



Individual and Combined Effects of Vermicompost and Vermicompost Tea on Fenugreek (*Trigonella foenum-graecum* L.) Anatomical Traits, Yield Components, and Seed Quality.

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Abstract: Vermicompost is a nutrient- and growth-promoter-rich biofertilizer that provides a holistic strategy for sustainable agriculture and environmental restoration. This study investigates the individual and combined effects of vermicompost (VC) and vermicompost tea (VCT) on the anatomical yield attributes, and seed quality of fenugreek (*Trigonella foenum-graecum* L., Giza-2 cultivar), compared to plants receiving 100% of the recommended NPK fertilizer. Treatments included soil amendments with VC at 60 g (VC₁) and 120 g (VC₂) per pot and foliar VCT applications three (VCT₁) or six times (VCT₂), along with their combinations (VC₁+VCT₁, VC₁+VCT₂, VC₂+VCT₁, VC₂ +VCT₂). The experiment followed a randomized complete block design with 9 treatments and 4 replicates. Results showed that all VC and VCT treatments significantly improved fenugreek's anatomical traits, yield attributes, and seed quality compared to untreated plants, with combined treatments outperforming individual ones. The combined VC₂ + VCT₂ treatment was the most effective, leading to the highest increases in stem vascular bundle thickness (21.93%) and width (26.53%), leaf vascular bundle thickness (57.66%), and width (66.66%), and mesophyll tissue thickness (36.67%). This treatment also significantly improved yield attributes over the control in both growing seasons. The first season saw increases in seed yield (616.94%), number of branches (110.53%), pods per plant (98.78%), seeds per pod (111.68%), 100-seed weight (70.26%), economical yield (230.50%), biological yield (91.40%), and harvest index (75.00%); similar improvements were observed in the second season. Seed quality mirrored yield improvements; with VC₂ + VCT₂ achieving the highest increases in seed carbohydrates, proteins, fats, fiber, and NPK levels. The study recommends using 120 g of vermicompost per pot (VC₂) combined with six foliar applications of vermicompost tea (VCT₂) as a sustainable eco-friendly strategy for enhancing productivity and yield quality of fenugreek and other food and medicinal plants.

Keywords: Anatomy, Bioconstituents, Fenugreek, Vermicompost, Vermicompost-tea

1.Introduction

Fenugreek (*Trigonella foenum-graecum* L.), an annual legume belonging to the Fabaceae family, is renowned for its nutraceutical and therapeutical properties. It is frequently utilized as a spice, condiment, vegetable, and in traditional medicinal systems (Petropoulos, 2002; Bishnoi *et al.*, 2019). Fenugreek seeds, the main economic product, are rich in minerals, proteins, lipids, dietary fiber, and bioactive constituents such as saponins, alkaloids, polyphenols,

galactomannans, and vitamins. These constituents underpin a range of medicinal effects, including antidiabetic, anticancer, anti-inflammatory, antibacterial, hepatoprotective, hypocholesterolemic, and lactation-promoting activities. Moreover, these compounds function as emulsifiers, adhesives, and stabilizers within food technology (Gavahian *et al.*, 2024; Tewari *et al.*, 2024). Agriculturally, fenugreek enhances soil fertility via biological nitrogen fixation, supports crop rotation, and serves as livestock feed,

illustrating its versatility across food, medicinal, and agricultural domains (Sadeghzadeh-Ahari *et al.*, 2009).

Global demand for fenugreek seeds is rising, driven by recognized health benefits and increasing incorporation into functional foods and herbal (Tewari *et al.*, 2024). To satisfy this demand and sustain the expanding interest in medicinal plants for traditional medicine, pharmaceuticals, and functional foods, expansion of commercial cultivation is warranted. Nevertheless, production is impeded by challenges such as water scarcity, soil and water salinity, and agricultural pollution (Motawea, 2024; Nuruzzaman *et al.*, 2025; Wanas *et al.*, 2025a).

Agricultural pollution arises from suboptimal farming practices, including excessive application of inorganic fertilizers, herbicides, and pesticides, alongside air pollution from industrial emissions and contamination of irrigation water. These factors deteriorate soil quality, adversely affect crop production, and pose substantial environmental and health risks. Systematic assessment of pollution risks is critical to ensure safe food production and the protection of ecosystems (Nuruzzaman *et al.*, 2025). Implementing preventive strategies to minimize pollution is essential for sustainable agriculture, environmental health, and human well-being.

There is a rising trend toward the use of organic enhancers, such as plant extracts and organic fertilizers, as eco-friendly biostimulants in contemporary agriculture. These natural additives support the sustainable production of both agricultural and medicinal crops (Mohite *et al.*, 2024; Motawea, 2024; Wanas *et al.*, 2025a).

Vermicomposting converts agro-industrial and domestic wastes, through the action of earthworms, into vermicompost, a nutrient- and growth-promoter-rich product that outperforms conventional composts and chemical fertilizers. This approach reduces reliance on synthetic inputs, thereby lowering environmental pollution and farming's carbon footprint (Alshehrei & Ameen, 2021; Mohite *et al.*, 2024). Vermicompost is a nutrient-rich biofertilizer that enhances soil fertility, boosts crop productivity, and supports waste management. Its unique composition, comprising essential plant nutrients, phytohormones, humic substances, and beneficial microorganisms, improves various soil properties, increases nutrient availability, and enhances water retention, which together elevate yields and plant health. It also features a higher cation exchange capacity than traditional compost, enabling more efficient long-term nutrient retention and release (Kauser & Khwairakpam, 2022; Boruah & Deka, 2023; Mohite *et al.*, 2024). Vermicompost contains macro- and micro-nutrients

and a diverse microbial community, including phosphate-solubilizing bacteria, nitrogen-fixing bacteria, *Bacillus*, *Pseudomonas*, and *Trichoderma*, with populations capable of suppressing pathogens, thereby acting as both organic fertilizer and biopesticide (Bellitürk *et al.*, 2017; Mohite *et al.*, 2024). Digestive enzymes produced by earthworms and associated microbes (e.g., chitinases, cellulases, lipases, dehydrogenases, phosphatases, and ureases) contribute to nutrient cycling and soil health (Sundararasu & Jeyasankar, 2014; Saheed *et al.*, 2017). Vermicompost improves soil structure and enhances a range of physicochemical properties, such as soil texture, aggregation, pH, electrical conductivity, bulk density, organic matter, water-holding capacity, and biological properties, including enzyme activity and microbial populations (Piya *et al.*, 2018), supporting sustainable organic agriculture and offering a greener alternative to conventional farming systems.

In the first part, Wanas *et al.* (2025_b) evaluated the effects of vermicompost (VC) as a soil amendment at 60 and 120 g/pot and vermicompost tea (VCT) as a foliar spray applied 3 and 6 times, both individually and in combination, on fenugreek growth and chemical composition. The results showed significant improvements in growth parameters, photosynthetic pigments, and leaf bioconstituents and mineral content across all treatments, with combined VC and VCT treatments proving more effective than individual applications. Since morphological changes often coincide with anatomical alterations that influence plant growth and productivity, this study aims to investigate how vermicompost and its liquid extract (vermicompost tea) affect anatomical features and yield attributes of fenugreek.

