	49.9 <sup>de</sup>	55.5 <sup>de</sup>	52.7 <sup>de</sup>
T11	32.8 <sup>bcd</sup>	34.6 <sup>cde</sup>	33.7 <sup>cd</sup>	50.0 <sup>bcd</sup>	51.1 <sup>cde</sup>	50.6 <sup>cd</sup>	54.7 <sup>bc</sup>	59.0 <sup>bcd</sup>	56.9 <sup>bc</sup>
T12	34.4 <sup>ab</sup>	37.2 <sup>ab</sup>	35.8 <sup>ab</sup>	53.4 <sup>a</sup>	53.0 <sup>abc</sup>	53.2 <sup>ab</sup>	55.5 <sup>ab</sup>	60.1 <sup>abc</sup>	57.8 <sup>b</sup>
CD ( $p \leq 0.05$ )	1.621	1.621	1.497	2.477	2.477	1.497	4.360	4.360	2.511
Sd (m)	0.552	0.552	0.510	0.844	0.844	0.510	1.486	1.486	0.856

Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by the LSD for mean separation.

**Fig. 1.** Meteorological data at the site between 2022 and 2023, with rainfall (mm), relative humidity (%) and maximum and minimum temperature (°C).



**Fig. 2.** Residual impact of AMF and *Rhizobium* on plant height and chlorophyll index of pigeon pea at 30, 60 and 90 DAS.

chlorophyll production (15).

The accumulation of biomass in pigeon pea crop residues, influenced by AMF and *Rhizobium*, significantly affected the dry biomass of pigeon pea (Fig. 3, Table 3). Compared with the control treatment (T<sub>1</sub>), T<sub>8</sub> showed a significant increase in dry weight at 60 and 90 DAS, with the highest value recorded at 90 DAS (30.7%) under T<sub>8</sub>, followed by T<sub>4</sub> (25.9%), T<sub>11</sub> (22.3%) and T<sub>3</sub> (16.7%). The bar graphs comparing dry biomass and the number of primary branches across treatments (T<sub>1</sub>–T<sub>12</sub>) at 40 and 80 DAS. Treatments viz. T<sub>6</sub>, T<sub>8</sub> and T<sub>12</sub> generally show higher values for both parameters,

indicating better growth performance. Treatments with the same letters are not significantly different, as shown by the statistical grouping above each bar. The maximum number of primary branches was recorded at 90 DAS under the treatments T<sub>4</sub> (48.5%) and T<sub>8</sub> (39.8%), followed by T<sub>3</sub> (38.6%) and T<sub>12</sub> (32.7%). In contrast, the fewest primary branches were recorded under the control treatment T<sub>1</sub> (Table 4).

The increase in pigeon pea plant dry biomass may be due to AMF, which enhances the uptake of vital nutrients, including P and K (potassium), as well as micronutrients essential for

**Table 3.** Residual effects of AMF and *Rhizobium* co-inoculation on dry matter accumulation in pigeon pea during the 2022 and 2023 seasons

