Revitalizing Fertility of Nutrient-Deficient Virgin Sandy Soil Using Leguminous Biocompost Boosts Phaseolus vulgaris Performance

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Abstract: During the 2019 and 2020 seasons, nutrient-deficient virgin sandy soil was examined along with the investigation of the response of Phaseolus vulgaris plants to soil application with biocompost in integration with chemical fertilizers applied to soil and plants. Four treatments (100% of the recommended NPK fertilizer dose (control), 75% NPK applied to soil + 25% foliar spray, 75% NPK applied to soil + 25% foliar spray + leguminous compost (C1), and 75% NPK applied to soil + 25% foliar spray + C1 containing Bacillus subtilis (biocompost; C1B)) were applied in a randomized complete block design. The 75% NPK applied to soil + 25% foliar spray + C1B was the best treatment, which exceeded other treatments in improving soil fertility and plant performance. It noticeably improved soil physicochemical properties, including available nutrients, activities of various soil enzymes (cellulase, invertase, urease, and catalase), soil cation exchange capacity, organic carbon content, and pH, as well as plant growth and productivity, and plant physiobiochemistry, including nutrients and water contents, and various antioxidant activities. The results of the 2020 season significantly outperformed those of the 2019 season, indicating the positive effects of biofertilizers as a strategy to combine soil supplementation with NPK fertilizers and allocate a portion of NPK fertilizers for foliar spraying of plants in nutrient-deficient sandy soils.

Keywords: virgin soils; bio-organic and chemical fertilizer; soil properties; Phaseolus vulgaris

1. Introduction

Sandy soils are characterized by low nutrient content and water holding capacity, which leads to the frequent application of nutrients and water to meet crop requirements and improve soil quality [1–5]. Virgin sandy soils, which were not used for cultivation before [6], are found in nearly all regions of Egypt, from a few hundred square kilometers to more than a hundred thousand kilometers, covering most of Egypt’s total area [7–11].

Soil can generally be enriched with nutrients by adding them in solid form or dissolved in water, and the plant can also be nourished directly with nutrients through foliar application. Historically, soil application is the most common fertilization practice, but it depends on several factors including soil and plant characteristics and the physiological state, as well as weather conditions [12]. Generally, the availability of most nutrients is
limited in soils with higher calcium carbonate content [13], which are common throughout Egypt. However, foliar application improves the uptake and the efficiency of these nutrients [14,15]. Hence, to alleviate micro- and macronutrient deficiencies in sandy soils, foliar fertilization is increasingly adopted [16]. Foliar fertilization results in rapid nutrient absorption and avoidance of several environmental factors such as antagonism, leaching, and deposition of elements [17]. Hence, it can avoid some of the problems of challenges associated with soil application of nutrients in sandy soils. [17,18]. The foliar application does not substitute for soil application, but supplements it [19,20]. However, fertilization of major nutrients, especially NPK, is more effective via soil application, whereas secondary nutrients, e.g., calcium, magnesium, and sulfur, as well as micronutrients, e.g., zinc, iron, manganese, copper, molybdenum, and boron, proved to be more effective via foliar application [19].

Chemical fertilizers are essential for plant nutrition, but they can cause environmental pollution [21], particularly nitrogen, which leads to an increase of NO$_3^-$ ions in the soil [20]; phosphorous may also cause soil contamination with Cd$^{2+}$, which is readily absorbed and translocated into different parts of the plant [22]. As one of the basic organic fertilizers, leguminous compost can be utilized to reduce the quantities of chemical fertilizers applied [23,24]. The use of leguminous compost has multiple benefits including sanitation, reduced mass and bulk, and a lower C/N ratio [21]. Besides, it has the potential to maintain the fertility of soils in agricultural systems [25,26]. Legume plants can contribute as much as 50–250 kg/ha of nitrogen [27,28], and their litter can be utilized as a highly valuable compost (organic fertilizer). In contrast, traditional organic materials, e.g., crop residues, animal manure, etc., cannot alone improve soil fertility, as they are usually not available in sufficient quantities and require intensive labor [29].