2. Materials and Methods

2.1. Experimental design

Two pot experiments were conducted at the Nursery of the Faculty of Agriculture, Damietta University, Egypt (31°25'39.1"N, 31°39'06.2"E) during the 2021/2022 and 2022/2023 winter seasons. These studies investigated the comparative and combined effects of vermicompost (VC) and vermicompost tea (VCT) on the anatomical features as well as seed yield and quality of fenugreek (*Trigonella foenum-graecum* L., Giza-2 cultivar). The seeds used in the experiments were obtained from the Legumes Department, Agricultural Research Center, Giza, Egypt. The experimental treatments were as follows:

- T₁: Control treatment, with 100% of the recommended NPK fertilizers applied.
- T₂: Vermicompost added to the soil at 60 g per pot (VC₁).
- T₃: Vermicompost added to the soil at 120 g per pot (VC₂).

- T₄: Vermicompost tea foliar spray applied three times (VCT₁).
- T₅: Vermicompost tea foliar spray applied six times (VCT₂).
- T₆: Combination of VC₁ & VCT₁.
- T₇: Combination of VC₁ & VCT₂.
- T₈: Combination of VC₂ & VCT₁.
- T₉: Combination of VC₂ & VCT₂.

The experiment utilized 35 cm diameter plastic pots filled with a 3:2:1 (v/v/v) mixture of sand, farm soil, and peat moss, weighing 15 kg per pot. A layer of small limestone gravel, comprising 5% of the volume, was placed at the base of each pot. Vermicompost was added to T₂, T₃, T₆, T₇, T₈, and T₉ pots 21 days before sowing to aid decomposition. Seeds were sown on November 14th, with four seeds per pot. The study followed a randomized complete-block design with nine treatments and four replicates, each consisting of five pots. Two weeks after sowing, seedlings were thinned to two per pot. Starting at 21 days after sowing (DAS), vermicompost tea foliar spraying (100 ml per plant) was applied three times for T₄, T₆, and T₈ plants and six times for T₅, T₇, and T₉ plants, with one-week intervals between applications. Irrigation with tap water and conventional fenugreek cultivation practices were followed as recommended. For T₁ (control), granular

urea (46% N) was applied at 0.75 g per pot during soil preparation and two weeks after sowing. Single superphosphate (15% P₂O₅) at 2.5 g per pot and potassium sulfate (50% K₂O) at 1.25 g per pot were added and mixed with urea during soil preparation.

2.2. Soil sampling and analysis

Soil samples were randomly taken from the soil mixture used in the main experiment prior to sowing during the 2021/2022 and 2022/2023 seasons. These samples were examined using Miller & Miller's (1987) method to assess physical properties and underwent chemical analysis following Dewis and Freitas (1970) and Jackson (1973). The results are presented in Table 1.

2.3. Vermicompost and Vermicompost tea

Vermicompost was obtained from a private farm in Alexandria, Egypt. A part was made into a liquid extract (vermicompost tea) by adding 1 kg of vermicompost into 4 liters of non-chlorinated tap water and mixing thoroughly until froth or bubbles are visible. The combination was aerobically fermented for 72 hours, then filtered through a 2 mm mesh and diluted with non-chlorinated tap water to yield 5 liters (20% vermicompost tea) following Edwards *et al.* (2010). This extract was utilized as a foliar spray three times on T₄, T₆, and T₈ plants, and six times on T₅, T₇, and T₉. Both vermicompost and vermicompost tea were tested for pH, electrical conductivity (EC) (Jackson, 1973), hygroscopic water content, organic carbon (Dewis & Freitas, 1970), and organic matter content (Minasny *et al.*, 2020). Nutrient concentrations, including available nitrogen, phosphate, and potassium, were measured using methods outlined by Horneck & Miller (1998), Olsen *et al.* (1954), and Hesse (1971). The findings are shown in Tables 2 and 3.

Table 1: Physical and chemical properties of the experimental soil before sowing in both growing seasons.

Soil properties	2021/22	2022/23	Soil properties	2021/22	2022/23
Soil particles distribution%			Soluble cations (mg 100g ⁻¹)		
Sand	60.00	57.12			
Silt	25.22	27.02			
Clay	14.78	15.86	Mg ⁺²	10.33	13.23
			Ca ⁺²	102.25	96.56
Textural class	Sandy loam		Na ⁺	58.05	56.37
Soil pH	8.21	8.17	K ⁺	4.12	3.22
EC (ds/m)	2.03	1.92			
Organic Matter (%)	1.22	1.13			
			Soluble anions (mg 100g ⁻¹)		
Total CaCO ₃ (%)	4.51	3.83	Cl ⁻	69.03	65.41
Available N (mg kg ⁻¹)	10.12	10.25	HCO ₃ ⁻	22.14	15.33
Available P (mg kg ⁻¹)	4.02	4.71	CO ₃ ⁼	-	-
Available K (mg kg ⁻¹)	130	127	SO ₄ ⁼	63.58	68.64

Table 2: Chemical composition of vermicompost.

pH	EC (ds/m)	Hygroscopic water (%)	Organic carbon (%)	Organic matter (%)	Available N (%)	Available P (%)	Available K (%)
7.73	2.00	5.00	23.67	40.81	3.52	0.26	0.44

Table 3: Chemical composition of vermicompost tea.

pH	EC (ds/m)	Organic carbon (g l ⁻¹)	Organic matter (g l ⁻¹)	Available N (mg l ⁻¹)	Available P (mg l ⁻¹)	Available K (mg l ⁻¹)
7.25	0.89	2.93	5.05	120.12	23.74	62.00

2.4. Sampling and collecting data

2.4.1. Anatomical Study

A comparative anatomical study was performed during the second season to examine the anatomical changes in the main stem and 5th leaf caused by the applied treatments in comparison to the control.

At 70 DAS, 1 cm-long specimens were collected from the middle of the 5th apical internode and the terminal leaflet of the 5th apical leaf on the main stem. These were immediately fixed in an aqueous solution containing 2.5% glutaraldehyde and 2.5% paraformaldehyde for a minimum of 48 hours. After rinsing with phosphate buffer, the specimens were post-fixed in 1% osmium tetroxide for two hours, followed by another phosphate buffer rinse. The samples were dehydrated in a standard ethanol series, embedded in resin, and sectioned into 1 µm-thick slices using a LEICA EM UC7 ultra microtome. Sections were stained with toluidine blue. Slides were examined under a microscope, and measurements and counts were taken using a micrometer eyepiece (Tizro *et al.*, 2018).

2.4.2. Yield attributes

At 138 DAS (harvest time), four plants per treatment were randomly selected, and the following characteristics were measured: number of pods per plant, seeds per pod, 100-seed weight (g), and total seed yield (g) per plant. Additionally, economical yield (dry seed weight (g) per plant) and biological yield (total dry weight of plant, including roots, stems, leaves, and pods) were recorded. Harvest index was calculated as the percentage of economical yield divided by biological yield, following Vazin (2012).