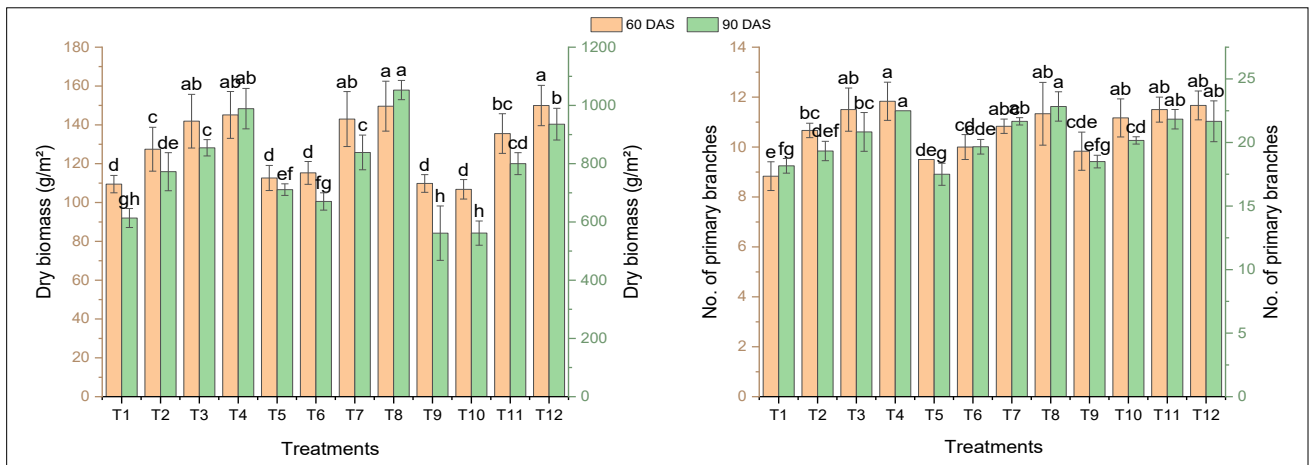
Treatments	30 DAS			60 DAS			90 DAS		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	1.4 <sup>cde</sup>	1.6 <sup>b</sup>	1.5 <sup>def</sup>	14.9 <sup>cd</sup>	12.4 <sup>f</sup>	13.6 <sup>d</sup>	167.9 <sup>e</sup>	194.1 <sup>de</sup>	181.0 <sup>gh</sup>
T2	1.6 <sup>abc</sup>	1.7 <sup>ab</sup>	1.7 <sup>abcd</sup>	15.7 <sup>c±</sup>	16.1 <sup>bcd</sup>	15.9 <sup>c</sup>	200.9 <sup>c</sup>	200.8 <sup>bcd</sup>	200.9 <sup>de</sup>
T3	1.7 <sup>ab</sup>	1.7 <sup>ab</sup>	1.7 <sup>abc</sup>	18.2 <sup>ab</sup>	17.3 <sup>abc</sup>	17.7 <sup>ab</sup>	208.7 <sup>bc</sup>	213.5 <sup>b</sup>	211.1 <sup>c</sup>
T4	1.8 <sup>a</sup>	1.7 <sup>ab</sup>	1.8 <sup>ab</sup>	18.5 <sup>ab</sup>	17.7 <sup>ab</sup>	18.1 <sup>ab</sup>	214.6 <sup>b</sup>	241.3 <sup>a</sup>	227.9 <sup>ab</sup>
T5	1.4 <sup>cde</sup>	1.5 <sup>b</sup>	1.5 <sup>ef</sup>	12.8 <sup>f</sup>	15.3 <sup>cde</sup>	14.0 <sup>d</sup>	182.7 <sup>d</sup>	199.9 <sup>bcd</sup>	193.2 <sup>ef</sup>
T6	1.4 <sup>de</sup>	1.5 <sup>b</sup>	1.5 <sup>ef</sup>	14.2 <sup>de</sup>	14.5 <sup>de</sup>	14.4 <sup>d</sup>	179.4 <sup>d</sup>	196.9 <sup>cde</sup>	188.1 <sup>fg</sup>
T7	1.5 <sup>bcd</sup>	1.6 <sup>b</sup>	1.6 <sup>cdef</sup>	18.0 <sup>ab</sup>	17.7 <sup>ab</sup>	17.8 <sup>ab</sup>	209.2 <sup>bc</sup>	209.2 <sup>bc</sup>	209.1 <sup>c</sup>
T8	1.7 <sup>ab</sup>	2.0 <sup>a</sup>	1.8 <sup>a</sup>	19.3 <sup>a</sup>	18.1 <sup>ab</sup>	18.7 <sup>a</sup>	234.1 <sup>a</sup>	237.8 <sup>a</sup>	235.9 <sup>a</sup>
T9	1.3 <sup>e</sup>	1.5 <sup>b</sup>	1.4 <sup>f</sup>	13.7 <sup>def</sup>	13.7 <sup>ef</sup>	13.7 <sup>d</sup>	163.9 <sup>e</sup>	185.2 <sup>ef</sup>	174.5 <sup>h</sup>
T10	1.3 <sup>e</sup>	1.6 <sup>ab</sup>	1.4 <sup>ef</sup>	13.0 <sup>ef</sup>	13.6 <sup>ef</sup>	13.3 <sup>d</sup>	174.6 <sup>de</sup>	174.6 <sup>f</sup>	174.6 <sup>h</sup>
T11	1.4 <sup>cde</sup>	1.5 <sup>b</sup>	1.5 <sup>ef</sup>	17.3 <sup>b</sup>	16.5 <sup>abcd</sup>	16.9 <sup>bc</sup>	204.5 <sup>bc</sup>	204.2 <sup>bcd</sup>	204.3 <sup>d</sup>
T12	1.4 <sup>cde</sup>	1.8 <sup>ab</sup>	1.6 <sup>bcdde</sup>	19.0 <sup>a</sup>	18.4 <sup>a</sup>	18.7 <sup>a</sup>	205.5 <sup>bc</sup>	237.1 <sup>a</sup>	221.3 <sup>b</sup>
CD ( $p \leq 0.05$ )	0.225	0.367	0.208	1.308	2.066	1.394	3.2006	14.294	8.0344
Sd (m)	0.076	0.125	0.071	0.446	0.704	0.475	3.62	4.873	2.739

Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by LSD for mean separation.

**Table 4.** Residual effects of AMF and *Rhizobium* co-inoculation on the number of branches of pigeon pea during the 2022 and 2023 seasons