Continuous use of inorganic fertilizers negatively affects soil fertility as it eventually leads to reduced crop yields. Moreover, its cost is much higher compared with organic fertilizers, which impacts the overall profits of agricultural production. Hence, it is of prime importance to appropriately combine inorganic with organic fertilizers [23] to overcome the environmental impacts and maximize the overall income. The objective of the present study is to evaluate the effectiveness of chemical and organic fertilizers (leguminous biocompost) in improving the fertility of nutrient-deficient sandy soil and its reflection on the growth and yield of *Phaseolus vulgaris* using a foliar and/or soil addition. We hypothesized that the combined application of soil and foliar chemical fertilizers with a bio-organic fertilizer would improve the fertility of the investigated sandy soil along with the growth and production of *Phaseolus vulgaris* plants.

2. Materials and Methods

2.1. Experimental Preparation and Setup

Two field trials were conducted over two consecutive summer seasons (20 February 2019 and 25 February 2020). Each summer season was preceded by the fall season (the first of September 2018 and 2019), which was planted with Egyptian clover (*Trifolium alexandrinum*) crop mixed with the soil when plants were 10 weeks old. Then, the soil was irrigated and left until the main planting seasons (February 2019 and 2020). Next to the Agriculture College (Fayoum University) trials station (29°17′06″ N and 30°54′55″ E), an area of sandy soil (not cultivated before) with an area of 600 m$^2$ was employed for this study. This area was characterized by moderate weather throughout the experimental period during the two growing seasons. Average daily temperatures were 24.5 ± 2.5 °C, mean relative humidity was 64.6 ± 6.4%, and light/dark averaged throughout the day 12/12 h.

Bronco cultivar of *Phaseolus vulgaris* (L.) was obtained from the Horticultural Research Institute (Egyptian Center for Agricultural Research). A sterile solution of sodium hypochlorite at a concentration of 1% was prepared to be used to sterilize the surface of the seeds for 5 min, then the seeds were cleaned with distilled water. Then, the seeds were prepared for planting after air drying for 1 h.
Before sowing and after harvesting the crop in the 2019 and 2020 seasons, the top 0–20 cm of the soil was sampled \((n = 5)\) and analyzed for soil chemical and physical properties, applying the methods detailed in Page et al. \[30\] and Klute and Dirksen \[31\]. The soil area specified for this study was divided into 40 experimental units of 10.5 m\(^2\) each, excluding the area of the main boundaries and irrigation canals (180 m\(^2\)). Each unit consists of five rows of 3 m in length, and each row consists of 30 hills each planted with three seeds. After full emergence, seedlings were thinned to one hill\(^{-1}\), counting 150 plants 10.5 m\(^2\). The recommended doses of NPK fertilizers (e.g., ammonium sulfate (20.5% N), Ca-superphosphate (15.5% P\(_2\)O\(_5\)), and K-sulfate (48% K\(_2\)O)) were added to the soil at a rate of 380 kg N, 380 kg P\(_2\)O\(_5\), and 190 kg K\(_2\)O ha\(^{-1}\). During preparation, the soil was supplemented with a half-dose of N with a full dose of P and K. Thirty days after sowing (DAS), the soil was supplemented with another half-dose of N. These NPK amounts were applied at 100% of the recommended doses as a control treatment. The second treatment was 75% of the recommended NPK doses (0.30, 0.30, and 0.15 kg per 10.5 m\(^2\), respectively) applied to the soil, +25% (0.10, 0.10, and 0.05 kg 10.5 m\(^{-2}\), respectively) applied as three foliar sprays (each spraying with a third of the 25%); 15, 30, and 45 days after sowing. Foliar sprays of NPK were performed with a hand atomizer, and the spray solution amount (to runoff) was sprayed, and Tween 20 (a few drops) was utilized as a surfactant. The third treatment was similar to the second treatment, in addition to leguminous compost that was added at 1.2 kg m\(^{-2}\). The fourth treatment was as the second treatment, in addition to leguminous compost \((C_L; 1.2 \text{ kg m}^{-2})\) containing bacteria \((\textit{Bacillus subtilis})\) as a biocompost fertilizer \((C_LB)\). The bacteria were prepared in a microbiological laboratory and added to the \(C_L\) at approximately \(0.6 \times 10^9 \text{ CFU g}^{-1}\) along with humic acid at 0.01% and amino acids at 0.01% to form a \(C_LB\). The experimental treatments are summarized in Table 1.