2.4.3. Chemical constituents of fenugreek seeds

The chemical constituents in fenugreek seeds were determined by analyzing seed samples collected from four plants per treatment at harvest time. The samples were dried at 70°C until reaching constant weight, then ground into a fine powder using a grinder (NIMA BL-888A, Japan). The analysis included bioconstituents such as total carbohydrates (Dubois *et al.*, 1956), total fats (AQSIQ, 2016), and total fibers (Maynard, 1970). Chemical analysis also included total nitrogen (Horneck & Miller, 1998), phosphorus (Jackson, 1973), and potassium (Horneck & Hanson, 1998). Protein content was calculated by multiplying total nitrogen by 6.25 (AOAC, 2023), and results are presented as g 100g⁻¹ DW.

2.5. Statistical Analysis

Data on yield and chemical constituents were subjected to one-way ANOVA under a randomized complete block design using IBM SPSS Statistics

(version 29.0.1.0). Treatment means were compared to the control using the LSD test ($P \leq 0.05$), following Snedecor & Cochran (1989).

3. Results

3.1. Anatomical study

3.1.1. Stem anatomy

Table 4 and Fig. 1 show the anatomical changes in fenugreek stems under different vermicompost (VC₁, VC₂) and vermicompost tea (VCT₁, VCT₂) treatments, as well as their combinations (VC₁ + VCT₁, VC₁ + VCT₂, VC₂ + VCT₁, and VC₂ + VCT₂). All individual and combined treatments markedly increased the cross-sectional diameter of the stem by enhancing the thickness of the epidermis, cortex, and parenchymatous pith and by increasing the number, thickness, and width of vascular bundles. The vascular bundle improvements were primarily due to thicker fibers, phloem, and xylem tissues, along with a higher number of xylem vessels per bundle. Individual vermicompost treatments resulted in greater anatomical improvements than vermicompost foliar sprays, while combined VC + VCT treatments proved more effective than individual applications. The VC₂ + VCT₂ combination showed the most notable effects, increasing stem diameter by 19.72%, epidermis thickness by 18.49%, cortex thickness by 11.77%, pith diameter by 19.78%, vascular bundle number by 37.50%, vascular bundle thickness by 21.93%, and vascular bundle width by 26.53%, with a 47.62% increase in the number of vessels per bundle compared to the control.

3.1.2. Leaf anatomy

The comparative anatomical study of treated fenugreek leaves versus untreated plants during the second season revealed remarkable histological differences due to the applied treatments. Table 5 and Fig. 2 illustrate that anatomical features of the leaf midvein and lamina were substantially enhanced with VC and VT treatments, both individually and in combination, compared to untreated plants. Midvein thickness, vascular bundle thickness and width, and the number thickness also improved, primarily due to the thickening of its constituent tissues, including the upper and lower epidermises, palisade tissue, and spongy tissue. Vermicompost treatments exhibited greater anatomical improvements than vermicompost tea foliar sprays, with integrated VC + VCT treatments outperforming individual applications. Notably, the VC₂ + VCT₂ combination was the most effective, enhancing midvein thickness by 67.39%, vascular

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bundle thickness by 57.66%, vascular bundle width by 66.66%, phloem thickness by 31.26%, xylem thickness by 65.45%, and xylem vessel number per bundle by 108.33%. Additionally, lamina thickness increased by

32.63%, upper epidermis by 26.92%, lower epidermis by 5.29%, palisade tissue thickness by 38.22%, and spongy tissue thickness by 35.05% compared to the control.

Table 4: Effect of vermicompost and vermicompost tea treatments applied separately and in combination on certain anatomical aspects of the 5th apical internode of fenugreek main stem at 70 DAS during the 2022/2023 season.

Measurements (μm) & counts Treatments		Stem diameter	Thick. of epidermi	Thick. of cortex	No. of vascular bundles	Thick. of vascular	Width of vascular bundle	Thick. of phloem	Thick. of phloem	Thick. of xylem tissues	No. of xylem vessels	Pith diameter
Control*	$\bar{X}$	2808.04	22.12	127.05	16.00	448.74	331.58	84.92	36.55	327.27	21.00	1612.22
	$\pm\%$											
VC ₁	$\bar{X}$	2954.72	23.10	133.40	17.00	472.50	373.17	100.13	39.88	332.49	26.00	1696.72
	$\pm\%$	+5.22	+4.43	+4.99	+6.25	+5.29	+12.54	+17.91	+9.11	+1.60	+23.81	+5.24
VC ₂	$\bar{X}$	3202.03	25.52	140.83	19.00	532.41	412.98	119.74	55.62	357.05	28.00	1804.51
	$\pm\%$	+14.03	+15.37	+10.84	+18.75	+18.65	+24.55	+41.00	+52.18	+9.100	+33.33	+11.92
VCT ₁	$\bar{X}$	2841.27	22.26	127.17	17.00	459.59	331.91	90.14	36.61	332.84	22.00	1623.23
	$\pm\%$	+1.17	+0.63	+0.10	+6.25	+2.41	+0.10	+6.15	+0.16	+1.70	+4.76	+0.68
VCT ₂	$\bar{X}$	2917.55	22.34	130.74	17.00	467.07	359.51	92.57	38.84	335.66	25.00	1677.25
	$\pm\%$	+3.90	+0.10	+2.90	+6.25	+4.08	+8.42	+9.01	+6.27	+2.56	+19.05	+4.03
VC ₁ +VCT ₁	$\bar{X}$	3074.11	24.00	135.94	18.00	515.49	387.35	112.67	42.93	359.89	27.00	1723.25
	$\pm\%$	+9.48	+8.50	+7.00	+12.50	+14.87	+16.82	+32.68	+17.46	+9.97	+28.57	+6.89
VC ₁ +VCT ₂	$\bar{X}$	3126.00	24.51	137.40	18.00	520.02	409.35	114.42	45.18	360.42	27.00	1762.14
	$\pm\%$	+11.32	+10.80	+8.14	+12.50	+15.88	+22.55	+34.74	+23.61	+10.13	+28.57	+9.30
VC ₂ +VCT ₁	$\bar{X}$	3274.32	25.66	141.12	20.00	542.67	416.12	122.81	53.63	365.23	28.00	1855.42
	$\pm\%$	+16.61	+16.00	+11.07	+25.00	+20.93	+25.49	+44.62	+46.73	+11.60	+33.33	+15.08
VC ₂ +VCT ₂	$\bar{X}$	3361.79	26.21	142.01	22.00	547.12	419.54	124.43	55.78	366.91	31.00	1931.11
	$\pm\%$	+19.72	+18.49	+11.77	+37.50	+21.93	+26.53	+46.53	+52.61	+12.11	+47.62	+19.78

Table 5: Effect of vermicompost and vermicompost tea treatments applied separately and in combination on certain anatomical aspects of the terminal leaflet of the 5th apical leaf on fenugreek main stem at 70 DAS during the 2022/2023 season.

