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Sustainable Bioproduction of Common Bean: Improving Sandy Soil Fertility, Yield and Seed Quality With Novel Organic Amendments

Muziri Mugwanya¹  | Fahad Kimera²  | Sakr M. Amna³ | Hussein H. Hadeer³ | Mohamed F. Salem⁴  | Hani Sewilam^{5,6} 

¹Centre for Applied Research on the Environment and Sustainability (CARES), The American University in Cairo, New Cairo, Cairo, Egypt | ²Centre for Applied Research on the Environment and Sustainability (CARES), The American University in Cairo, New Cairo, Cairo, Egypt | ³Organic Agriculture Research Unit, BioPyramids Biotech, Sadat, Menofia, Egypt | ⁴Department of Environmental Biotechnology, University of Sadat City, Sadat, Menofia, Egypt | ⁵Professor and Director, Centre for Applied Research on the Environment and Sustainability (CARES), The American University in Cairo, New Cairo, Cairo, Egypt | ⁶UNESCO Chair in Hydrological Changes and Water Resources Management, RWTH Aachen University, Aachen, North Rhine-Westphalia, Germany

Correspondence: Fahad Kimera (fkim@aucegypt.edu) | Hani Sewilam (sewilam@ifi.rwth-aachen.de)

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ABSTRACT

This study addresses the critical need for eco-friendly, sustainable nutrient sources to improve soil quality, crop yield and seed quality in newly reclaimed lands. The research investigated the effects of using microbial-based fertilisers (Nova Plus and Nova Q) co-applied with functional compost on sandy soil properties, growth, and seed quality of common bean (*Phaseolus vulgaris* L.). The experiment was conducted in a randomised complete block design (RCBD) with four treatments: the combined application (T1), functional compost only (T2), inorganic fertiliser (T3), and an unfertilised control (T4). Results showed that both organic treatments significantly enhanced soil quality. T1 and T2, respectively, exhibited the highest concentrations of organic matter (OM) (0.96% and 1.02%), nitrogen (98 and 136 mg/kg), and phosphorus (9.26 and 8.22 mg/kg). In terms of plant growth, T1 was superior, leading to better plant height (18.80 cm), leaflet area (55.70 cm²), chlorophyll content (SPAD 39.60), and a greater number of root nodules (25). However, yield data demonstrated that T2 achieved the highest pod weight (110 t/ha), followed by T1 (98.4 t/ha), T3 (55.70 t/ha), and T4 (52.30 t/ha), respectively. Furthermore, the combined application (T1) resulted in the highest seed quality, boosting protein (25%), nitrogen (3.77 mg/L), potassium (200.34 mg/L), and copper content (1.16 mg/L) compared to T3 and T4. In conclusion, the co-application of microbial-based fertilisers and functional compost successfully enhanced soil properties, yield, and common bean seed quality. This study uniquely establishes that organic production using functional compost can yield higher common bean outputs in sandy soils than conventional production.

1 | Introduction

Common beans (*Phaseolus vulgaris* L.) are one of the most economically important leguminous crops in developing countries due to their high protein, macro and micronutrient content, in addition to their rich content of fibre, vitamins, polyphenols, and

antioxidants [1, 2]. Compared with animal proteins, the lower market prices of common beans, their ease of production, and long storage shelf-life have made this crop an important nutritional delicacy in poor families [1, 3]. According to FAOSTAT [4], the global total dry bean production and area harvested stood at ~28.5 million tons and 37.8 million hectares, respectively, as of

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2023. As such, the production of dry beans and the area harvested have increased by 60% and 36%, respectively, since 1990. Asia is the leading producer of dry beans (43%), followed by the Americas (29%), Africa (26%) and Oceania (2%), respectively [4, 5]. In Egypt, dry bean production and area harvested as per 2023 stood at ~174,178 tons and 38,291 ha [4]. However, its production has been constrained by soil infertility, crop pests, and diseases [6]. In the last three decades, the production of dry beans has increased due to several factors such as the use of improved seed varieties and sustainable agronomical practices aimed at improving soil fertility, suppressing weeds, pest infestations, and plant pathogens, as well as maximising production with limited inputs [2, 7].

The application of microbial-based fertilisers and/or functional compost is among the most widely applied sustainable agronomical practices in organic agriculture, since this practice reduces the dependence on synthetic agrochemicals such as fertilisers, pesticides and herbicides that pollute the environment [8, 9]. Although *P. vulgaris* can minimise the risks related to the use of nitrogen fertilisers by naturally establishing an association with nitrogen-fixing bacteria [7, 10, 11], this does not always guarantee higher yields in the field, as this crop is considered to be poor at biological nitrogen fixation (BNF) [12]. Therefore, it is necessary to apply microbial-based fertilisers and/or functional compost to enhance the soil's nutrient efficiency to achieve optimum plant growth and yield [13–17].

Microbial-based fertilisers are defined as “the preparations containing live microbes that help in enhancing soil fertility by fixing atmospheric nitrogen, solubilising phosphorus or decomposing organic wastes or by elevating plant growth through the production of growth hormones with their biological activities.” [18]. The major aim of bio-fertilisation is to enhance the activities of beneficial microorganisms, which augment the bio-availability of nutrients (e.g., nitrogen, phosphorus and iron) that can easily be absorbed by plants, as well as improve the microbial profile of the rhizosphere [18–20]. Several genera, such as *Bacillus*, *Rhizobium*, *Pseudomonas*, *Clostridium*, *Glomus*, *Pezizella*, *Laccaria*, *Boletus*, *Azotobacter*, *Azospirillum*, and *Priestia*, among others, are regarded as the most widely used microbes in microbial-based fertilisers [19, 21, 22]. Previous studies have shown that inoculation of plants with beneficial microbes alone or in combination with organic and inorganic fertilisers, as well as soil amendments, improves the rhizosphere microbial profile, nutrient availability, and plant growth in *Solanum lycopersicum* [23–26], *P. vulgaris* [27–30], *Cucumis sativus* [31–34], *Oryza sativa* [35–38] and *Zea mays* [39–42].

The potential of compost from different raw materials as an organic fertiliser that enhances the soil nutrient content and plant production has been widely studied. For example, Al-Tawara et al. [43] studied the growth response of *P. vulgaris* as affected by two different types of organic fertilisers, vermicompost and compost, applied at different application rates. The authors reported superior vegetative growth and yield in plants treated with 50%–100% vermicompost compared with the lower application rates. Pellejero et al. [44] investigated the potential of mixtures of onion residue compost and bovine manure as an organic fertiliser for *Solanum lycopersicum* L. The authors observed improved plant growth and yield at the application rates of 60 and 80 Kg/ha. These yields were similar to those observed in the chemical treatment, whereas the control treatment recorded the lowest yield. In another study, Hasnain et al.

[45] elucidated changes in soil physiochemical properties and plant growth of *S. lycopersicum* after the application of a mixture of cow manure compost and inorganic fertilisers at different application times. The authors demonstrated that applying a mixture of chemical fertiliser and cow manure compost at 30% and 70%, respectively, improved the soil nutrient composition (i.e., available nitrogen, phosphorus, and organic matter [OM]) as well as plant growth and yield. However, Wu et al. [46] observed that applying a mixture of 75% chemical fertiliser and 25% cow manure improved the soil's physiochemical properties, the microbial nitrification process, and plant growth compared with 100% cow manure.

It is worth noting that composting of OM (i.e., manure or poultry litter) from different sources reduces the risk of soil pollution with pesticide and antibiotic residues, antibiotic resistance genes (ARGs), and proliferation of pathogenic microorganisms, which would hamper plant growth and development [47]. Different composting techniques have been used to remove contaminants such as pesticides and antibiotic residues, break down ARGs, destroy pathogenic microbes, and enrich the treated compost with beneficial microorganisms and nutrients aimed at improving soil health and plant production [48–51]. For instance, Sun et al. [52] demonstrated that adding cellulases during composting improved the rate of decomposition of spent mushroom substrate, compost quality, and microbial structure and composition. Similarly, Hu et al. [53] observed that adding cellulase-degrading microorganisms during the co-composting process of spent mushroom substrate and swine manure led to a decrease in ARGs and mobile genetic elements. Moreover, the treatment led to improved microbial structure and compost quality. Given the importance of enriching compost with beneficial microorganisms, this led us to use functional compost to break down antibiotic residues and ARGs, hence converting it into a functional suppressive compost. Likewise, we hypothesise that our composting process ensured the bioavailability of sulphur and phosphorus by the action of certain microbes present in microbial-based fertilisers. This is important given the fact that sandy soils are usually deficient in sulphur and phosphorus, among other essential nutrients. This is attributed to the low OM content and leaching in coarse-textured sandy soils [54]. To the best of our knowledge, no prior research has directly compared the yield of common beans grown in sandy soils using conventional methods against the combined application of functional compost and microbial-based fertilisers. This knowledge gap directly motivated the specific objectives of this investigation, which are:

To improve the OM content of sandy soils via the application of functional compost alone or in combination with microbial-based fertilisers.

Enhancing the bioavailability of key elements (nitrogen, phosphorus, potassium and sulphur) in sandy soils via the co-application of functional compost with microbial-based fertilisers.

Assessing the yield and seed quality of common beans (*P. vulgaris*) cultivated under our experimental conditions.

This is a proof-of-concept study aimed at the sustainable bioproduction of common beans in sandy soils, and the study results will be of great benefit to policymakers and farmers in newly reclaimed lands.

TABLE 1 | Biochemical constituents of Nova Plus and Nova Q.