**Table 1.** The description of the experimental fertilization treatments for soil and plant.

| Treatment  | Description                                                                 |
|------------|-----------------------------------------------------------------------------|
| 1. \(SCF100\) | 100% of the recommended NPK doses were applied to the soil as a control.     |
| 2. \(SCF75 + FC_{25}\) | 75% of the recommended NPK doses were applied to the soil, +25% of the recommended NPK doses were applied as three foliar sprays (each spraying with the third of the 25%). |
| 3. \(SCF75 + FC_{25} + C_L\) | 75% of the recommended NPK doses were applied to the soil, +25% of the recommended NPK doses were applied as three foliar sprays (each spraying with the third of the 25%) + 1.2 kg leguminous compost m\(^{-2}\). |
| 4. \(SCF75 + FC_{25} + C_{LB}\) | 75% of the recommended NPK doses were applied to the soil, +25% of the recommended NPK doses were applied as three foliar sprays (each spraying with the third of the 25%) + 1.2 kg compost containing bacteria \((\textit{Bacillus subtilis})\) m\(^{-2}\). |

All soil additions were spread manually on the soil surface after mixing with an appropriate amount of sand, then incorporated into the 20 cm upper layer. The treatments were secured for a randomized complete block design with ten unit (10.5 m\(^2\)) replicates for each of the four treatments in both 2019 and 2020 seasons. All other practices recommended for standard cultivation for commercial \textit{Phaseolus vulgaris} production were followed \[32\].

2.2. Compost Preparation

Twenty-five kg of green shoots of faba bean were incorporated into a similar weight containing different organic materials, including 0.5 kg and 0.5 kg of bulking agents and potassium humate (K–H), respectively, along with 12.0 kg and 12.0 kg of cattle manure and Egyptian clover plants, respectively, as N sources. For the compost mixture, green shoots of faba bean, bulking agents, potassium humate, cattle manure, and Egyptian clover plants contributed 50.0, 0.5, 0.5, 24.0, and 24.0%, respectively. After mixing well, these mixtures were composted in a pilot plant utilizing the turning-pile system in trapezoidal piles (dimensions of the base were 5.0 \(\times\) 20.0 \(\times\) 7.5 m in height, length, and width, respectively). From August to February, during the bio-oxidative phase, overturning was performed every two weeks for the piles, keeping the level of moisture in the range of 40–60% while
monitoring the temperature. The obtained compost was analyzed, and the resulting data were as follows: pH = 7.5, EC = 2.1 dS m\(^{-1}\), content of organic matter = 19.6\%, K = 152 g kg\(^{-1}\), P = 33 g kg\(^{-1}\), and N = 115 g kg\(^{-1}\).

2.3. Soil Sampling

Before sowing and after harvesting the *Phaseolus vulgaris* crop, three samples were randomly gathered from the 0–20 cm upper soil layer of three randomly selected experimental units and immediately transported to the laboratory and sieved with a 2 mm stainless-steel soil sampler.

2.4. Assessments of Soil CEC, Organic Matter, and Nutrient Contents

The procedures detailed in [30,31] were applied to evaluate each of cation exchange capacity (CEC), organic matter (%), CaCO\(_3\) (%), and nutrient contents (e.g., N, P, K, Fe, Mn, and Zn).