Measurements (μm) & counts Treatments		Thick. of mid vein	Thick. of VB	Width of VB	Thick. of phloem tissues	Thick. of xylem tissues	No. of vessels/ VB	Thick. of lamina	Thick. of UP	Thick. of LP	Thick. of PT	Thick. of ST	Thick. of MT
Control*	$\bar{X}$	342.23	91.10	141.26	20.76	70.34	12.00	217.64	22.03	21.14	88.97	85.50	174.47
	$\pm\%$												
VC ₁	$\bar{X}$	515.55	102.72	176.79	22.44	80.28	18.00	271.53	26.37	21.74	112.30	111.12	223.42
	$\pm\%$	+50.64	+12.76	+25.15	+8.09	+14.13	+50.00	+24.76	+19.70	+2.84	+26.22	+29.96	+28.06
VC ₂	$\bar{X}$	526.38	120.76	195.16	23.94	96.82	19.00	284.51	26.68	22.12	122.21	113.50	235.71
	$\pm\%$	+53.81	+32.56	+38.15	+15.32	+37.65	+58.33	+30.73	+21.11	+4.64	+37.36	+32.75	+35.10
VCT ₁	$\bar{X}$	500.80	100.83	157.45	21.17	79.66	12.00	245.89	22.56	21.19	106.28	95.86	202.14
	$\pm\%$	+46.33	+10.68	+11.46	+1.97	+13.25	0.00	+12.98	+2.40	+0.24	+19.46	+12.12	+15.86
VCT ₂	$\bar{X}$	505.03	101.56	166.70	21.88	79.68	13.00	254.07	26.30	21.76	107.88	99.13	207.01
	$\pm\%$	+47.57	+11.48	+18.01	+5.29	+13.28	+8.33	+16.74	+19.38	+2.93	+21.25	+15.94	+18.65
VC ₁ +VCT ₁	$\bar{X}$	521.22	116.58	182.98	22.17	94.41	18.00	272.19	26.08	21.67	113.06	111.38	224.44
	$\pm\%$	+52.30	+27.97	+29.53	+6.79	+34.22	+50.00	+25.06	+18.38	+2.50	+27.08	+30.27	+28.64
VC ₁ +VCT ₂	$\bar{X}$	525.68	119.19	185.59	22.86	96.33	19.00	275.48	26.76	21.71	115.08	111.93	227.01
	$\pm\%$	+53.60	+30.83	+31.38	+10.16	+36.95	+58.33	+26.58	+21.47	+2.70	+29.35	+30.91	+30.11
VC ₂ +VCT ₁	$\bar{X}$	564.32	124.71	198.95	25.73	98.98	20.00	285.13	26.51	22.00	122.25	114.37	236.62
	$\pm\%$	+64.87	+36.89	+40.83	+23.94	+40.72	+66.67	+31.01	+20.34	+4.07	+37.41	+33.77	+35.62
VC ₂ +VCT ₂	$\bar{X}$	572.87	143.63	235.43	27.25	116.38	25.00	288.66	27.96	22.26	122.97	115.47	238.44
	$\pm\%$	+67.39	+57.66	+66.66	+31.26	+65.45	+108.33	+32.63	+26.92	+5.29	+38.22	+35.05	+36.67

Control* = Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, DAS= Days after sowing, No. = Number, Thick. = Thickness, VB = Vascular bundle, UP = Upper epidermis, LE = Lower epidermis, MT = Mesophyll tissue, $\pm\%$ = the percent increase or decrease relative to the control.

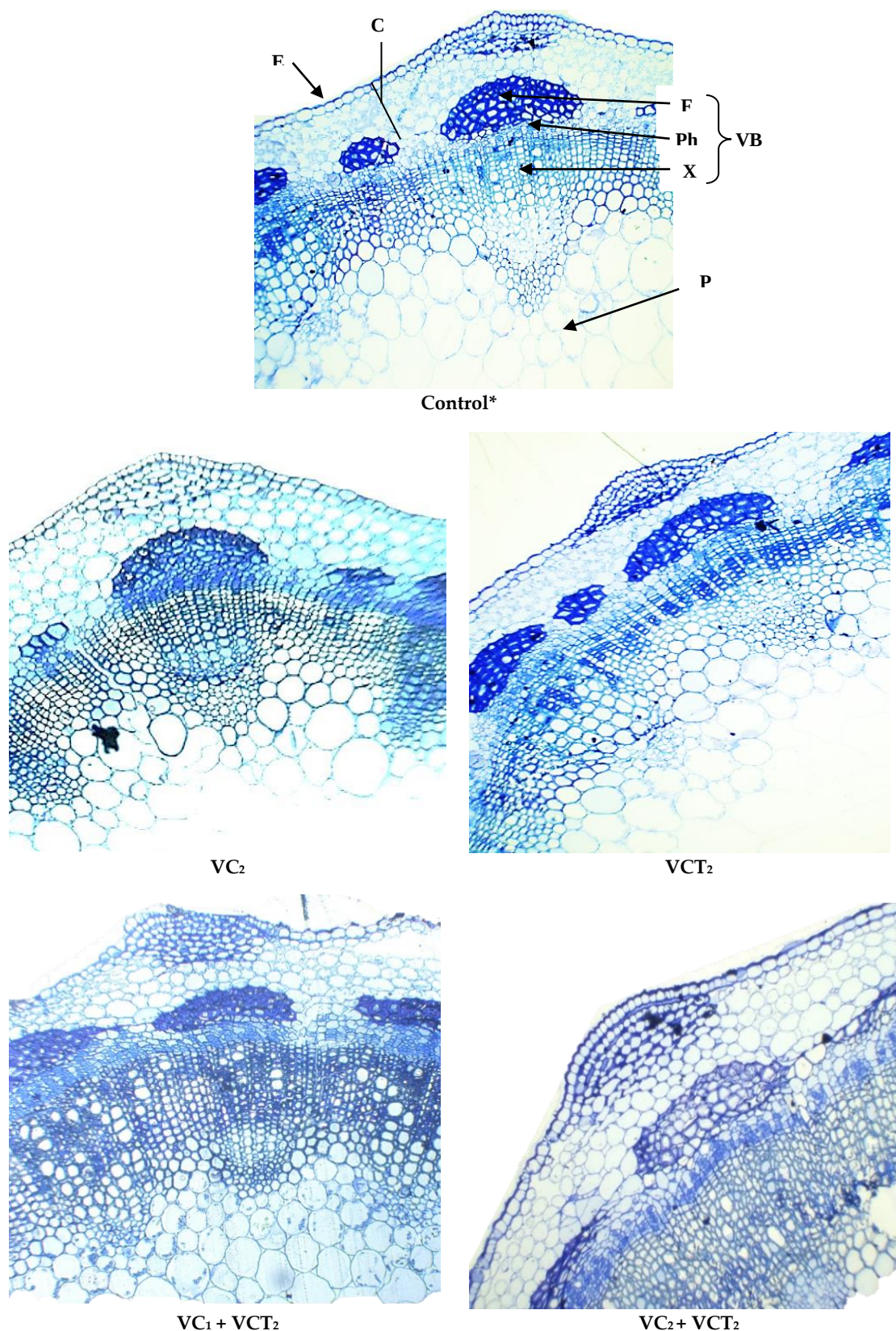


Figure 1: Transverse sections (100 X) through the middle part of the 5th apical internode of the fenugreek main stem.