Nova Plus				
Zn	Fe	Mg	S	Organic acids
1%	2%	1%	2.22%	8%

Nova Q				
Zn	Fe	Mg	S	Organic acids
1%	2%	1%	1.65%	10%

Note: Elements: Zn: zinc, Fe: iron, Mg: magnesium, and S: sulphur.

2 | Materials and Methods

2.1 | Experimental Setup

Phaseolus vulgaris L. seeds were obtained from the Agricultural Research Centre (ARC) in Giza, Egypt. A field trial was conducted at the Centre for Applied Research on the Environment and Sustainability, The American University in Cairo, New Cairo, Egypt (30° 01' 11.7"N 31°29' 59.8"E). The experiment was conducted between November 2022 and April 2023 and followed a randomised complete block design (RCBD) with four treatments and three replications namely, T1: a combination of Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, and T4: No fertiliser (control). The size of each experimental plot was 3 m x 4 m, and seeds were planted in rows with an inter- and intra-row spacing of 20 and 60 cm, respectively. The plots had been previously cultivated with onions.

Organic fertilisers (functional compost) were applied at the rate of 8000 kg/ha [55, 56] in T1 and T2. For inorganic fertilisers (T3), phosphorus was added before sowing at the rate of 95 kg/ha as calcium superphosphate (Ca(H₂PO₄)₂ · H₂O), nitrogen (N) was added at a rate of 143 kg N/ha as ammonium nitrate (33.5% N),

and potassium (K) was added at the rate of 143 kg K₂O/ha as potassium sulphate (48% to 50% K₂O). Continuous fertilisation with N and K fertilisers was carried out in three equal doses at 15, 35 and 50 days after sowing (DAS), as per the recommendations of the Egyptian Ministry of Agriculture [57]. Nova Plus was sprayed on the plants in the early morning once a week at the rate of 5/100 L of water. At the flowering stage, another foliar application of Nova Q was conducted in the early morning at the rate of 1/ 30 L of water once a week in treatment plots for T1. Table 1 summarises the biochemical constituents of Nova Plus and Nova Q. Weather data recorded during the experimental period are presented in Figure 1.

Soil samples were obtained at the beginning of the study and taken to the Soils, Water and Environment Research Institute (SWERI) at the ARC for analysis of the physiochemical parameters (electroconductivity [EC], pH, particle size distribution, available anions and cations and macroelements) as described by Kimera et al. [58]. Table 2 shows the physical and chemical properties of the soil sample.

2.2 | Compost Preparation and Analysis

The compost was prepared by co-composting 400 kg of sugarcane mud + 20 L NovaPlus + 40 kg Sulphur + 20 kg Superphosphate. The composting process took 28 days under anaerobic and acidic (pH 5.6–5.8) conditions. Elemental analysis of the compost sample was done using coupled plasma–optical emission spectrometry (ICP–OES). Briefly, 350 mg of the sample was obtained and digested using nitric acid (69%) in a microwave (speedwave, Berghof Products + Instruments Ltd, Eningen, Germany). Certified reference material matching the sample matrix and blank samples was included in each run. The digested samples were diluted to 50 mL with ultrapure water (Milli-Q Element, Millipore, Merck KGaA, Darmstadt, Germany) and stored at room temperature until analysis. Nutrient composition analysis was performed with ICP-OES. The modified Baermann funnel technique was

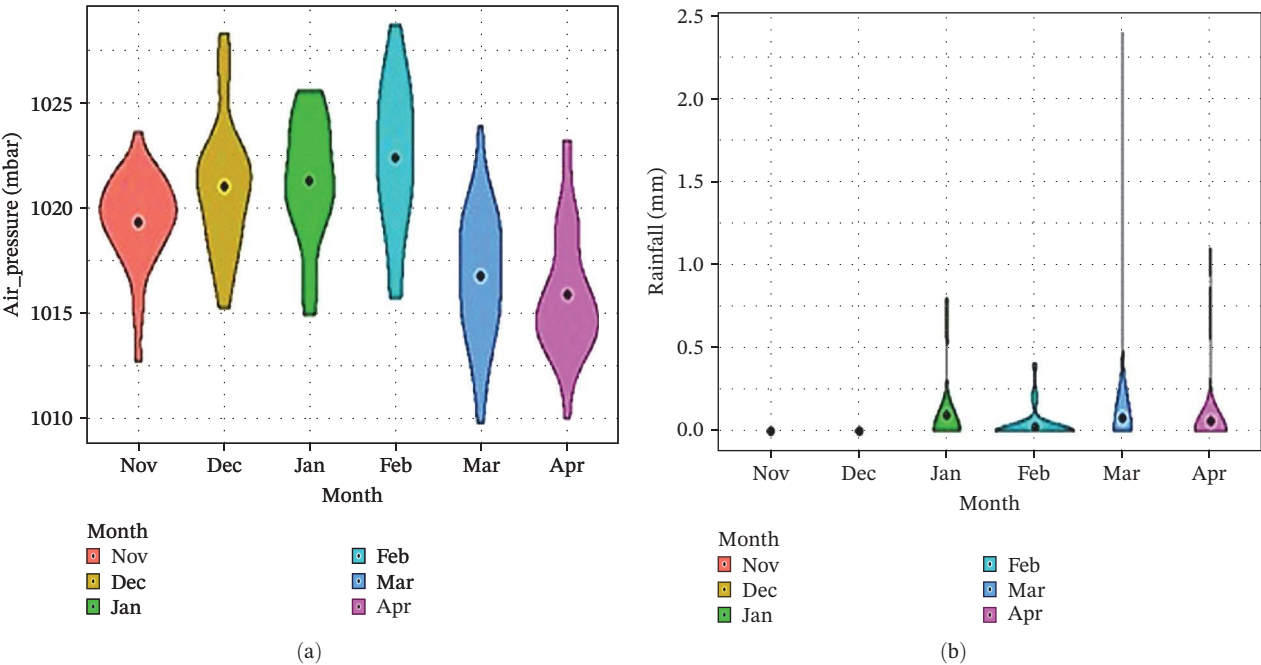


FIGURE 1 | (Continued)