2.5. Soil Organic Carbon and Soil Enzyme Activity Determinations

Soil samples with a size of up to 2 mm were utilized to assess the organic C content and enzyme activities in the tested soil. The samples were randomly gathered from all experimental units of all tested treatments, including the comparison units. The wet oxidation–redox titration method of Carter and Gregorich [33] was applied to determine organic C content. Cellulases were determined as the system of an enzyme, by which cellulose was degraded and reducing sugars were released as the end product. Cellulase activity was expressed as mg sugars released g\(^{-1}\) dry soil, 37 °C, 24 h. Then, the procedure (anthrone colorimetric analysis) of Hope and Burns [34] was applied to determine the reducing sugars. The procedures detailed in both Schinner and von Mersi [35] and Miller [36] were applied to assay soil invertase (EC 3.2.1.26) activity (mg sugars released g\(^{-1}\) dry soil, 37 °C, 24 h) and the content of reducing sugars. The buffered procedure of Kandeler and Gerber [37] was applied to assay soil catalase (EC 1.11.1.6) activity (µmol H\(_2\)O\(_2\) g\(^{-1}\) dry soil, 25 °C, 24 h).

Soil enzyme activities were evaluated using controls made by mixing the buffer solution with either the soil fractions or the substrate solution. The values were corrected by subtracting the combined absorbance values of the sample and substrate controls from those of the analytical samples.

2.6. Assessment of Growth and Yield Components

Fifty days after sowing, shoots of 10 plants were randomly gathered from each treatment (10 experimental units; one plant from each unit) to evaluate fresh weight (g), and after drying these shoots at 70 °C, dry weight was recorded after two or more constant weights of each shoot.

Sixty-two to 70 days after sowing (green pod marketing stage), 10 plants from each treatment (10 experimental units; one plant from each unit) were randomly assigned to assess the average pod weight (g) and total plant green pods (g). Eighty days after sowing (dry seed marketing stage), the remaining plants were applied for dry seeds’ weight (g per plant) after pods were picked to air dry for 3 d.

2.7. Leafy Nutrient Contents

Uniform leafy samples were collected from 10 plants randomly gathered from each treatment (10 experimental units; one plant from each unit) to be dried (at 70 °C for 72 h) and digested to assess leafy content of nutrients. The micro-Kjeldahl technique was applied to assess total N content (mg g\(^{-1}\) DW). The content (mg g\(^{-1}\) DW) of P was colorimetrically evaluated with the use of the reagent of stannous chloride–ammonium molybdate [40], following the extraction with NaHCO\(_3\) [41]. The flame photometer (ELE Flame Photometer,
Leighton Buzzard, UK) technique was utilized to assess the content (mg g\(^{-1}\) DW) of K\(^+\). Besides this, the atomic absorption spectrophotometry apparatus was utilized to determine the contents (mg g\(^{-1}\) DW) of Fe\(^{2+}\), Mn\(^{2+}\), and Zn\(^{2+}\) nutrients spectrophotometry [42].

2.8. Total Chlorophyll, Osmoprotectants, and Antioxidants Contents

The total chlorophyll content was spectrophotometrically (UV-160A, Spectrometer, Shimadzu, Kyoto, Japan) evaluated applying the method of [43], utilizing leaf discs (0.5 g). The leafy samples were homogenized with acetone solution (80%, v/v) and then the centrifugation process was practiced (3000 \(\times\) g, 20 min) for obtaining the supernatant to measure the absorbances on 470, 645, and 663 nm.