Treatments	60 DAS			90 DAS			120 DAS		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	8.3 <sup>d</sup>	9.3 <sup>e</sup>	8.8 <sup>e</sup>	17.3 <sup>d</sup>	19.0 <sup>ef</sup>	18.2 <sup>fg</sup>	16.7 <sup>gh</sup>	17.0 <sup>e</sup>	16.8 <sup>d</sup>
T2	11.0 <sup>a</sup>	10.3 <sup>bcdde</sup>	10.7 <sup>bc</sup>	18.0 <sup>cd</sup>	20.7 <sup>de</sup>	19.3 <sup>def</sup>	18.3 <sup>fg</sup>	21.0 <sup>bc</sup>	19.7 <sup>c</sup>
T3	11.7 <sup>a</sup>	11.3 <sup>abc</sup>	11.5 <sup>ab</sup>	19.3 <sup>bcd</sup>	22.3 <sup>bcdde</sup>	20.8 <sup>bc</sup>	23.3 <sup>bc</sup>	23.3 <sup>ab</sup>	23.3 <sup>ab</sup>
T4	11.7 <sup>a</sup>	12.0 <sup>a</sup>	11.8 <sup>a</sup>	20.0 <sup>abc</sup>	25.0 <sup>a</sup>	22.5 <sup>a</sup>	25.3 <sup>a</sup>	24.7 <sup>a</sup>	25.0 <sup>a</sup>
T5	9.3 <sup>cd</sup>	9.7 <sup>de</sup>	9.5 <sup>de</sup>	17.3 <sup>d</sup>	17.7 <sup>f</sup>	17.5 <sup>g</sup>	15.3 <sup>h</sup>	18.7 <sup>cde</sup>	17.0 <sup>d</sup>
T6	9.7 <sup>c</sup>	10.3 <sup>bcdde</sup>	10.0 <sup>cd</sup>	20.0 <sup>abc</sup>	19.3 <sup>ef</sup>	19.7 <sup>cde</sup>	17.0 <sup>gh</sup>	17.7 <sup>de</sup>	17.3 <sup>d</sup>
T7	10.3 <sup>bc</sup>	11.3 <sup>abc</sup>	10.8 <sup>abc</sup>	21 <sup>a</sup>	21.7 <sup>cd</sup>	21.7 <sup>ab</sup>	22.3 <sup>cd</sup>	23.0 <sup>ab</sup>	22.7 <sup>b</sup>
T8	11.0 <sup>ab</sup>	11.7 <sup>ab</sup>	11.3 <sup>ab</sup>	22.0 <sup>a</sup>	23.7 <sup>ab</sup>	22.8 <sup>a</sup>	24.3 <sup>ab</sup>	22.7 <sup>ab</sup>	23.5 <sup>ab</sup>
T9	9.7 <sup>c</sup>	10.0 <sup>cde</sup>	9.8 <sup>cde</sup>	17.3 <sup>d</sup>	19.7 <sup>e</sup>	18.5 <sup>efg</sup>	15.7 <sup>h</sup>	18.7 <sup>cde</sup>	17.2 <sup>d</sup>
T10	11.3 <sup>ab</sup>	11.0 <sup>abcd</sup>	11.2 <sup>ab</sup>	18.7 <sup>bcd</sup>	21.7 <sup>cd</sup>	20.2 <sup>cd</sup>	16.3 <sup>h</sup>	19.0 <sup>cde</sup>	17.7 <sup>d</sup>
T11	11.3 <sup>ab</sup>	11.6 <sup>ab</sup>	11.5 <sup>ab</sup>	20.3 <sup>ab</sup>	23.3 <sup>abc</sup>	21.8 <sup>ab</sup>	19.7 <sup>ef</sup>	20.0 <sup>cd</sup>	19.8 <sup>c</sup>
T12	11.6 <sup>a</sup>	11.7 <sup>ab</sup>	11.7 <sup>ab</sup>	20.7 <sup>ab</sup>	22.7 <sup>bc</sup>	21.7 <sup>ab</sup>	21.3 <sup>de</sup>	23.3 <sup>ab</sup>	22.3 <sup>b</sup>
CD ( $p \leq 0.05$ )	1.276	1.493	1.116	2.051	1.766	1.493	1.997	2.603	1.822
Sd (m)	0.435	0.509	0.380	0.699	0.602	0.509	0.681	0.887	0.621

Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by the LSD for mean separation.



**Fig. 3.** Residual impact of AMF and *Rhizobium* on dry weight and number of primary branches of pigeon pea at 60 and 90 DAS.

numerous metabolic activities and biomass accumulation. A synergistic relationship between AMF and *Rhizobium* enables the plant to receive an equal delivery of nutrients and nitrogen, supporting robust growth and leading to a significant increase in dry biomass accumulation (16). Arbuscular mycorrhizal fungi and *Rhizobium* increase nutrient uptake, promoting cell differentiation and division to form additional primary branches. Increased P through AMF supports lateral bud growth, whereas *Rhizobium* provides nitrogen for growth regulation. Improved nutrient status triggers auxin and cytokinin synthesis, which in turn boost lateral bud outgrowth. The combined outcome ensures balanced nutrient and hormonal levels, leading to more primary branches (17, 18).

The data presented in Fig. 4 and Table 5 reveal the residual effects of AMF and *Rhizobium* on CGR dynamics at 60 and 90 DAS. The maximum percentage increase was recorded under the treatment T<sub>8</sub>, followed by T<sub>4</sub>, compared with the control, at 79.3 % and 67.5 %, respectively (7, 8). Similarly, the lowest RGR was recorded under the control and maximum crop growth at 90 DAS was observed under T<sub>8</sub>, followed by T<sub>4</sub>, T<sub>5</sub> and T<sub>12</sub>, i.e., 12.7 %, 11.1 %, 6.6 % and 6 % respectively. The increased CGR and RGR in pigeon pea plants, resulting from the residual influence of AMF and *Rhizobium*, have been scientifically linked to enhanced resource acquisition and improved photosynthetic efficiency. Arbuscular mycorrhizal fungi promote increased absorption of critical nutrients such as phosphate and micronutrients, which drive metabolic activities and biomass formation, hence enhancing CGR (19). *Rhizobium* also fixes atmospheric nitrogen, a crucial building block for proteins and chlorophyll, thereby increasing

photosynthetic capacity and driving RGR. The synergistic interaction between AMF and *Rhizobium* enhances nutrient supply and photosynthetic performance, resulting in faster growth rates and higher biomass in pigeon pea (20).

### Yield attributes

Yield attributes are presented in Fig. 5 and summarized in Table 6. The residual impact of AMF and *Rhizobium* significantly alters the pod length of pigeon pea. The highest increase in pod length was observed under T<sub>12</sub> (25.5 %), followed by T<sub>4</sub> (24.3 %), T<sub>8</sub> (19.2 %) and T<sub>3</sub> (19.2 %), with the lowest plant height recorded under the control treatment T<sub>1</sub> (163.30 cm). The maximum percentage increase in grain per pod was recorded after harvesting under T<sub>4</sub> (35.4 %), followed by T<sub>12</sub> (30.8 %), T<sub>7</sub> (21.5 %) and T<sub>3</sub> (21.5 %) compared with the control treatment. The number of pods is directly proportional to grain yield; as the number of pods increases, grain yield subsequently increases. The highest number of pods per plant was recorded under the T<sub>4</sub> treatment. Test weight reflects the amount of biomass accumulated per 100 grains. The maximum test weight was recorded under T<sub>12</sub> (12.0 %), followed by T<sub>4</sub> (11.2 %), T<sub>8</sub> (10.7 %) and T<sub>7</sub> (4.9 %), compared with the control treatment. The improvement in grain per pod, pod length, pods per plant and test weight of pigeon pea may be attributed to AMF and *Rhizobium*, which enhance the mobilisation of nutrients and hormonal control during the reproductive stage. Arbuscular mycorrhizal fungi facilitate improved P uptake and other essential nutrients required for flower production, pod set and seed development. At the same time, *Rhizobium* provides a consistent nitrogen input, which is crucial for protein synthesis and the effective translocation of photosynthates into developing