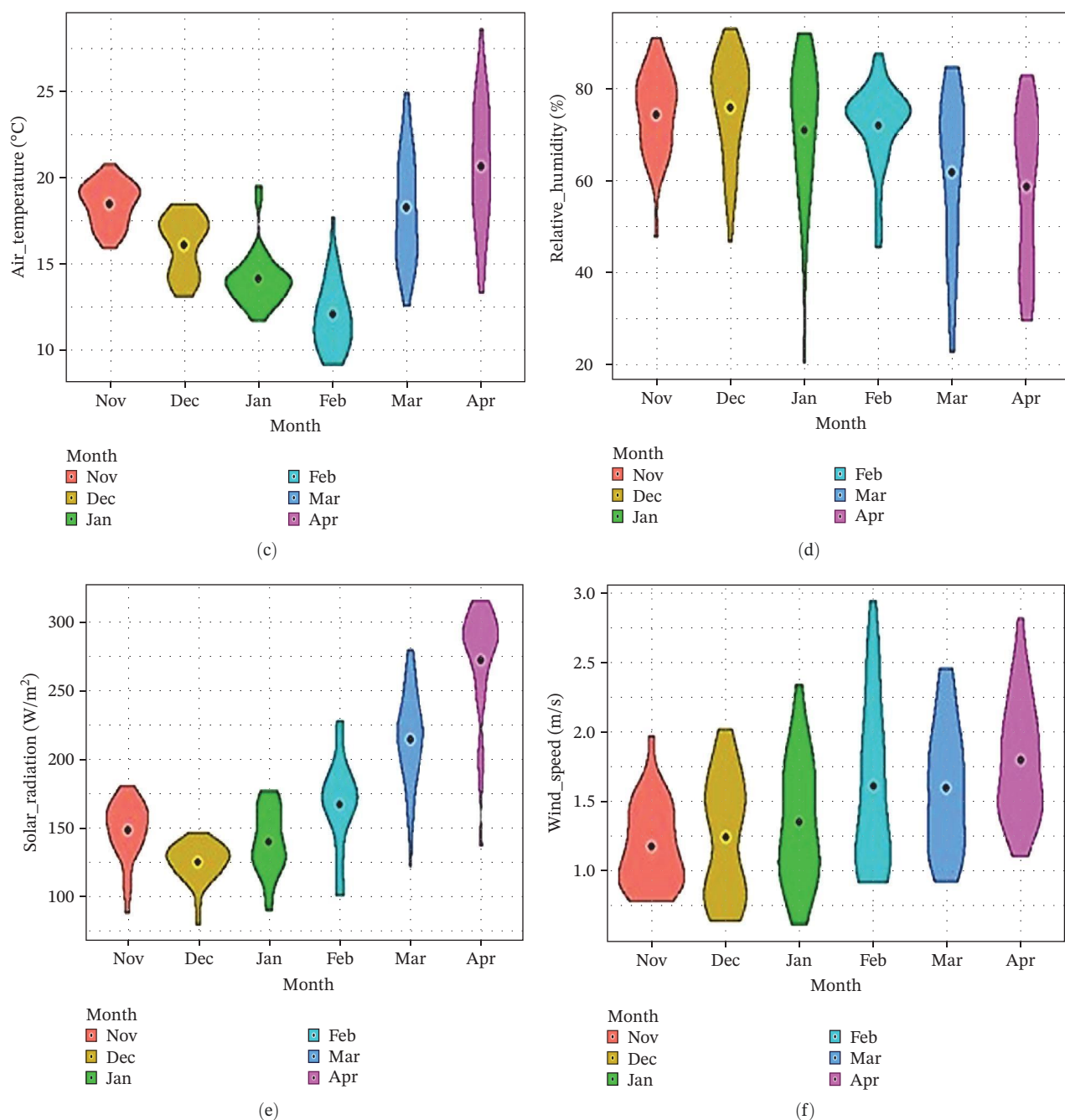


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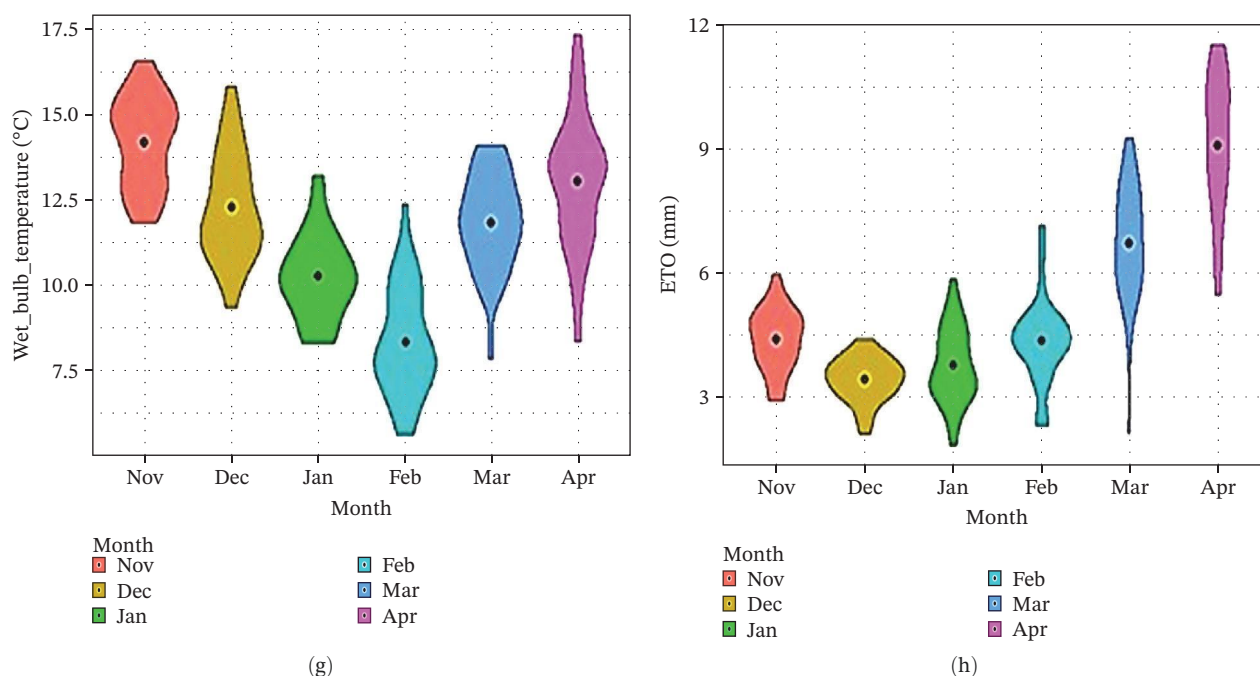


FIGURE 1 | Violin plots of Mean weather parameters were recorded throughout the experimental period (a) air pressure, (b) rainfall, (c) air temperature, (d) relative humidity, (e) solar radiation, (f) wind speed, (g) wet bulb temperature and (h) evapotranspiration. Black dots represent the mean values.

TABLE 2 | Soil physical and chemical properties of the saturated soil paste before sowing.

pH	EC (dS/m)	SP	HCO ₃ ⁻ (meq/L)	Cl ⁻ (meq/L)	SO ₄ ²⁻ (meq/L)	Cu ²⁺ (meq/L)	Zn ²⁺ (meq/L)	Fe ²⁺ (meq/L)	N (mg/kg)	P (mg/kg)	K (mg/kg)
9.09	0.52	25	0.50	3.5	1.17	0.32	1.18	1.02	63	7.92	45.5

Note: Anions: HCO₃⁻: hydrogen carbonate, Cl⁻: chloride, SO₄²⁻: sulphate. Cations: Cu²⁺: copper, Zn²⁺: zinc, and Fe²⁺: iron. Macro elements: N: nitrogen, P: phosphorus, and K: potassium.

Abbreviations: EC, electroconductivity; SP, particle size distribution.

used to detect nematode larvae in the compost. Table 3 summarizes the results of the chemical and biological analysis of functional compost.

2.3 | Plant Growth Parameters

For data collection, five uniformly developed plants were randomly selected and tagged from each replicate within every treatment group at 30, 60 and 90 DAS. Plant height was measured from the base (crown) to the topmost growing point using a standard metre rule. The number of leaves per plant was counted, and the mean values were calculated. Leaflet area was assessed using a CI-202 Portable Laser Leaf Area Meter (CID Bio Science, Washington, USA). Chlorophyll content was measured in the evening using an MC-100 chlorophyll metre (Apogee Instruments, Inc., Utah, USA), with results expressed as average SPAD values. Root nodules were counted per plant, and the average number was recorded.

At harvest, pods were collected from each tagged plant, counted, and averages determined. Likewise, the pod length and diameter were measured using digital vernier callipers. Pod weight, leaf fresh weight (LFW), stem fresh weight (SFW) and root fresh weight (RFW) were determined using a laboratory weighing balance, after which the samples were oven-dried at 70°C for 72 h to constant weight to obtain the dry weights.

TABLE 3 | Chemical and biological properties of functional compost used in the study.

Constituents	Value
Weight of cubic metre	370 kg/m ³
Humidity	36%
pH (1:10)	7.89
EC (1:10)	7.99 ds/m
Ammonium Nitrogen	7.99 ppm
Nitrate Nitrogen	48 ppm
C/N ratio	14:1
Organic matter	60.96%
Ash	39.04%
Total nitrogen	2.52%
Total phosphorus (P ₂ O ₅)	1.68%
Total potassium	0.87%
Percentage of weeds	Not found
Larvae (nematodes)	Not found

Note: C: carbon, N: nitrogen.

Abbreviation: EC, electroconductivity.

2.4 | Soil Analysis

Soil samples per treatment per replicate were collected at a depth of 30 cm and pooled for the soil physical and chemical properties analysis. The samples were taken to the Soil and Water Analysis Institute of the ARC in Giza, Egypt. As described by Kimera et al. [58] soil particle size distribution was analysed using the pipette technique. EC was determined from the extract of a saturated soil paste, while soil pH was measured in a 1:2.5 soil-to-water suspension. Available nitrogen was extracted using a 1:10 ratio of soil to potassium chloride (5 g soil to 50 mL KCl) and quantified via the micro-Kjeldahl method. Potassium availability was assessed using a flame photometer, and concentrations of other elements were measured using inductively coupled plasma (ICP) spectrometry (Ultima 2 JY Plasma model) [59].

2.5 | Seed Nutrient Analysis

At harvest, seeds of *Phaseolus vulgaris* L. per treatment per replicate were collected and immediately stored at -20°C until further analysis. Seeds were crushed with a blender, and protein quantification was conducted using the Kjeldahl technique. For mineral elements, 300 mg of the sample per replicate per treatment was obtained and microwave digested, and the mineral element analysis was conducted using the ICP mass spectrometry as previously described by Mugwanya et al. [60].

2.6 | Ureide and Leghemoglobin (LHb) Measurements

The ureide-N concentration was analysed by the calorimetric technique as described by Goos et al. [61] whereas LHb concentration in nodules was assayed spectrophotometrically (540 nm) using a Drabkin solution as the “blank” [62].

2.7 | Statistical Analysis

Statistical analysis was conducted using R Statistical Programming Language (version 4.3.2). Datasets were tested for normality and equality of variances using QQ-plots and Levene’s test, respectively. Analysis of variances (ANOVA) was conducted to detect significant differences among means. Fisher’s LSD test was applied to determine the differences in treatment means at $\alpha = 0.05$. Datasets were normalised to compute Pearson correlation coefficients and the principal component analysis (PCA) to determine the linear relationship between the dependent variables and to explain the variance of the dependent variables. Plots were generated using Microsoft Excel and the ggplot package of the R software.

3 | Results

3.1 | Soil Physical and Chemical Properties

Data on the physical and chemical properties of the soil are presented in Table 4. Results of this study indicate that the soil pH ranged between 8.4 and 8.5. The EC of the saturated soil paste was higher in the T4 treatment compared with other treatments. Likewise, chloride and sodium ion concentrations were higher in the T4 than in other treatments. However, the OM content was lower in the T4 compared with other treatments. The available soil macro and micronutrients are presented in Table 5. Results of this study showed a high concentration of nitrogen in T2, followed by T1, T4 and T3, respectively. The concentration of phosphorus and potassium was higher in treatment T1 compared with other treatments. However, the lowest concentration of iron was recorded in this treatment.

TABLE 4 | Chemical analysis of saturated soil pastes and organic matter at harvest.

Treatment	pH	EC (dS/m)	SP	HCO ₃ [−] (meq/L)	Cl [−] (meq/L)	SO ₄ ^{2−} (meq/L)	Ca ²⁺ (meq/L)	Mg ²⁺ (meq/L)	Na ⁺ (meq/L)	K ⁺ (meq/L)	OM (%)
T1	8.5	0.84	22.00	0.50	5.50	2.38	2.00	1.50	4.70	0.18	0.96
T2	8.4	0.92	21.00	0.50	5.50	3.17	2.50	1.50	5.00	0.17	1.02
T3	8.4	0.88	22.00	0.50	5.50	2.78	2.50	1.50	4.60	0.18	0.60
T4	8.5	1.01	22.00	0.50	6.50	3.07	2.50	1.50	5.75	0.32	0.59

Note: Anions; HCO₃[−]: hydrogen carbonate, Cl[−]: chloride, SO₄^{2−}: sulphate. Cations; Ca²⁺: calcium, Mg²⁺: magnesium, Na⁺: sodium, and K⁺: potassium. OM: organic matter content. Treatments: T1: Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

Abbreviations: EC, electroconductivity; SP, saturation point.