At the field level, standardized, uniform leaves were assigned to measure chlorophyll fluorescence at 360 \(\mu\)mol mol\(^{-1}\) CO\(_2\), 21 °C, and 600 \(\mu\)mol m\(^{-2}\) s\(^{-1}\) PPFD utilizing a potable pulse-modulated fluorometer (FMS-2, Hansatech, Norfolk, UK) according to the procedure of Li et al. [44]. The maximum quantum yield of photosystem II (PSII) (Fv/Fm) was computed using the Maxwell and Johnson [45] formulae. According to the equal absorption, photosynthesis PI\(_{\text{ABS}}\) was computed according to the formula of Clark et al. [46].

Phaseolus vulgaris leaf RWC was evaluated applying the procedure of Osman and Rady [47] with the use of leafy discs (\(n = 20\)) after exclusion of the midrib. The fresh, turgid, and dry mass were recorded for applying in the following formula:

\[
\text{RWC} (\%) = \left(\frac{\text{fresh mass} - \text{dry mass}}{\text{turgid mass} - \text{dry mass}}\right) \times 100
\]

The Irigoyen et al. [48] method was used (using ethyl alcohol 96%, v/v) to extract and determine soluble sugar content (mg g\(^{-1}\) DW) in the standardized, uniform leafy samples. The same leafy tissues were utilized to determine the content of free proline (\(\mu\)g g\(^{-1}\) DW) following the Bates et al. [49] method. Besides this, the full procedures of Griffith [50] and Mukherjee and Choudhari [51] were applied for determining glutathione (nmol glutathione g\(^{-1}\) FW) and ascorbate (\(\mu\)mol g\(^{-1}\) FW) contents, respectively.

2.9. Assaying the Activities of Antioxidative Enzymes

Leafy samples (from all treatments, 0.5 g) were extracted applying the full Mukherjee and Choudhari [51] procedure. After centrifuging the homogenates (15,000 \(\times\) g, 10 min) the obtained supernatants were utilized to assay enzyme activities (guaiacol peroxidase (GPD), catalase (CAT), and superoxide dismutase (SOD)). The full procedures of Giannopolitis and Ries [52], Aebi [53], and Putter [54] were applied for assaying SOD (EC1.15.1.1), CAT (EC1.11.1.6), and GPD activities, respectively. For enzyme, nitro blue tetrazolium (NBT), H\(_2\)O\(_2\), and guaiacol with H\(_2\)O\(_2\) solutions were the substrates utilized, respectively.

Besides this, the full method of [55] was applied for assessing the protein content.

2.10. Data Analysis

Analysis of data was performed with IBM\textsuperscript{®} SPSS\textsuperscript{®} (SPSS Inc., IBM Corporation, New York, NY, USA) Statistics Version 25 (2017) for Windows. To verify the normal distribution of data the Shapiro–Wilk test was used [56,57] for main effects and interactions. Due to the data having normal distribution (\(p \leq 0.05\)), parametric statistical tests were applied. The two-way ANOVA was performed to highlight the effect of four fertilization treatments, two growing seasons, and the interaction between fertilization treatments and growing seasons. Two-way ANOVA, followed by a post hoc LSD test was used for multiple comparisons among means of fertilization treatments, growing seasons, and the interaction between fertilization treatments and growing seasons. All statistical tests were two-tailed, and a \(p\)-value less than or equal to 0.05 was considered statistically significant. A confidence interval was estimated at 95%. 

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3. Results
3.1. Soil Physical and Chemical Properties Response to \(S_{CF75} + F_{CF25} + C_{LB}\) Supplementation for Two Seasons (2019 and 2020)

Data in Table 2 show the desired changes in soil characteristics during the two seasons (2019 and 2020) resulting from soil supplementation with \(S_{CF75} + F_{CF25} + C_{LB}\) (chemical fertilizers applied to the soil at 75% of recommended NPK doses + chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses + bio compost; leguminous compost (1.2 kg m\(^{-2}\)) containing bacteria) as the best treatment. The soil composition of clay, silt, and sand was not changed in either of the 2019 and 2020 growing seasons with \(S_{CF75} + F_{CF25} + C_{LB}\) application. Other characteristics (e.g., pH, EC, and CaCO\(_3\) content) were slightly affected.