Control* = Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, E = Epidermis, C = Cortex, F = Fibers, Ph = Phloem, X = Xylem, VB = Vascular bundle, P = Pith..

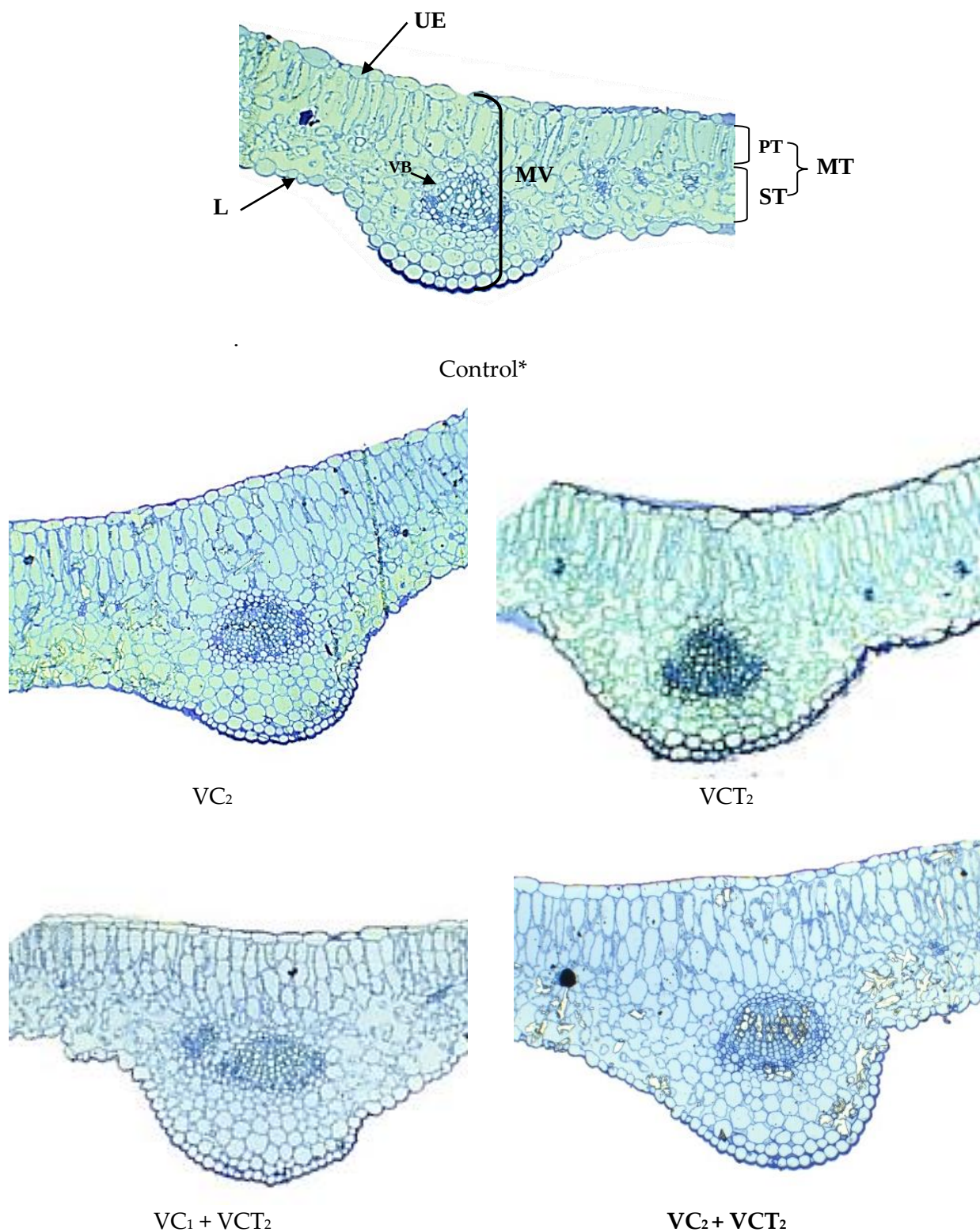


Figure 2: Transverse sections (100 X) through the middle part of a terminal leaflet blade of the 5th apical leaf on the fenugreek mean stem.

Control* = Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, MV= Midvein, VB= Vascular bundle, LE = Lower epidermis, UE = Upper epidermis, PT= Palisade tissue, ST= Spongy tissue, MT = Mesophyll tissue.

3.2. Yield characteristics

Figures 3 & 4 illustrate the mean total seed yield per plant and related traits for the 2021/2022 and 2022/2023 seasons, including percentage changes due to treatments relative to the control. Significant increases ($p \leq 0.05$) in seed yield were observed with vermicompost (VC_1 & VC_2) and vermicompost tea (VCT_1 & VCT_2) treatments, as well as their combinations, across both seasons. Vermicompost, applied at 60 g (VC_1) and 120 g (VC_2) per pot, consistently outperformed vermicompost tea, which was applied foliarly three (VCT_1) and six (VCT_2) times. The percentage increases in seed yield relative to the control for VC_1 were 112.43% & 100.44%, for VC_2 were 314.05% & 298.00%, for VCT_1 were 56.58% & 46.34%, and for VT_2 were 59.28% & 52.11% across the two seasons, respectively, demonstrating the superiority of VC_2 . Among integrative treatments, VC_2+VCT_2 showed the highest increases (616.94% & 562.08%), followed by VC_2+VCT_1 (419.45% & 399.11%), VC_1+VCT_2 (310.81% & 285.81%), and VC_1+VCT_1 (201.44% & 185.37%), confirming VC_2+VCT_2 as the most effective treatment.

The improvement in seed yield per plant under individual and combined VC and VCT treatments was matched by significant increases in its components, including the number of branches per plant, pods per plant, and seeds per pod, as well as 100-seed weight, compared to the control. These gains aligned with the positive effects of each treatment on total seed yield. The combined treatment VC_2+VCT_2 , which produced the highest seed yield increases relative to the control (616.94% & 562.08%), also showed the greatest relative improvements during the 2021/2022 and 2022/2023 seasons, with increases of 98.78% & 98.60% in pod number per plant, 111.68% & 107.31% in seed number per pod, and 70.26% & 60.27% in 100-seed weight. Additionally, all individual and combined VC and VCT treatments significantly enhanced economical yield (dry seed weight per plant), biological yield (total plant dry weight, including pods), and harvest index compared to the control in both study seasons. The increases followed a pattern similar to those observed in total seed yield and its components, with VC_2+VCT_2 being the most effective treatment.