TABLE 5 | Available soil macro and micronutrient content.

Treatment	N (mg/kg)	P (mg/kg)	K (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)
T1	98.00	9.26	107.00	6.45	0.92	4.47	0.04
T2	136.00	8.22	26.00	9.37	1.16	5.90	0.03
T3	41.00	6.98	26.00	10.42	0.70	5.47	0.04
T4	60.00	6.64	26.00	11.34	1.35	6.03	0.05

Note: Macro and micronutrients: N: nitrogen, P: phosphorus, K: potassium, Fe: iron, Zn: zinc, Mn: manganese, Cu: copper. Treatments: T1: Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

3.2 | Plant Growth Parameters

Plant growth parameters on plant height, leaf number, leaf area, and chlorophyll content (SPAD) were recorded at 30, 60 and 90 DAS (Table 6). At 30 DAS, the T4 significantly ($p < 0.05$) recorded lower values for plant height, leaf number, leaf area and SPAD compared with other T3, T2 and T1 fertiliser treatments. Data at 60 DAS indicated that the T4 significantly ($p < 0.05$) recorded lower values for plant height, leaf number, and leaflet area compared with other treatments. However, no significant differences in SPAD values were noted across other treatments except for T1. At 90 DAS, the results of this study showed that T4 significantly ($p < 0.05$) recorded lower values for plant height, leaf number, and leaflet area compared with other treatments. No significant differences in SPAD values were noted across all treatments.

Pearson's correlation analysis of plant growth parameters is shown in Figure 2. Strong and Positive correlations were noted between SPAD and leaflet area ($r = 0.926$), SPAD and plant height ($r = 0.976$), and SPAD and leaf number ($r = 0.999$). Likewise, strong and positive correlations were noted between leaflet area and plant height ($r = 0.986$), leaflet area and leaf number ($r = 0.975$), as well as plant height and leaf number ($r = 0.999$).

3.3 | Yield Parameters

Table 7 presents the yield performance of *Phaseolus vulgaris* under various treatment conditions. The findings revealed that Treatment 1 (T1) produced significantly higher values ($p < 0.05$) for both the number of pods and the weight of 1000 seeds compared to the other treatments. In contrast, no statistically significant

differences were observed among treatments for pod length, pod diameter, or pod weight.

LFW, SFW and RFW and dry weights are presented in Figure 3. Both T4 and T3 significantly ($p < 0.05$) recorded the lowest values for LFW (Figure 3a) and SFW (Figure 3b) compared with other treatments. However, there was a variation in the LDW and SDW, with T1 significantly ($p < 0.05$) recording higher values than T3. T3 significantly ($p < 0.05$) recorded lower values for RFW than T2. However, no significant differences were noted in the root dry weight (RDW) (Figure 3d) across other treatments.

Figure 4 presents harvest-stage data. Treatments T3 and T4 showed significantly lower pod fresh and dry weights (Figures 4a,b) compared to other treatments ($p < 0.05$). The root-to-shoot ratio was highest in T4, significantly differing from other treatments except T3 (Figure 4c). No significant differences were observed in the number of root nodules per plant across treatments (Figure 4d).

3.4 | PCA of Yield and Growth Parameters

The changes in yield and plant growth parameters were investigated by a PCA as shown in Figure 5. PC1 and PC2 explained 41.1% and 13.6% of the total variance, respectively. T2 and T3 share similarities in yield and plant growth parameters compared with T1. Likewise, T3 and T4 share similarities in certain plant growth parameters (i.e., root–shoot ratio), showing an opposite behaviour to other treatments. The positive and negative correlation of variables is shown in Figure S1. The PCA biplots indicated no similarities in yield and plant growth parameters were shared between T1 and T2, T1 and T3, T1 and T4, and T2 and T4.

TABLE 6 | Plant growth parameters of *Phaseolus vulgaris* cultivated under different treatments.

Treatments	Plant height (cm)	Leaf no/plant	Leaflet area (cm ²)	SPAD
30DAS				
T1	10.10 ^a ± 1.11	4.47 ^a ± 0.83	45.70 ^a ± 9.01	36.40 ^a ± 4.25
T2	9.43 ^a ± 1.51	4.40 ^a ± 0.63	41.90 ^{ab} ± 6.03	37.90 ^a ± 3.41
T3	7.93 ^{ab} ± 1.43	3.73 ^{ab} ± 0.59	34.60 ^{bc} ± 6.65	34.90 ^{ab} ± 4.44
T4	7.30 ^b ± 1.11	3.60 ^b ± 0.63	30.70 ^c ± 6.04	31.80 ^b ± 3.55
60 DAS				
T1	18.20 ^a ± 1.28	13.30 ^a ± 1.75	54.30 ^a ± 7.14	45.80 ^a ± 3.80
T2	16.50 ^b ± 2.11	11.70 ^{ab} ± 2.50	52.90 ^a ± 9.67	41.70 ^b ± 3.84
T3	13.50 ^c ± 1.91	10.70 ^{bc} ± 1.71	36.40 ^b ± 3.31	38.70 ^b ± 3.51
T4	12.70 ^c ± 2.31	9.80 ^c ± 1.74	37.40 ^b ± 5.54	39.10 ^b ± 3.46
90 DAS				
T1	18.80 ^a ± 2.60	13.20 ^a ± 1.97	56.70 ^a ± 7.99	39.60 ^a ± 6.82
T2	16.50 ^a ± 3.08	12.10 ^a ± 2.07	55.50 ^a ± 11.70	33.10 ^a ± 5.58
T3	12.90 ^b ± 2.23	10.10 ^b ± 2.31	41.40 ^b ± 10.40	33.20 ^a ± 7.59
T4	10.90 ^b ± 3.10	9.33 ^b ± 2.35	34.50 ^b ± 6.79	32.70 ^a ± 6.43

Note: Data is expressed as mean ± SD. Mean values within the same column having different lower superscript letters at the same time points are significantly different ($p < 0.05$). Treatments: T1: Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

Abbreviation: DAS: days after sowing.

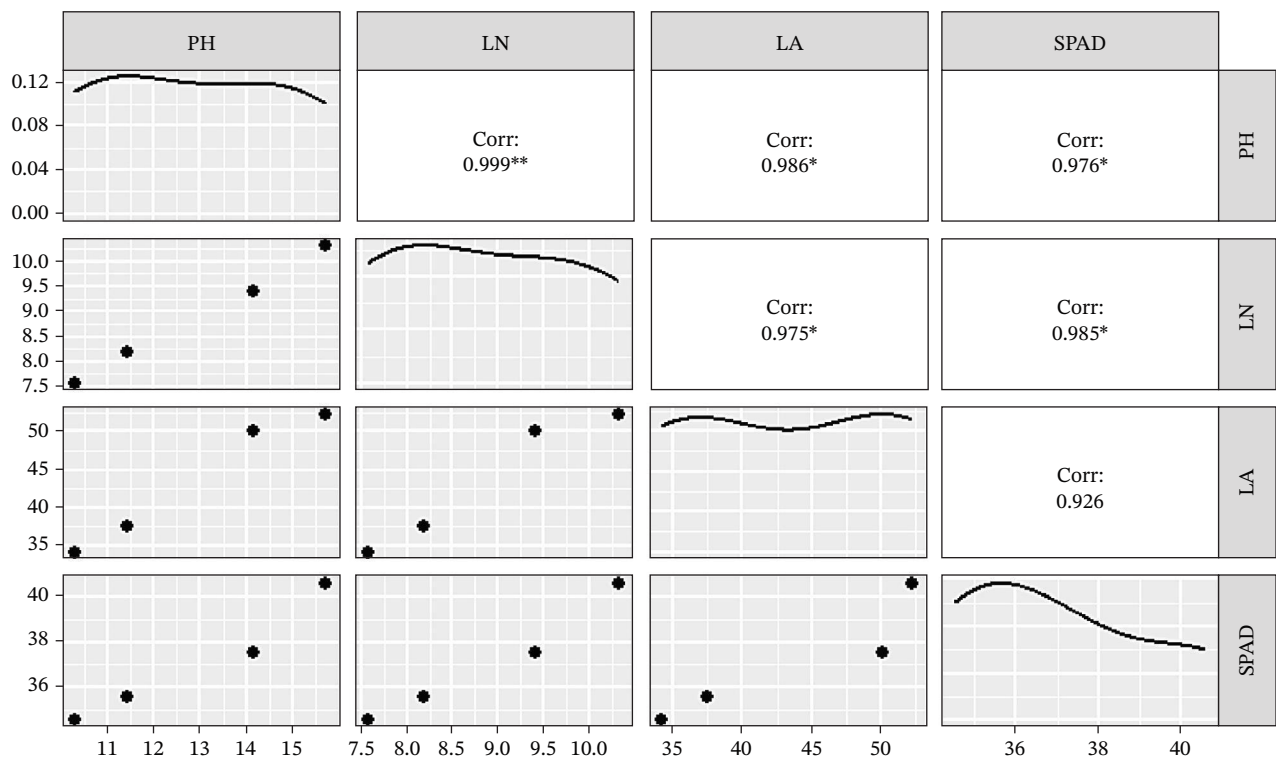


FIGURE 2 | Pearson correlation analysis of plant growth parameters. A plus and a minus sign, respectively, indicate the positive and negative correlations. Significance levels: * $p<0.05$, ** $p<0.01$, and *** $p<0.001$. LA, leaflet area; LN, leaf number; PH, plant height; SPAD, leaf chlorophyll content.