**Table 5.** Residual effect of AMF and *Rhizobium* co-inoculation on CGR and RGR of pigeon pea during the 2022 and 2023 seasons

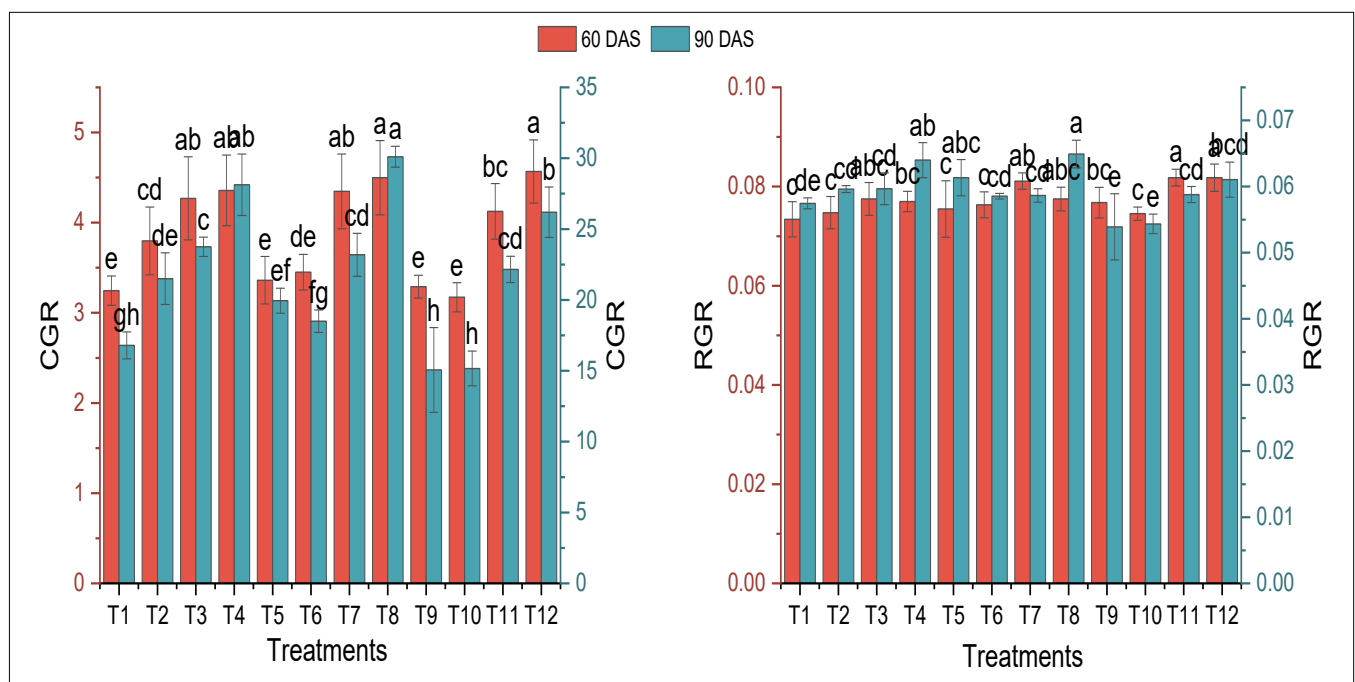
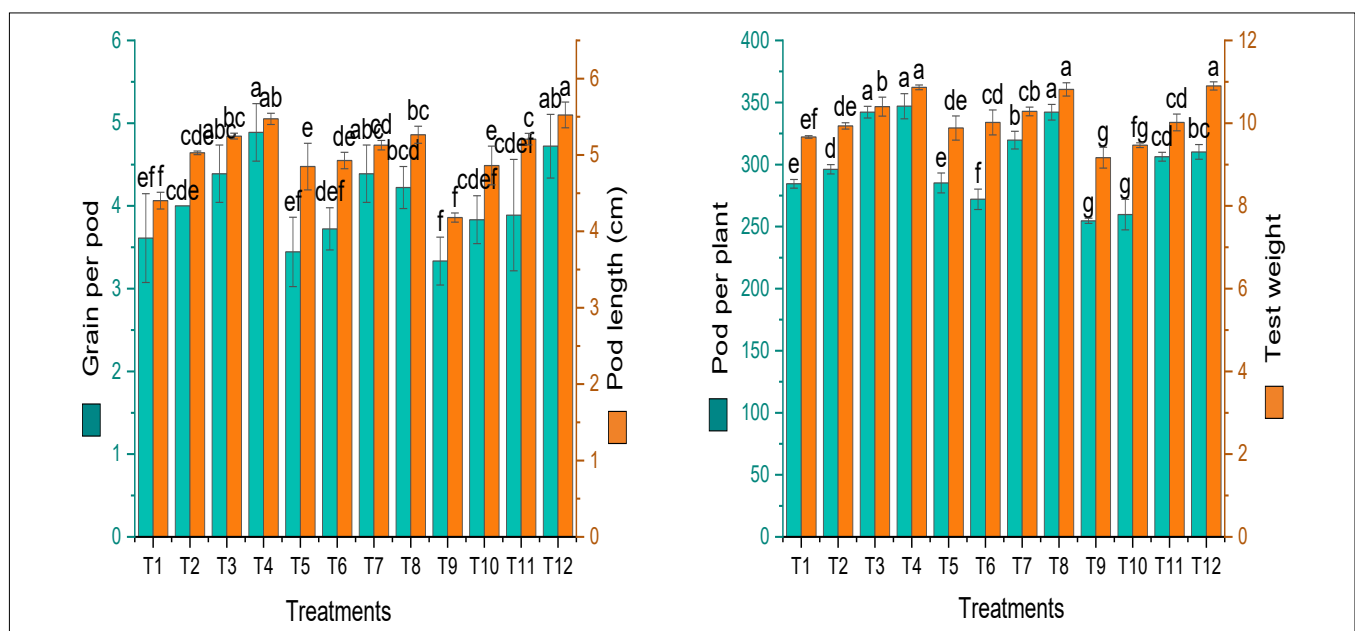
Treatments	30–60 DAS			60–90 DAS			30–60 DAS			60–90 DAS		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	3.61 <sup>cd</sup>	2.87 <sup>f</sup>	3.25 <sup>e</sup>	17.13 <sup>ef</sup>	16.46 <sup>cd</sup>	16.79 <sup>gh</sup>	0.078 <sup>cd</sup>	0.068 <sup>c</sup>	0.073 <sup>c</sup>	0.056 <sup>f</sup>	0.060 <sup>abc</sup>	0.057 <sup>de</sup>
T2	3.75 <sup>c</sup>	3.84 <sup>bcd</sup>	3.80 <sup>cd</sup>	25.75 <sup>b</sup>	17.26 <sup>bcd</sup>	21.50 <sup>de</sup>	0.076 <sup>de</sup>	0.074 <sup>abc</sup>	0.074 <sup>c</sup>	0.066 <sup>abc</sup>	0.054 <sup>cd</sup>	0.059 <sup>cd</sup>
T3	4.40 <sup>ab</sup>	4.13 <sup>abc</sup>	4.27 <sup>ab</sup>	27.16 <sup>b</sup>	20.35 <sup>b</sup>	23.76 <sup>c</sup>	0.080 <sup>bcd</sup>	0.075 <sup>abc</sup>	0.077 <sup>abc</sup>	0.063 <sup>abcd</sup>	0.056 <sup>bcd</sup>	0.060 <sup>cd</sup>
T4	4.46 <sup>ab</sup>	4.25 <sup>abc</sup>	4.36 <sup>ab</sup>	28.62 <sup>b</sup>	26.64 <sup>a</sup>	28.13 <sup>ab</sup>	0.078 <sup>cde</sup>	0.076 <sup>abc</sup>	0.076 <sup>bc</sup>	0.064 <sup>abcd</sup>	0.064 <sup>a</sup>	0.064 <sup>ab</sup>
T5	3.04 <sup>f</sup>	3.68 <sup>cde</sup>	3.36 <sup>e</sup>	22.67 <sup>c</sup>	17.22 <sup>bcd</sup>	19.94 <sup>ef</sup>	0.073 <sup>e</sup>	0.077 <sup>ab</sup>	0.075 <sup>c</sup>	0.068 <sup>a</sup>	0.055 <sup>cd</sup>	0.061 <sup>abc</sup>
T6	3.43 <sup>cde</sup>	3.46 <sup>de</sup>	3.45 <sup>de</sup>	20.37 <sup>cd</sup>	16.64 <sup>cd</sup>	18.50 <sup>fg</sup>	0.078 <sup>cde</sup>	0.075 <sup>abc</sup>	0.076 <sup>c</sup>	0.062 <sup>cd</sup>	0.056 <sup>cd</sup>	0.059 <sup>cd</sup>