3.3. Chemical constituents of Fenugreek seeds

Both individual and combined applications of VC and VCT treatments significantly enhanced the concentrations of total carbohydrates, proteins, lipids, fibers, nitrogen, phosphorus, and potassium in fenugreek seeds (Figs. 5 & 6). VC treatments, applied at 60 g/pot (VC_1) and 120 g/pot (VC_2), outperformed

VCT treatments, which were applied foliarly three times (VCT_1) and six times (VCT_2). However, the combination of VC + VT treatments yielded the highest increases, with $VC_2 + VCT_2$ being the most effective. This combined treatment achieved the maximum values for all bioconstituents and mineral nutrients, resulting in percentage increases of 8.95% & 8.77% for total carbohydrates, 14.06% & 12.70% for total proteins, 38.78% & 31.65% for total lipids, 55.21% & 55.31% for total fibers, 14.06% & 12.70% for total nitrogen, 65.22% & 56.00% for phosphorus, and 6.67% & 5.26% for potassium across the 2021/2022 and 2022/2023 seasons.

4. Discussion

Given global population growth and the pressing need for food security, especially amidst threats to agricultural sustainability from climate change, human mismanagement, soil degradation, water scarcity, salinization, and pollution, the importance of expanding legumes, such as fenugreek, has grown significantly due to their benefits for soil enhancement as well as human nutrition and health, with a focus on enhancing productivity through eco-friendly and sustainable practices. This study aimed to improve fenugreek's anatomical features, as well as seed yield and quality using vermicompost and its aqueous extract (vermicompost tea).

Our study showed that vermicompost (VC) soil amendments at 60 g (VC_1) and 120 g (VC_2) per pot and vermicompost tea (VCT) foliar spray 3 times (VCT_1) and 6 times (VCT_2) treatments, applied individually and in combination, markedly enhanced various anatomical features of fenugreek stems and leaves. These enhancements included thicker leaf mesophyll and increased xylem and phloem tissue in both organs. Such effects can be attributed to the organic fertilizers' richness in growth-promoting hormones like auxins, gibberellins, and cytokinins, which regulate some vital growth-associated processes like cell division, elongation, and differentiation (Taiz *et al.*, 2014). Two key factors likely contributed to these anatomical enhancements: (1) increased activity of the leaf blade ground meristem, resulting in more chlorenchyma layers that form the mesophyll tissue responsible for photosynthate creation, and (2) heightened procambium activity in both stems and leaves, leading to larger vascular bundles with thicker phloem and xylem tissues. These tissues play a crucial role in photosynthate production, distribution, and nutrient translocation. The treatments appear to have enhanced the translocation of raw materials (water and mineral nutrients) by improving xylem vessel efficiency and boosting nutrient absorption by roots. Additionally, they improved photosynthate creation

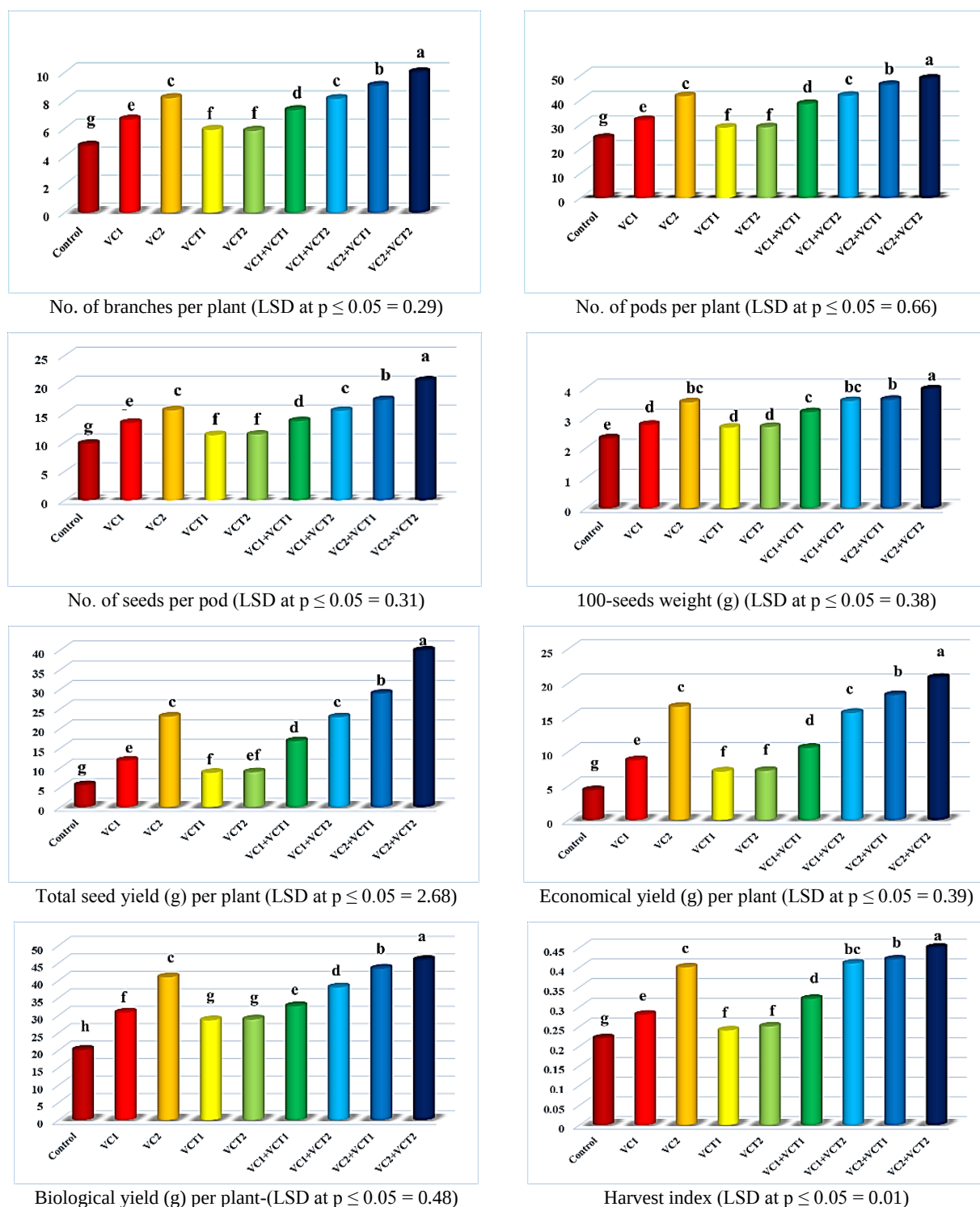


Figure 3: Effect of vermicompost and vermicompost tea treatments applied separately and in combination on yield characteristics of fenugreek plants at harvest time (138 DAS) during the 2021/2022 season.

Control*= Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, DAS= Days after sowing.



Figure 4: Effect of vermicompost and vermicompost tea treatments applied separately and in combination on yield characteristics of fenugreek plants at harvest time (138 DAS) during the 2022/2023 season.

Control*= Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, DAS= Days after sowing.