TABLE 7 | Yield parameters of *Phaseolus vulgaris* cultivated under different treatments.

Treatment	Pod No/plant	Pod length (mm)	Pod diameter (mm)	Pod weight (t/ha)	1000 seeds weight (g)
T1	9.00 ^a ± 2.67	129.00 ^a ± 8.49	12.90 ^a ± 0.93	98.40 ^a ± 14.40	687.00 ^a ± 10.00
T2	7.60 ^{ab} ± 1.30	130.00 ^a ± 8.80	12.80 ^a ± 0.63	110.00 ^a ± 7.10	567.00 ^d ± 36.10
T3	5.60 ^b ± 1.76	122.00 ^a ± 12.30	12.50 ^a ± 0.83	55.70 ^a ± 10.40	570.00 ^{cd} ± 8.66
T4	5.73 ^b ± 1.87	121.00 ^a ± 7.42	12.20 ^a ± 0.70	52.30 ^a ± 6.00	583.00 ^{bd} ± 26.50

Note: Data is expressed as mean ± SD. Mean values within the same column having different lower superscript letters are significantly different ($p<0.05$). Treatments: T1: Nova Plus, Nova Q and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

3.5 | Pearson Correlation Analysis of Yield and Biomass Parameters

Pearson correlation analysis of the yield and biomass parameters is presented in Figure 6. Significantly strong and positive

correlations were noted between pod width and pod length ($r=0.996$), LFW and pod length ($r=0.990$), SFW and pod length (0.992), SDW and pod length (0.992), leaf dry weight (LDW) and pod diameter ($r=0.980$), LFW and pod width ($r=0.979$), SFW

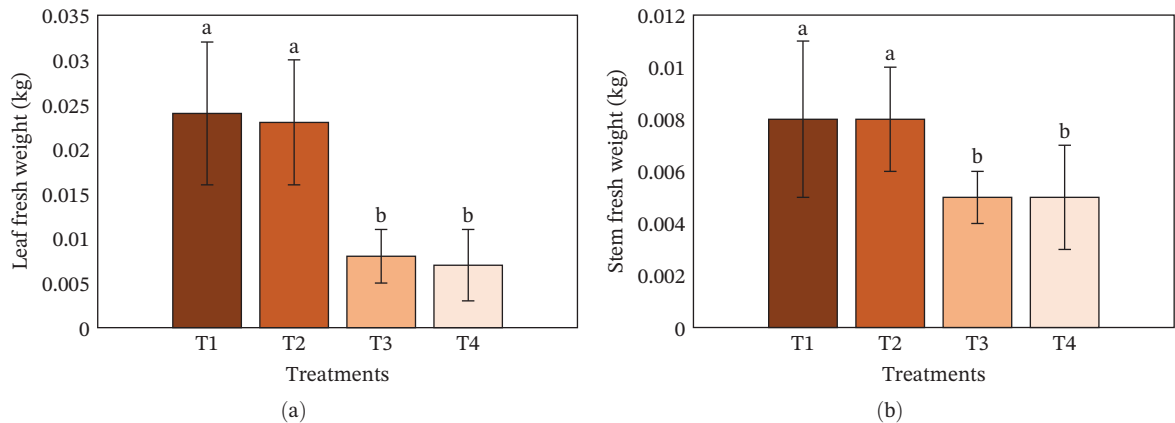


FIGURE 3 | (Continued)

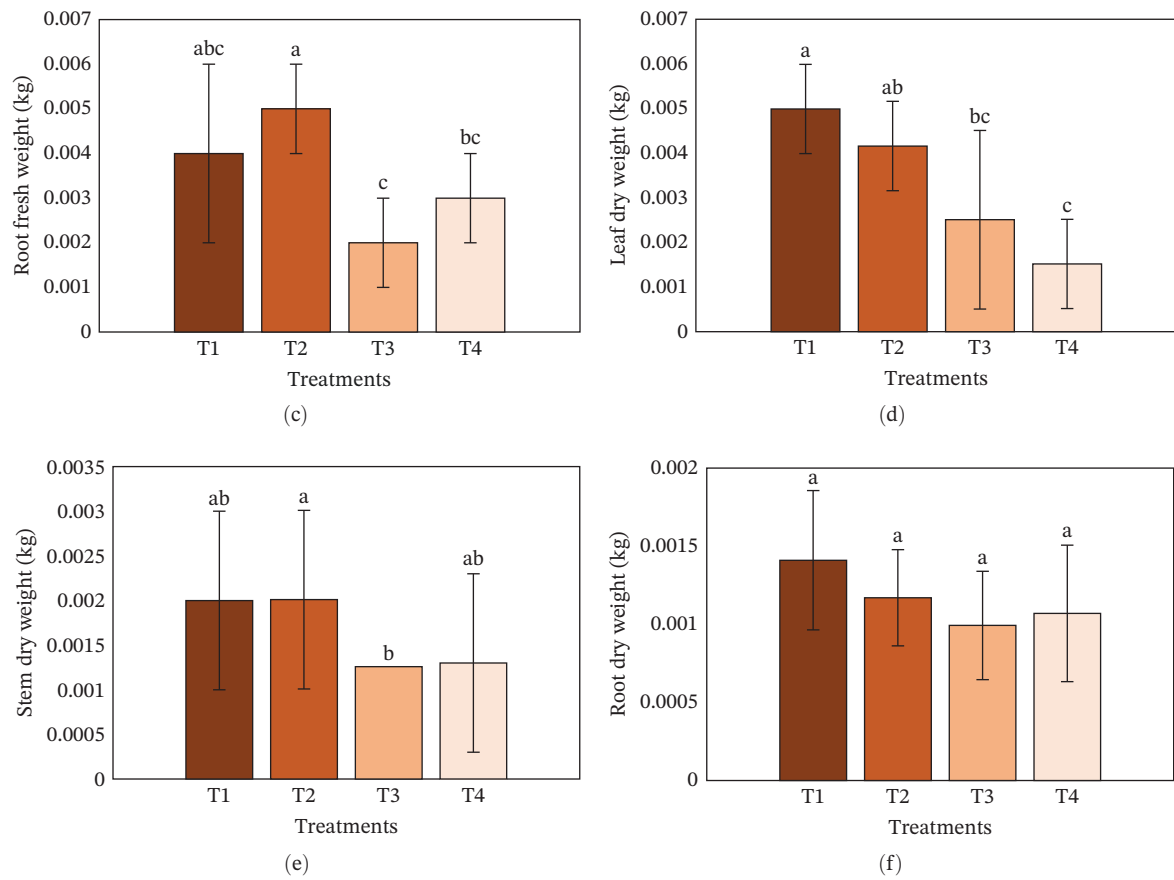


FIGURE 3 | Biomass measurements of *Phaseolus vulgaris* under different treatment conditions, including: (a) Leaf fresh weight, (b) Stem fresh weight, (c) Root fresh weight, (d) Leaf dry weight, (e) Stem dry weight, and (f) Root dry weight. Values are presented as mean $\pm$ standard deviation (SD). Error bars indicate SD, and bars labelled with different letters denote statistically significant differences at $p < 0.05$. The treatments were as follows: T1: Nova Plus, Nova Q, and functional compost, T2: Functional compost only, T3: Inorganic fertiliser and T4: No fertiliser.

and pod width ($r = 0.986$), SDW and pod width ($r = 0.986$), SFW and LFW ($r = 0.998$), SDW and LFW ($r = 0.998$), SDW and SFW ($r = 1.000$).

3.6 | Seed Nutrient Content

The protein content of the seeds of *Phaseolus vulgaris* is shown in Figure 7. The protein content of seeds ranged from 18.76% to 25.32%, with T1 significantly ($p < 0.05$) recording the highest

values, followed by T2, T4 and T3, respectively. No significant differences in the protein content were noted between T2 and T4.

The nitrogen concentration in seeds varied between 3.02% and 3.77%, with treatment T1 showing a significantly higher value ($p < 0.05$), followed by T2, T4 and T3 (Figure 8a). Potassium levels were significantly higher in T1 and T2 compared to T3 and T4, while T4 also showed a significantly greater potassium content than T3 (Figure 8b). Magnesium content ranged from 8.61 to 14.17 mg/L, with T3 exhibiting significantly higher levels than

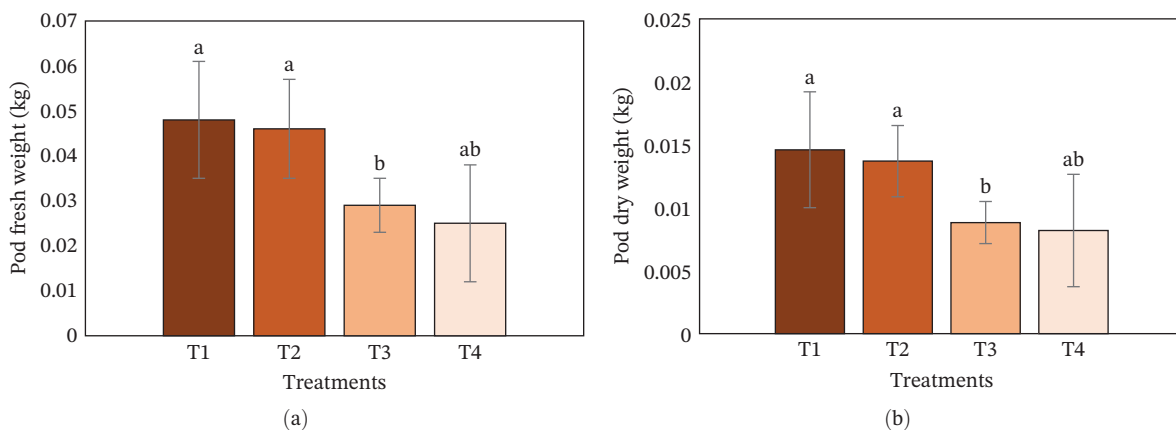


FIGURE 4 | (Continued)