T7	4.40 <sup>ab</sup>	4.29 <sup>ab</sup>	4.35 <sup>ab</sup>	27.30 <sup>b</sup>	19.07 <sup>bc</sup>	23.19 <sup>cd</sup>	0.082 <sup>abc</sup>	0.080 <sup>a</sup>	0.081 <sup>ab</sup>	0.063 <sup>abcd</sup>	0.054 <sup>cd</sup>	0.059 <sup>cd</sup>
T8	4.71 <sup>a</sup>	4.28 <sup>ab</sup>	4.50 <sup>a</sup>	33.62 <sup>a</sup>	26.59 <sup>a</sup>	30.11 <sup>a</sup>	0.082 <sup>abc</sup>	0.073 <sup>abc</sup>	0.077 <sup>abc</sup>	0.067 <sup>ab</sup>	0.062 <sup>a</sup>	0.065 <sup>a</sup>
T9	3.34 <sup>def</sup>	3.24 <sup>ef</sup>	3.29 <sup>e</sup>	16.38 <sup>f</sup>	13.74 <sup>de</sup>	15.06 <sup>h</sup>	0.080 <sup>bcd</sup>	0.073 <sup>abc</sup>	0.076 <sup>bc</sup>	0.057 <sup>ab</sup>	0.052 <sup>de</sup>	0.054 <sup>e</sup>
T10	3.15 <sup>ef</sup>	3.19 <sup>ef</sup>	3.17 <sup>e</sup>	19.40 <sup>de</sup>	10.93 <sup>e</sup>	15.16 <sup>h</sup>	0.078 <sup>cd</sup>	0.070 <sup>bc</sup>	0.074 <sup>c</sup>	0.063 <sup>abcd</sup>	0.046 <sup>e</sup>	0.054 <sup>e</sup>
T11	4.25 <sup>b</sup>	4.00 <sup>abcd</sup>	4.12 <sup>bc</sup>	26.25 <sup>b</sup>	18.05 <sup>bc</sup>	22.15 <sup>cd</sup>	0.084 <sup>ab</sup>	0.079 <sup>a</sup>	0.081 <sup>a</sup>	0.063 <sup>abcd</sup>	0.054 <sup>cd</sup>	0.059 <sup>cd</sup>
T12	4.70 <sup>a</sup>	4.43 <sup>a</sup>	4.57 <sup>a</sup>	26.07 <sup>b</sup>	26.32 <sup>a</sup>	26.19 <sup>b</sup>	0.086 <sup>a</sup>	0.077 <sup>ab</sup>	0.081 <sup>a</sup>	0.060 <sup>de</sup>	0.062 <sup>ab</sup>	0.061 <sup>bcd</sup>
CD ( $p \leq 0.05$ )	0.334	0.537	0.356	2.901	3.609	2.069	0.005	0.008	0.0044	0.0049	0.0061	0.0038
SEm ( $\pm$ )	0.114	0.183	0.121	0.989	1.230	0.705	0.001	0.002	0.0015	0.0017	0.0021	0.0013

Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by the LSD for mean separation.

**Table 6.** Residual effect of AMF and *Rhizobium* co-inoculation on pod length and grains per pod of pigeon pea during the 2022 and 2023 seasons

Treatments	Pod length			Grains per pod			Grain yield			Biological yield			Stover yield		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	4.4 <sup>ef</sup>	4.3 <sup>de</sup>	4.4 <sup>f</sup>	3.7 <sup>bcd</sup>	3.7 <sup>bc</sup>	3.6 <sup>ef</sup>	13.8 <sup>de</sup>	13.6 <sup>f</sup>	13.7 <sup>f</sup>	60.4 <sup>fg</sup>	53.3 <sup>de</sup>	53.7 <sup>fgh</sup>	46.6 <sup>cd</sup>	39.8 <sup>cd</sup>	40.1 <sup>def</sup>
T2	5.0 <sup>c</sup>	5.0 <sup>c</sup>	5.0 <sup>cde</sup>	4.0 <sup>bc</sup>	4.0 <sup>b</sup>	4.0 <sup>cde</sup>	13.9 <sup>d</sup>	14.4 <sup>de</sup>	14.2 <sup>e</sup>	58.5 <sup>efg</sup>	55.7 <sup>cde</sup>	56.1 <sup>efg</sup>	44.6 <sup>cd</sup>	41.3 <sup>cd</sup>	42.0 <sup>de</sup>
T3	5.2 <sup>abc</sup>	5.2 <sup>abc</sup>	5.2 <sup>bc</sup>	4.3 <sup>ab</sup>	4.3 <sup>b</sup>	4.4 <sup>a</sup>	14.4 <sup>bc</sup>	14.8 <sup>bc</sup>	14.6 <sup>cd</sup>	67.5 <sup>abc</sup>	60.2 <sup>cd</sup>	62.8 <sup>bcd</sup>	53.1 <sup>abc</sup>	45.4 <sup>c</sup>	48.2 <sup>bc</sup>
T4	5.4 <sup>a</sup>	5.5 <sup>ab</sup>	5.5 <sup>ab</sup>	4.3 <sup>ab</sup>	5.3 <sup>a</sup>	4.9	14.7 <sup>ab</sup>	15.0 <sup>a</sup>	14.9 <sup>ab</sup>	70.1 <sup>ab</sup>	60.5 <sup>bcd</sup>	64.3 <sup>bc</sup>	55.3 <sup>ab</sup>	45.5 <sup>c</sup>	49.4 <sup>bc</sup>
T5	4.5 <sup>de</sup>	5.1 <sup>c</sup>	4.8 <sup>e</sup>	3.3 <sup>cd</sup>	3.7 <sup>bc</sup>	3.4 <sup>ef</sup>	13.8 <sup>de</sup>	13.6 <sup>f</sup>	13.7 <sup>f</sup>	60.9 <sup>cdef</sup>	41.0 <sup>f</sup>	50.0 <sup>h</sup>	47.1 <sup>bcd</sup>	27.4 <sup>e</sup>	36.3 <sup>f</sup>
T6	4.7 <sup>d</sup>	5.0 <sup>c</sup>	4.9 <sup>de</sup>	3.0 <sup>d</sup>	4.3 <sup>b</sup>	3.7 <sup>def</sup>	13.8 <sup>de</sup>	14.3 <sup>e</sup>	14.0 <sup>e</sup>	60.0 <sup>def</sup>	54.3 <sup>cde</sup>	56.1 <sup>efg</sup>	46.2 <sup>cd</sup>	40.0 <sup>cd</sup>	42.1 <sup>de</sup>
T7	5.1 <sup>c</sup>	5.1 <sup>bc</sup>	5.1 <sup>cd</sup>	4.3 <sup>ab</sup>	4.3 <sup>b</sup>	4.4 <sup>abc</sup>	14.1 <sup>cd</sup>	14.7 <sup>cd</sup>	14.4 <sup>d</sup>	66.0 <sup>bcd</sup>	68.6 <sup>ab</sup>	66.3 <sup>ab</sup>	51.9 <sup>abc</sup>	54.0 <sup>ab</sup>	51.9 <sup>ab</sup>
T8	5.3 <sup>f</sup>	5.2 <sup>abc</sup>	5.3 <sup>bc</sup>	4.0 <sup>bc</sup>	4.3 <sup>b</sup>	4.2 <sup>bcd</sup>	14.4 <sup>bc</sup>	15.0 <sup>abc</sup>	14.7 <sup>bc</sup>	73.8 <sup>a</sup>	68.8 <sup>ab</sup>	70.3 <sup>a</sup>	59.4 <sup>a</sup>	53.8 <sup>ab</sup>	55.6 <sup>a</sup>
T9	4.1 <sup>f</sup>	4.1 <sup>e</sup>	4.2 <sup>f</sup>	3.7 <sup>bcd</sup>	3.0 <sup>c</sup>	3.3 <sup>f</sup>	13.9 <sup>d</sup>	13.7 <sup>f</sup>	13.8 <sup>f</sup>	61.4 <sup>cdef</sup>	57.2 <sup>cde</sup>	58.3 <sup>def</sup>	47.5 <sup>bc</sup>	43.6 <sup>cd</sup>	44.5 <sup>cd</sup>
T10	5.2 <sup>abc</sup>	4.6 <sup>d</sup>	4.9 <sup>e</sup>	3.7 <sup>bcd</sup>	4.0 <sup>b</sup>	3.8 <sup>cdef</sup>	13.4 <sup>e</sup>	14.1 <sup>e</sup>	13.7 <sup>f</sup>	52.5 <sup>g</sup>	50.7 <sup>e</sup>	50.6 <sup>gh</sup>	39.0 <sup>d</sup>	36.6 <sup>d</sup>	36.9 <sup>ef</sup>
T11	5.1 <sup>bc</sup>	5.3 <sup>abc</sup>	5.2 <sup>c</sup>	3.7 <sup>bcd</sup>	4.3 <sup>b</sup>	3.9 <sup>cdef</sup>	14.1 <sup>cd</sup>	14.9 <sup>abc</sup>	14.1 <sup>cd</sup>	59.8 <sup>defg</sup>	62.3 <sup>bc</sup>	60.1 <sup>cde</sup>	45.7 <sup>cd</sup>	47.5 <sup>bc</sup>	45.5 <sup>cd</sup>
T12	5.4 <sup>ab</sup>	5.6 <sup>a</sup>	5.5 <sup>a</sup>	5.0 <sup>a</sup>	4.3 <sup>b</sup>	4.7 <sup>ab</sup>	14.9 <sup>a</sup>	15.2 <sup>a</sup>	15.0 <sup>a</sup>	63.0 <sup>bcd</sup>	73.3 <sup>a</sup>	68.4 <sup>ab</sup>	48.0 <sup>bc</sup>	58.2 <sup>a</sup>	53.3 <sup>ab</sup>
CD ( $p \leq 0.05$ )	0.275	0.382	0.237	0.779	0.867	0.559	0.387	0.336	0.212	7.376	8.343	5.552	8.440	8.302	5.578
SEm ( $\pm$ )	0.093	0.130	0.081	0.265	0.295	0.190	0.132	0.114	0.072	2.515	2.844	1.893	2.877	2.830	1.902