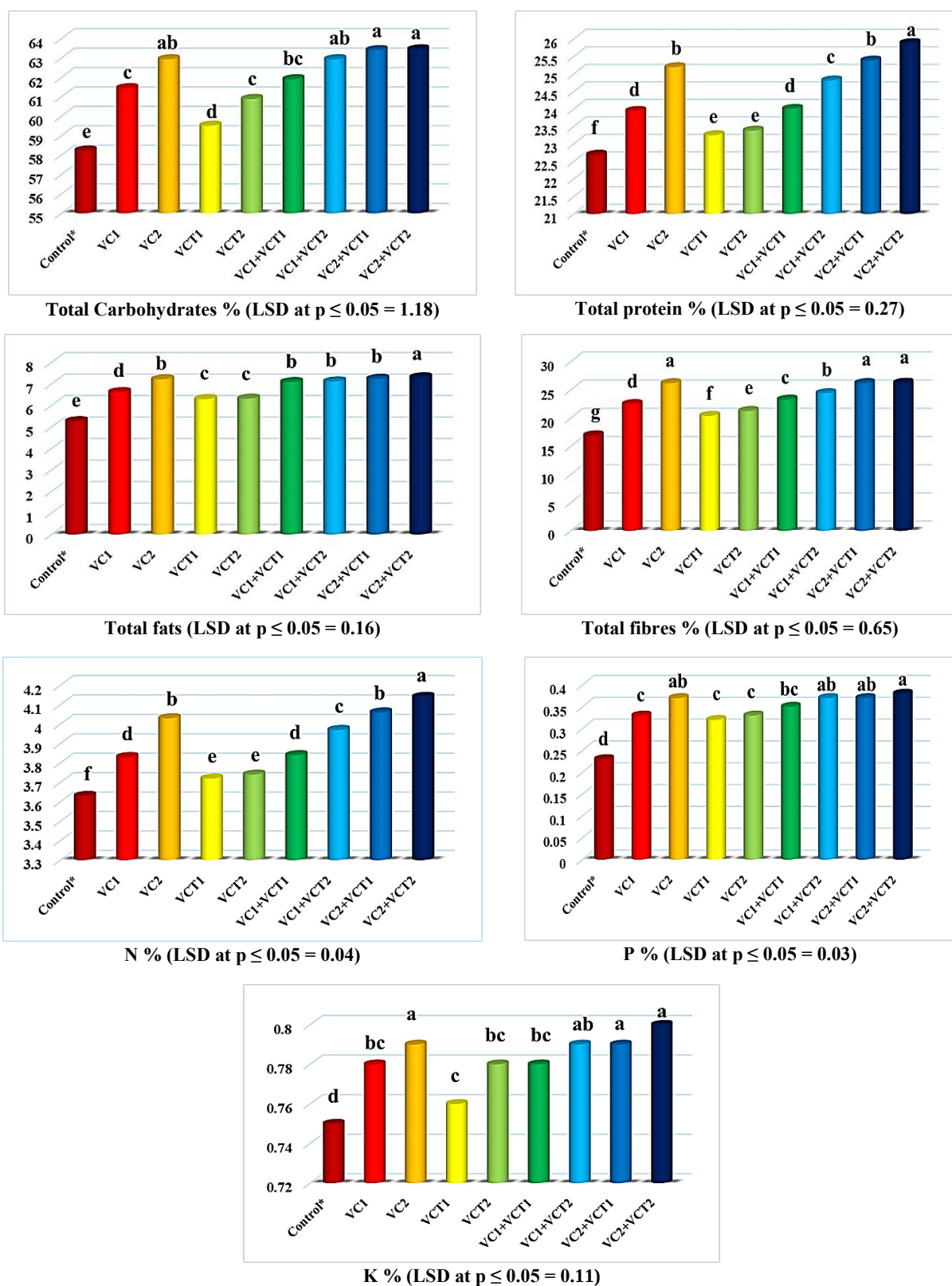


Figure 5: Effect of vermicompost and vermicompost tea treatments applied separately and in combination on certain bioconstituent and NPK concentrations $\text{g } 100\text{g}^{-1}$ in fenugreek seeds at harvest date (138 DAS) during the 2021/2022 season.

Control*= Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, DAS= Days after sowing.