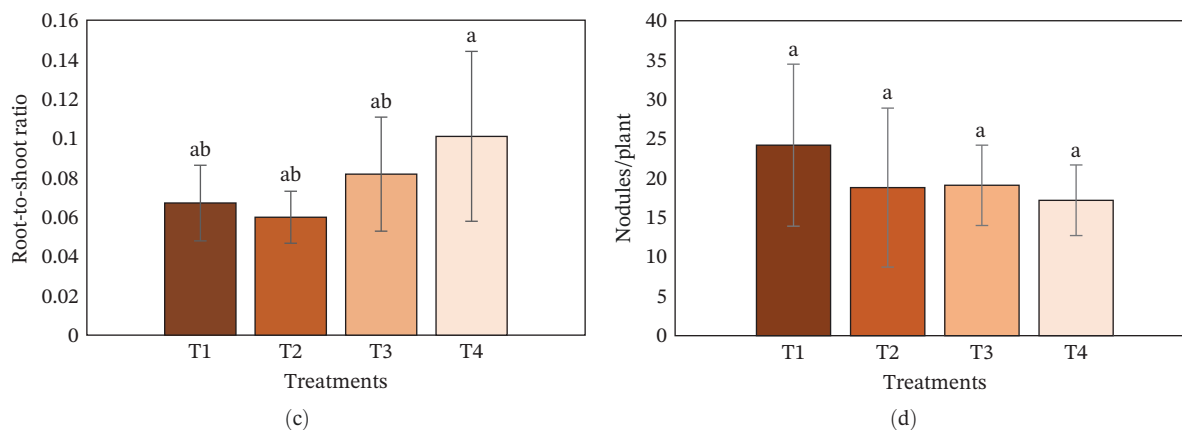


FIGURE 4 | Harvest metrics for *Phaseolus vulgaris* under various treatment conditions: (a) Fresh pod weight, (b) Dry pod weight, (c) Root-to-shoot ratio, and (d) Number of nodules per plant. Values are presented as mean $\pm$ standard deviation (SD). Error bars indicate SD. Bars marked with different letters denote statistically significant differences at $p < 0.05$. Treatments; T1: Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

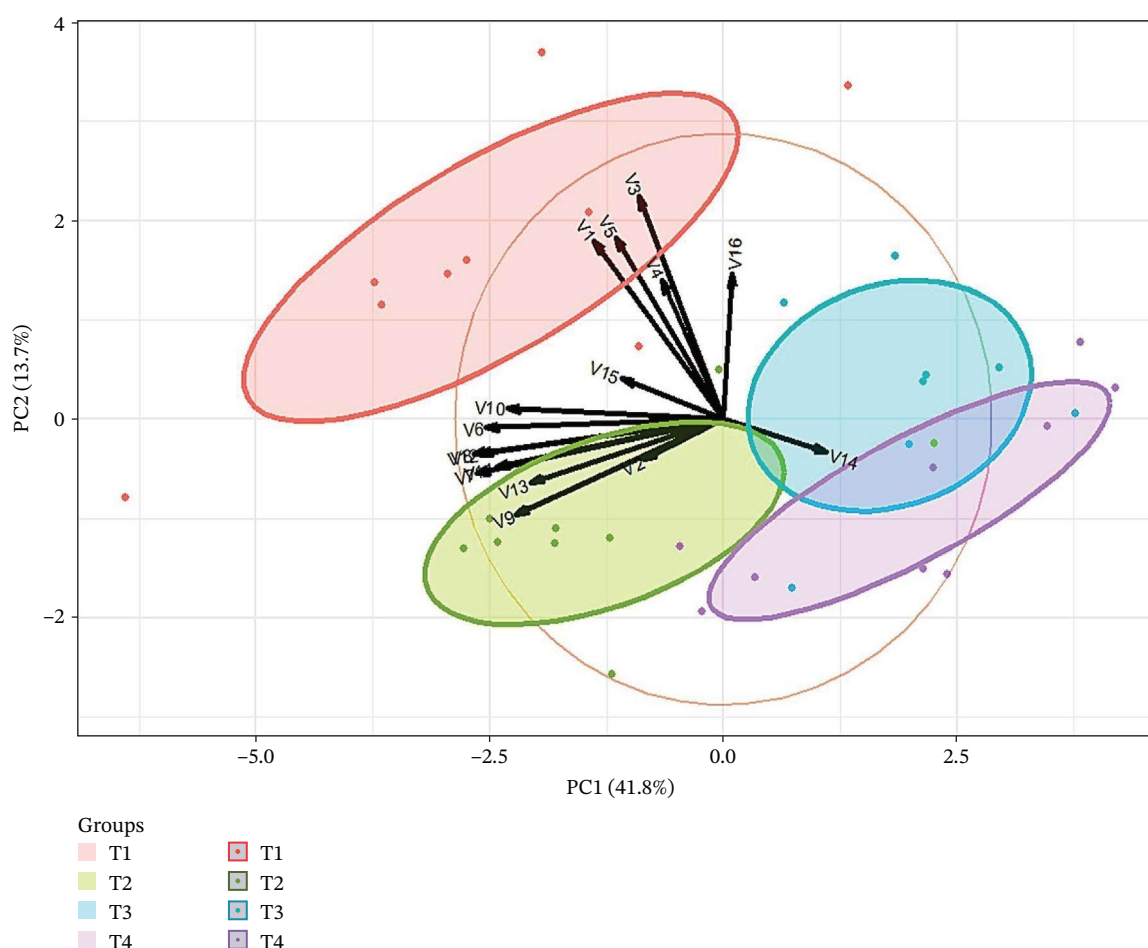


FIGURE 5 | Principal component analysis of yield and plant growth parameters of *Phaseolus vulgaris*. V1: seed weight, V2: number of root nodules, V3: number of pods, V4: SPAD, V5: leaf number, V6: leaf fresh weight, V7: stem fresh weight, V8: pod fresh weight, V9: root fresh weight, V10: leaf dry weight, V11: stem dry weight, V12: pod dry weight, V13: root dry weight, V14: root-shoot ratio, V15: pod length, V16: pod width, V17: plant height. Treatments; T1: Nova Plus, Nova Q and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

T4 ($p < 0.05$) (Figure 8c). Similarly, T3 recorded the highest manganese content among all treatments (Figure 8d). Zinc concentrations ranged from 5.24 to 10.60 mg/L, with T2 significantly outperforming the other treatments ($p < 0.05$) (Figure 8e). For

copper, both T1 and T2 had significantly higher values than T3 and T4 (Figure 8f). Lastly, iron content was lowest in T4, which was significantly different from the other treatments ($p < 0.05$) (Figure 8g).