Note: Means denoted by different letters are significantly different at  $p \leq 0.05$ , as determined by the LSD for mean separation.

**Fig. 4.** Residual impact of AMF and *Rhizobium* on CGR and RGR of pigeon pea at 60 and 90 DAS.**Fig. 5.** Residual impact of AMF and *Rhizobium* on grains per pod, pods length, pods per plant and test weight of pigeon pea.

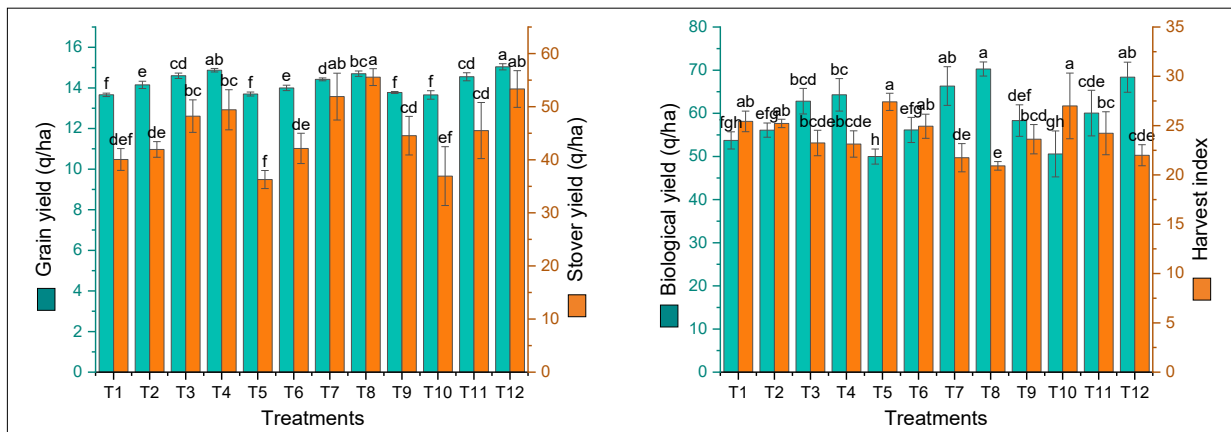
grains (19). This balanced nutrient delivery, enabled by AMF and *Rhizobium*, maximises pod development, enhances grain number per pod and favours grain fill completion, resulting in increased pod length and test weight. Furthermore, the improved nutrient status can positively influence hormonal signalling, promoting increased pod set and ultimately more pods per plant (21).