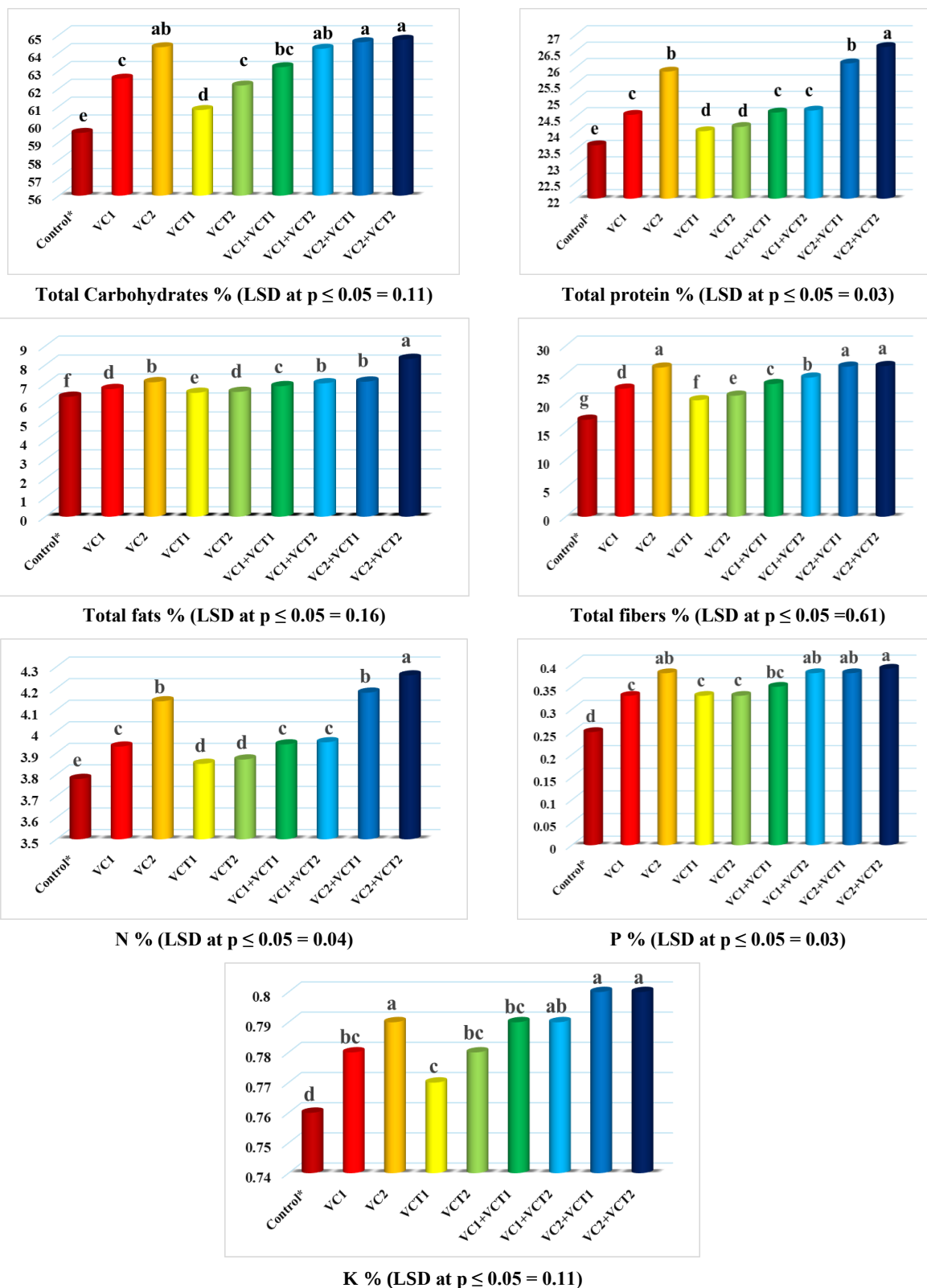


Figure 6. Effect of vermicompost and vermicompost tea treatments applied separately and in combination on certain bioconstituent and NPK concentrations $\text{g } 100\text{g}^{-1}$ in fenugreek seeds at harvest date (138 DAS) during the 2022/2023 season.

Control*= Control with 100% of the recommended NPK fertilizers, VC₁ = Vermicompost at 60 g per pot, VC₂ = Vermicompost at 120 g per pot, VCT₁ = Vermicompost tea applied as foliar spray 3 times, VCT₂ = Vermicompost tea applied as foliar spray 6 times, DAS= Days after sowing.

through enhanced mesophyll tissue and its distribution via phloem tissues to sink sites, such as developing pods and seeds. Previous studies have also emphasized the importance of enlarging phloem and xylem cross-sectional areas, alongside enhanced photosynthate production and nutrient uptake, to improve crop growth and productivity (Wanas, 2007; Taha *et al.*, 2021; Motawea, 2024; Wanas & Bazeed, 2025).

Our results also indicate that all individual and combined VC and VCT significantly elevated fenugreek seed yield and its constituents, such as number of branches and pods per plant, number of seeds per pod, and 100-seed weight, as well as biological and economical yields per plant. Similar results were reported by Saadatian *et al.* (2017), who evaluated the effects of vermicompost, vermiwash, and their combination on fenugreek. All organic treatments improved seed yield, pod length, pod freshness, and 1000-seed weight compared to the control, with vermicompost alone showing the greatest efficacy. Similarly, Abou El-Goud (2020) found that vermicompost applied at rates of 3.5 t/fed and 6.5 t/fed, with or without vermitea irrigation, significantly enhanced eggplant fruit yield and quality compared to the control. The highest yield was achieved with 6.5 t/fed of vermicompost combined with four vermitea applications.

The improvement of seed yield and its attributes through VC and VCT treatments can be attributed to their high content of macro- and micro-nutrients and organic matter, which ensures a gradual and sustained release of nutrients for plant uptake, thereby enhancing growth and productivity (Ratnasari *et al.*, 2023; Mohite *et al.*, 2024). The anatomical changes, particularly, the increased thickness of mesophyll and phloem tissues (Table 5 & Fig. 2), suggest enhanced photosynthate production and transport to sinks like branches, pods, and seeds. Additionally, a greater number of branches per plant typically results in more pods and seeds, increasing both economic and biological yields. Improved seed filling (100-seed weight) may result from better assimilate allocation and the mobilization of soluble stem reserves to developing seeds (Wanas & Bazeed, 2025). These biofertilizers are also rich in growth-promoting hormones like auxins, gibberellins, and cytokinins (Edwards *et al.*, 2006), which regulate cell division, expansion, and differentiation, as well as chlorophyll biosynthesis, delayed senescence, and enhanced mineral absorption (Taiz *et al.*, 2014). Cytokinins also promote branching and enhance assimilate supply to developing fruits (Wanas, 2007). These advantages complement the positive effects of these biofertilizers on soil properties, enabling the fenugreek plant to thrive and yield effectively.

Moreover, our study showed that individual and combined vermicompost (VC) and vermicompost tea (VTC) treatments significantly enhanced fenugreek seed quality by increasing levels of carbohydrates, proteins, fats, fibers, and specific macronutrients (NPK). These findings align with previous research on coriander (Sanwal *et al.*, 2017), eggplant (Abou El-Goud, 2020), and fenugreek (Al-Hadithi *et al.*, 2023). Fenugreek seeds typically contain 23-26% protein, 6-7% lipids, and 58% carbohydrates, with approximately 25% being dietary fiber (Wani & Kumar, 2018). They comprise both soluble and insoluble dietary fiber; soluble fibers dissolve in the digestive tract's aqueous environment, while insoluble fibers remain undigested (Nagulapalli Venkata *et al.*, 2017). The primary component of the soluble fiber wall is galactomannan, a polysaccharide found in the endosperm of fenugreek seeds. Galactomannans are among the most utilized polysaccharides by the human digestive tract after starch and cellulose (Ponzini *et al.*, 2019). These polysaccharides support liver health by aiding in the elimination of hepatotoxicity (Feki *et al.*, 2019). The high soluble fiber content in fenugreek seeds slows carbohydrate digestion and absorption (Mandal & Deb Mandle, 2016), potentially helping to reduce blood glucose levels.

The enhanced bioconstituent and nutrient content in fenugreek seeds can be attributed to improved vegetative growth, photosynthesis efficiency, nutrient uptake, and growth-promoting hormones due to the single and synergistic effects of VC and VCT (Wanas, *et al.*, 2025b). These treatments increased branch number, leading to more pods per plant, and enhanced photosynthetic efficiency and nutrient uptake. Anatomical improvements, such as increased mesophyll thickness and cross-sectional area of xylem and phloem, ensured a greater supply of assimilates and nutrients to developing pods, resulting in higher yields of high-quality seeds, with the combination of VC₂ (120 g/pot) and VCT₂ (six foliar sprays) being the most effective treatment.

5. Conclusion

It can be concluded that the combination of soil amendment with vermicompost (VC) and foliar application of vermicompost tea (VCT) exerts synergistic effects that substantially elevate fenugreek seed yield and quality, surpassing the individual treatments. Among the combinations tested, VC₂ plus VCT₂ emerged as the most effective. The observed enhancement is primarily attributed to the improved photosynthate creator (mesophyll tissue), photosynthate transporter (phloem), and route of water and nutrients (xylem), collectively ensuring a greater

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supply of assimilates and nutrients to developing pods. This led to higher yields of superior-quality seeds. Based on these findings, a practical recommendation is to apply vermicompost at 120 g per pot (VC₂) in combination with six foliar applications of vermicompost tea (VCT₂). This eco-friendly strategy not only boosts fenugreek productivity but is also potentially applicable to other medicinal plants seeking high-quality yields.

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