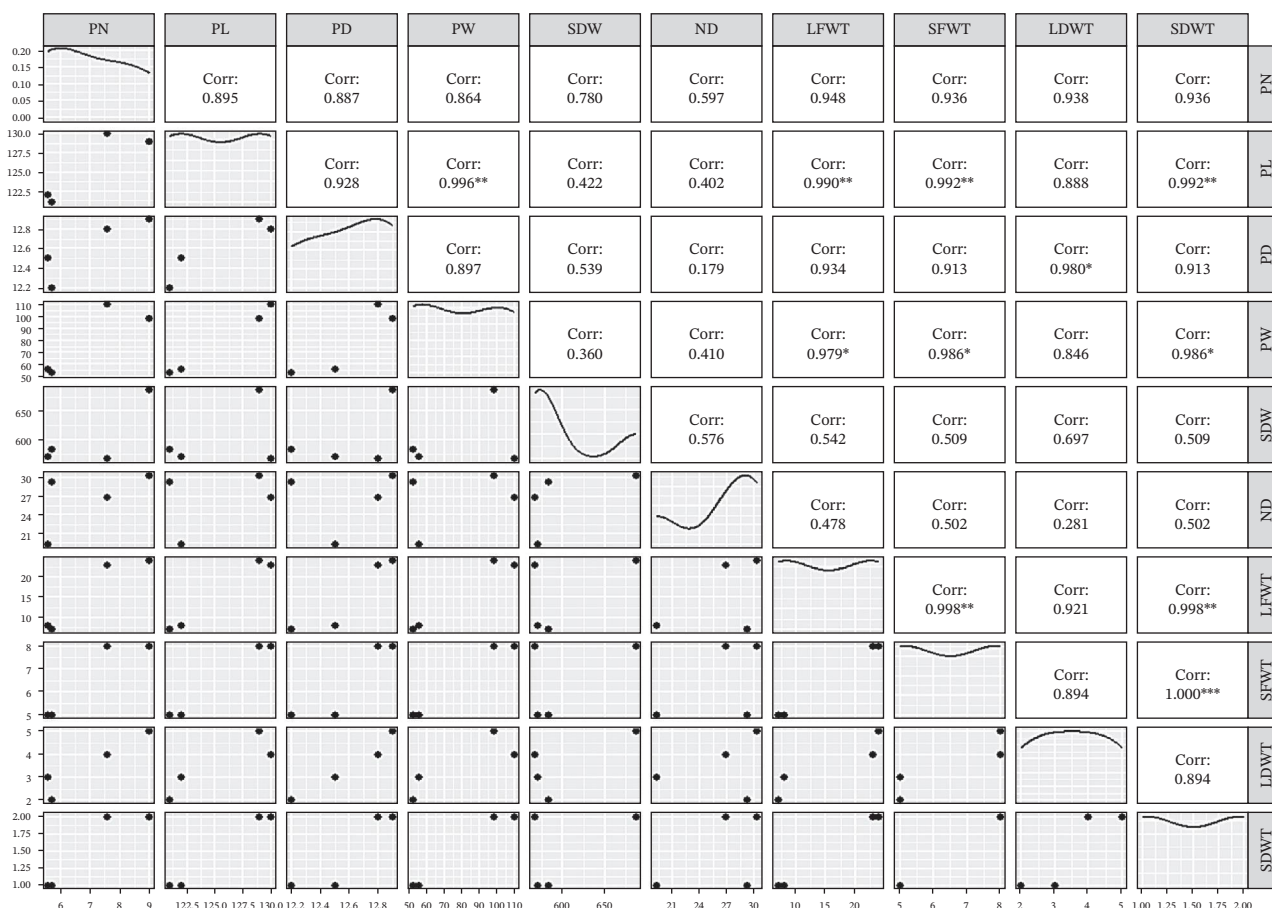


FIGURE 6 | Pearson correlation analysis of yield and biomass parameters. A plus and a minus sign, respectively, indicate the positive and negative correlations. Significance levels: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. PD, pod diameter; PL, pod length; PN, pod number; PW, pod width; LDWT: leaf dry weight; LFWT: leaf fresh weight; ND, nodules number; SDW: seed weight; SDWT: stem dry weight; SWDT, stem fresh weight.

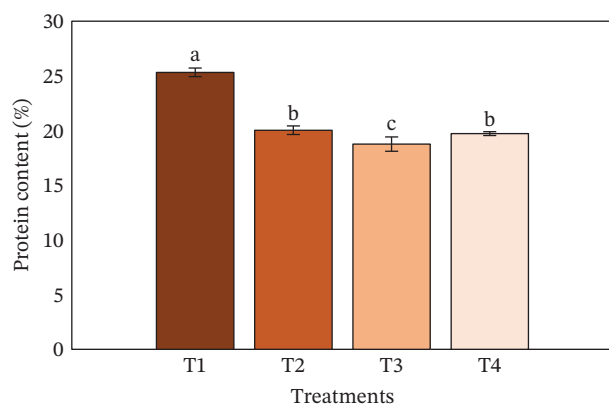


FIGURE 7 | Protein content of seeds of *Phaseolus vulgaris* cultivated under different treatments. Data is expressed as mean $\pm$ SD. Error bars represent the standard deviation. Bar columns having different letters are significantly different ($p < 0.05$). Treatments; T1: Nova Plus, Nova Q and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

3.7 | Ureide Contents and Fresh Weight of Root Nodules

Data shown in Figure 9a,b showed that at 60 DAS, the ureide contents of common bean nodules were significantly higher in T1 and T2 compared to other treatments. Likewise, results of the

root nodules' fresh weights obtained at 30, 60 and 90 DAS indicated that T1 significantly had higher values compared to T3 and T4 (Figure 9c).

4 | Discussion

After harvest, the soil OM, nitrogen (N), and phosphorus (P) were higher in T1 and T2 compared with other treatments (Tables 4 and 5). T1 and T2 contained compost that included inactive nutrients. The decomposition of inactive nutrients by microorganisms present in Nova Plus led to the release and accumulation of nutrients in the soil [52, 63, 64]. It is imperative to note that soil OM provides substrates for decomposing microorganisms and improves the water-holding capacity and structure of the soil [65]. As such, these results explicitly indicated that T1 and T2 could maintain soil fertility and provide nutrients for the next growing season. Most of the newly reclaimed soils in Egypt (i.e., where the study was conducted) are sandy with poor OM and nutrient content [66]. The application of these treatments (i.e., T1 or T2) could improve the physical-chemical properties of these newly reclaimed soils, thus leading to improved crop yields. On the other hand, these treatments could aid in soil salinity management as indicated by their low soil EC values, unlike in T4, whose EC values were high despite being below the critical value of 4.0 dS/m [65]. The application of soil amendments such as compost has been reported to stabilise the soil aggregates and

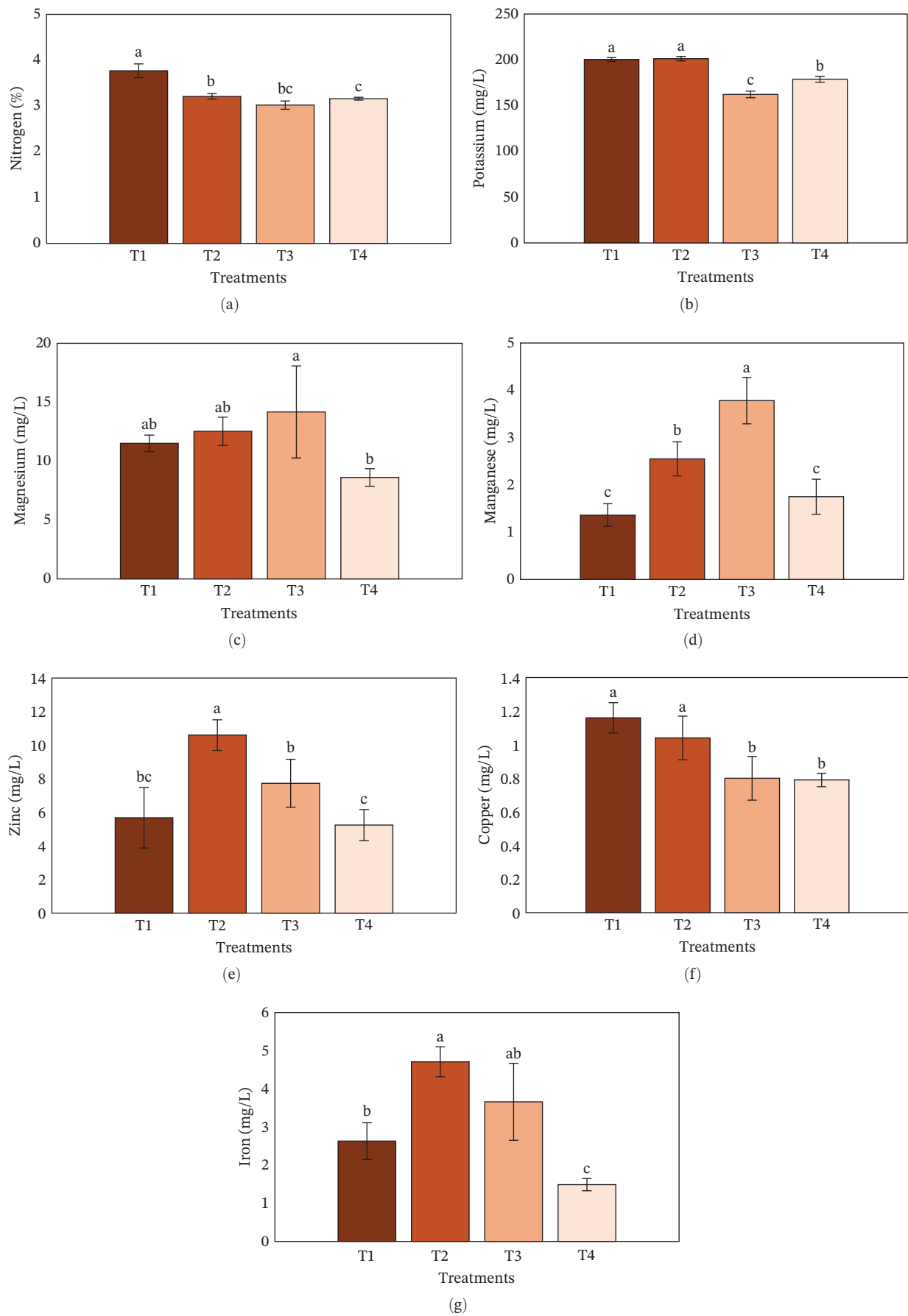


FIGURE 8 | Nutrient composition of *Phaseolus vulgaris* seeds grown under various treatment conditions. Results are shown as mean $\pm$ standard deviation (SD). Error bars indicate SD. Bars columns labelled with different letters represent statistically significant differences at $p < 0.05$. Treatments:

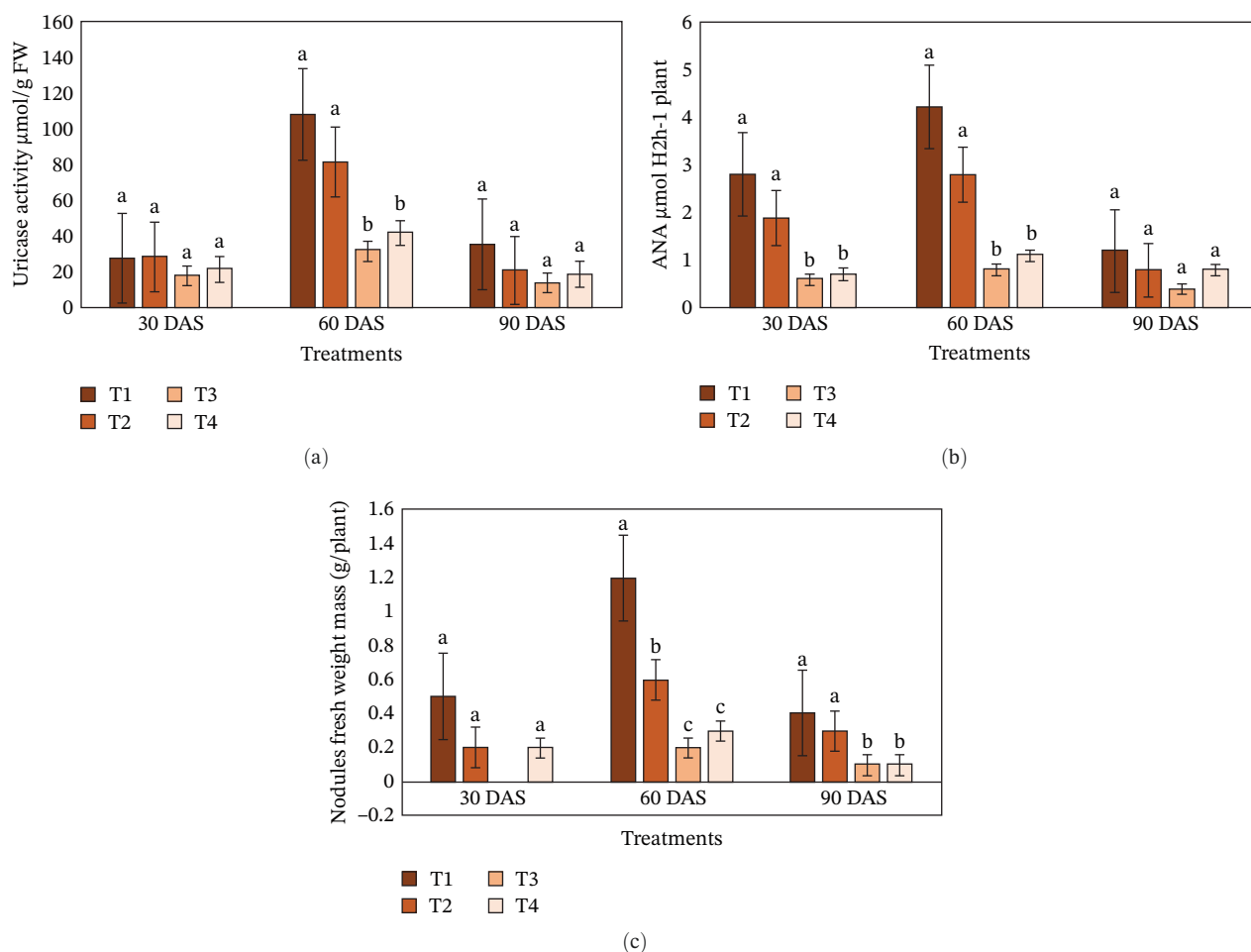


FIGURE 9 | Uricase enzymatic activity (a), apparent Nitrogenase activity (b), and (c) root nodule fresh weights of *Phaseolus vulgaris* cultivated under different treatments. Data is expressed as means $\pm$ standard error of mean (SEM). Treatments; T1: Nova Plus, Nova Q and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser.

improve its cation exchange capacity, hence favouring the attachment of dibasic cations to monobasic cations such as Na^+ [67, 68]. The highest levels of potassium (K) were noted in T1 compared with other treatments. This could be attributed to the presence of potassium-solubilising microorganisms in Nova Plus. Potassium-solubilising microbes synthesise and release several organic acids, exopolysaccharides and metal-complexing ligands that facilitate the release of K from minerals, thus leading to its accumulation in the soil [69–71].

Plant height, leaf number, leaflet area, and chlorophyll content (SPAD) were assessed throughout the experimental period (Table 6). The results of this study showed improved plant growth (i.e. plant height, leaf number and leaflet area) at 90 DAS in T1 and T2 compared with other treatments. Our results are consistent with previous studies that have reported improvement in plant morphological traits upon soil treatment with compost and/or application of microbial-based fertilisers [72–78]. Organic fertilisers in either compost or microbial-based form have been shown to improve soil fertility and structure better than inorganic fertilisers [45, 79, 80]. Moreover, different types of compost have

previously been reported to be essential in the sustainable restoration of soil quality [81–83]. Compared with inorganic fertilisers, organic fertilisers slowly release nutrients into the soil, which warrants less loss of soil nutrients as well as promotes the frequency of biological N-transformation in the rhizosphere, hence enhancing the soil's OM content, mineral content, and plant uptake of these mineral elements that are essential for plant growth [40, 45, 84, 85].

The yield and plant biomass parameters, such as pod number, pod weight, LFW, SFW, RFW, LDW, SDW, and RDW of *Phaseolus vulgaris* L. were assessed. The study results indicated higher yields and higher values for plant biomass parameters in T1 and T2 than in T3 and T4. Applying compost in soil either alone or in combination with microbial-based fertilisers improves nutrient uptake of nutrients thus enhancing plant yields and biomass production [86–88]. The increased uptake of nutrients in compost-treated soils is a result of improved diversity and richness of the rhizosphere microbiome and its interaction with plant roots to release signalling molecules and other root exudates, such as organic compounds that promote root development, solubilisation of

T1: Nova Plus, Nova Q, and functional compost, T2: functional compost only, T3: Inorganic fertiliser, T4: No fertiliser. Elements (a–g): nitrogen, potassium, magnesium, manganese, zinc, copper, and iron, respectively.

nutrients, and their uptake [89, 90]. The study also showed a higher root-to-shoot ratio in T4 compared with other treatments (Figure 4c), indicating a smaller root architecture in T4-treated plants. This could be attributed to several factors, such as N and P deficiency in the soil [91, 92]. On the other hand, Treatments T1 and T2 showed improved nodulation compared with T3 and T4. Similar results have been previously reported in other studies [78, 93, 94]. This could be attributed to the synergistic effect of the functional compost on root nodule-associated bacteria [94].

For seed nutrient analysis, T1 recorded higher protein (Figure 7) and nitrogen (Figure 8a) content than the other treatments. Similar results on the influence of organic fertilisers and/or biofertilisers on seed nitrogen and protein content have been previously reported in *Oryza sativa* [95–97], *Glycine max* [95, 98, 99], *Vicia faba* L. [100–103] and *Hordeum vulgare* [104–106]. The high seed protein and nitrogen content observed in this study is mainly ascribed to the fact that a combination of microbial-based fertilisers (Nova Plus and Nova Q) and functional compost produces a synergistic effect on the bioavailability of N in the soil. N is needed in the biosynthesis of chlorophyll, nucleic acids, enzymes, and amino acids [107]. Amino acids are the building blocks of protein and play crucial roles in several important functions [108, 109]. Other macro and micronutrients assessed in this study were potassium (K), magnesium (Mg), manganese (Mn), Zinc (Zn), copper (Cu) and iron (Fe) (Figure 8). T1 and T2 recorded higher values for K and Cu in the seeds compared with other treatments, and this could be attributed to the high bioavailability of K and Cu in the functional compost. The application of organic fertilisers has been linked to reduced potassium fixation in the soil and increased potassium release and uptake by plant roots [110]. On the other hand, current and previous literature suggest that OM influences the adsorption capacity of certain heavy metals, such as copper, hence increasing their bioavailability and uptake by plant roots [111–113]. Potassium plays significant regulatory roles in multiple plant physiological processes such as seed germination and emergence, protein synthesis, photosynthesis, enzyme activation, root development, etc. [114, 115]. As such, seeds sown in T1 and T2 plots germinated and emerged faster than those in other treatments (data not shown), and the plants exhibited higher values for root fresh and dry weights (Figure 3c,f). Moreover, lower values for the root-shoot ratio were noted in T1 and T2 (Figure 4c).

BNF occurs inside the root nodules by the action of nitrogenase enzyme activity, which fixes atmospheric N into ammonia (NH₃), which is converted into ureides (allantoin/allantoic acid) [116–118]. Our results indicated increased activity of these enzymes (Figure 9a,b) due to specific *Rhizobium* strains that were present in Nova Plus.

4.1 | Limitations of the Study

The generalizability of these results is constrained by a single season. Given the potential for annual environmental shifts to modulate treatment outcomes, further multi-season assessments are required to decouple the treatment effects from seasonal noise.

While phenotypic changes were observed, the study did not evaluate antioxidant enzymatic activity; consequently, the

specific metabolic mechanisms driving the plant's response to these treatments remain largely uncharacterised.

5 | Conclusion

This study highlights a sustainable strategy for revitalising sandy soil fertility and boosting *Phaseolus vulgaris* productivity using innovative organic amendments. Our findings demonstrate a synergistic effect between functional compost, both alone and in combination with microbial-based fertilisers, and soil physicochemical properties. Notably, functional compost alone increased soil OM by 72.9% relative to conventional inorganic methods. When combined with microbial fertilisers, potassium levels increased 4-fold and phosphorus by 39.5%. This dual application also significantly enhanced plant morphology, improving height by 86.14% and SPAD values by 8.79%. Ultimately, the co-application of microbial agents and functional compost optimises yield and seed nutrient profiles, offering an eco-friendly alternative that minimises reliance on environmentally harmful synthetic fertilisers.

Author Contributions

Mohamed F. Salem, Muziri Mugwanya, Hani Sewilam, and Fahad Kimera: conceptualisation. **Fahad Kimera, Muziri Mugwanya, and Mohamed F. Salem:** research design. **Muziri Mugwanya, Sakr M. Amna, Hussein H. Hadeer:** data collection. **Muziri Mugwanya:** data analysis and software. **Muziri Mugwanya, Fahad Kimera, Mohamed F. Salem:** paper writing, reviewing, and editing. **Hani Sewilam:** supervision.

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Disclosure

All authors reviewed the manuscript.

Ethics Statement

All plant materials and related procedures in this study were done per the guidelines of the Institutional Review Board of the American University in Cairo and the Ministry of Agriculture and Land Reclamation in Egypt.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. ([Supporting Information](#))

Figure 1 Pearson correlation of growth, biomass, and yield parameters. The positive and negative correlations are indicated by a plus sign and a minus sign, respectively.