The statistics for yield attributes are presented in Fig. 6. The graph shows that the residual effects of AMF and *Rhizobium* significantly increase grain yield, straw yield, biological yield and harvest index compared with the alternative condition across all treatments. Statistically significant differences are seen, with the residual impact of AMF and *Rhizobium* consistently outperforming in crop yield parameters. The results highlight that proper treatment selection greatly enhances crop productivity and efficiency. Grain yield (economic yield), recorded the highest percentage increase under T<sub>12</sub> (19.2 %), followed by T<sub>4</sub> (16.9 %), T<sub>8</sub> (14.5 %) and T<sub>3</sub> (13.1 %) compared with the control. While the highest stover yield per percentage increment was recorded under T<sub>8</sub> (38.8 %) and T<sub>12</sub> (33.1 %), followed by T<sub>7</sub> (29.6 %) and T<sub>4</sub> (23.4 %), compared with the control treatment. The total biomass, which is the combined weight of grain and stover yield, showed the greatest increase under T<sub>8</sub> (17.5 %), followed by T<sub>12</sub> (15.5 %), T<sub>7</sub> (13.3 %) and T<sub>4</sub> (11.2 %) compared with the non-amended treatment. Compared to the control treatment T<sub>1</sub>, T<sub>8</sub> showed the highest percentage increase (17.7 %), followed by T<sub>7</sub> (14.5 %), T<sub>12</sub> (13.5 %) and T<sub>4</sub> (9.0 %). Pigeon pea grain yield, stover yield,

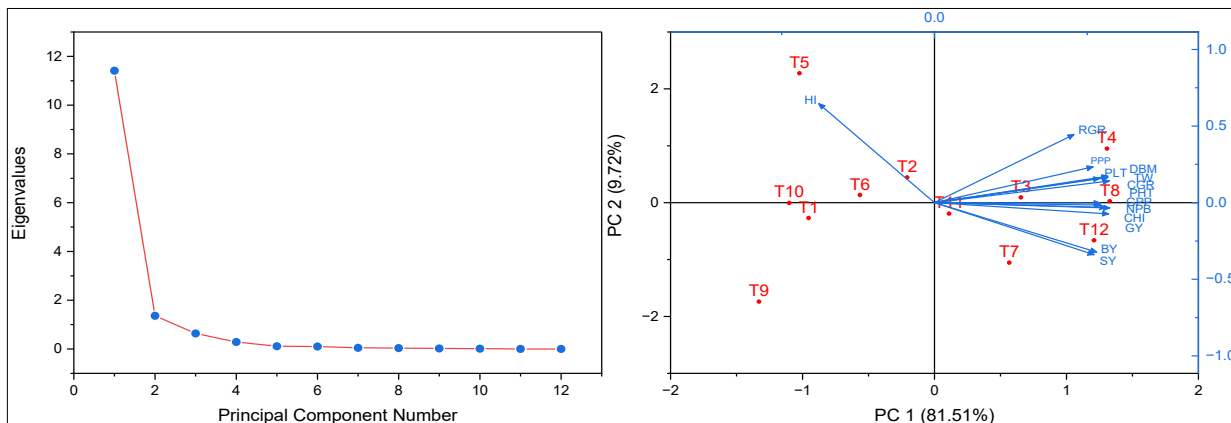
biological yield and harvest index increase as a result of the synergistic effects of AMF and *Rhizobium*, owing to improved nutrient uptake and effective resource allocation (22). The combined effects of enhanced nutrient uptake and nitrogen fixation improve plant metabolism, leading to greater grain filling and ultimately higher grain yield. Furthermore, enhanced resource partitioning for grain production results in a higher harvest index, indicating that a larger percentage of total biomass is allocated to the economically significant grain yield (22, 23).

### Principal component analysis

The biplot analysis shows the interactions between traits and treatments, with PC1 and PC2 accounting for 91.2 % of the variance in the observations (Fig. 7). The first two components were geometrically represented in a Cartesian coordinate system, constructing a dimensional reduction framework to identify prominent discriminatory variables in the observation data. In coordinates, T<sub>4</sub>, T<sub>8</sub> and T<sub>3</sub> were clustered, with vectors RGR, GPP, PLT, PPP, PHT and TW displayed, indicating strong bonding. In coordinate-2 T<sub>12</sub>, T<sub>7</sub> and T<sub>1</sub> were clustered, where vectors CHI, NPB, GY, BY and SY were used. Principal component analysis is a statistical method for extracting meaningful information from high-dimensional data and representing it in a lower-dimensional space. It is a very effective way to group highly correlated variables. In this study, PCA was employed to describe treatments, examine trait relationships and efficiently discriminate among them. Principal component analysis has been widely used for similar



**Fig. 6.** Residual impact of AMF and *Rhizobium* on grain yield, stover yield, biological yield and harvest index of pigeon pea.



**Fig. 7.** Eigenvalues representing the variance explained by the first two principal components (PC1 and PC2). The biplot depicts the distribution of treatments and their associations with 14 growth, physiological and yield parameters along PC1 and PC2.

BY = biological yield; CHI = chlorophyll index; CGR = crop growth rate; DBM = dry biomass; GPP = grains per pod; GY = grain yield; HI = harvest index; NPB = number of primary branches; PHT = plant height; PLT = pod length; PPP = pods per plant; RGR = relative growth rate; SY = stover yield; TW = test weight.

applications across various crop characteristics. Here, we applied PCA to investigate the residual effects of AMF and *Rhizobium* on plant height and dry biomass accumulation, which significantly enhanced RGR and CGR, ultimately contributing to increased pigeon pea yield (24).

## Conclusion

The findings of this study confirm that AMF and *Rhizobium* inoculation exert substantial residual effects on pigeon pea, resulting in sustained improvements in crop performance. The enhanced nutrient availability from these beneficial microorganisms promotes plant growth and healthy biomass accumulation, ultimately resulting in increased grain yield. This is a sustainable agricultural practice, providing the farmer with a double benefit: first, gains from AMF and *Rhizobium* on maize and second, a beneficial carryover effect on the growth and yield of pigeon pea during the following season. This practice promotes efficient resource use and reduces reliance on chemical fertilisers, resulting in a more sustainable, environmentally friendly cropping system.

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## Authors' contributions

AKY carried out the field experiment, collection and analysis of data, participated in the sequence alignment and drafted the manuscript. CMM participated in the design of the study, supervised the whole research and helped in compiling the manuscript. GS conceived the study and participated in data collection, compiling and analysis. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

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