### Table 2. The physicochemical properties of the tested soil before sowing and following and after harvest.

| Parameters          | Properties                                                                 |
|---------------------|-----------------------------------------------------------------------------|
|                     | Before Sowing | After Harvest | Before Sowing | After Harvest |
| Clay                | 8.2 ± 0.6    | 8.2 ± 0.5    | 8.2 ± 0.7    | 8.3 ± 0.8    |
| Silt                | 10.7 ± 0.8   | 10.8 ± 0.8   | 10.8 ± 0.7   | 10.9 ± 1.0   |
| Sand                | 81.1 ± 7.2   | 81.0 ± 6.9   | 81.0 ± 6.7   | 80.8 ± 6.2   |
| Soil texture        | Loamy Sand   | Loamy Sand   | Loamy Sand   | Loamy Sand   |
| pH                  | 8.35 ± 0.51  | 8.12 ± 0.48  | 8.02 ± 0.42  | 7.82 ± 0.38  |
| EC (dS m\(^{-1}\))  | 3.20 ± 0.24  | 3.24 ± 0.24  | 3.31 ± 0.26  | 3.44 ± 0.25  |
| CaCO\(_3\) (%)      | 8.62 ± 0.54  | 8.52 ± 0.55  | 8.44 ± 0.50  | 8.10 ± 0.48  |

* Values ± SE, dS m\(^{-1}\) = deciSiemens per meter, and \(S_{CF75} + F_{CF25} + C_{LB}\) = chemical fertilizers applied to the soil at 75% of recommended NPK doses + chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses + bio compost; leguminous compost (1.2 kg m\(^{-2}\)) containing bacteria.

3.2. Response of Soil Chemical Properties and Plant Performances to the Growing Season

The growing season as the main factor in this study affected the chemical properties of the tested soil, soil and plant contents of essential nutrients, activities of various enzymes, plant growth and productivity, and plant physiobiochemistry. The 2020 growing season significantly outperformed the 2019 growing season in terms of all the examined parameters of the soil and \(Phaseolus vulgaris\) plant, which are presented in Tables 3–6 and Figures 1–12.

### Table 3. Response of soil nutrient contents to growing season (2019 and 2020) and different fertilization strategies applied to virgin sandy soil.

| Source of Variation | Available Macronutrient Contents (mg kg\(^{-1}\) Soil) |
|---------------------|------------------------------------------------------|
|                     | Available N | Available P | Available K |
| Season (S)          | *           | ns          | *           |
| 2019                | 30.3 ± 0.2  | 17.5 ± 0.2  | 37.5 ± 0.3  |
| 2020                | 35.9 ± 0.3  | 17.5 ± 0.2  | 45.5 ± 0.4  |
| Fertilization (F)   | *           | **          | **          |
| \(S_{CF100}\)       | 27.5 ± 0.3  | 11.8 ± 0.1  | 34.3 ± 0.4  |
| \(S_{CF75} + F_{CF25}\)| 27.1 ± 0.2  | 11.5 ± 0.1  | 33.4 ± 0.3  |
| \(S_{CF75} + F_{CF25} + C_{LB}\) | 34.9 ± 0.3  | 17.5 ± 0.2  | 43.9 ± 0.4  |
| \(S_{CF75} + F_{CF25} + C_{LB}\) | 43.1 ± 0.4  | 21.8 ± 0.2  | 54.5 ± 0.4  |
Table 3. Cont.

| Source of Variation | Available Macronutrient Contents (mg kg\(^{-1}\) Soil) |
|---------------------|-----------------------------------------------------|
|                     | Available N | Available P | Available K |
| S × F               | *           | **          | **          |
| 2019 × SCF100       | 25.6 ± 0.2\(^d\) | 10.4 ± 0.1\(^e\) | 31.2 ± 0.3\(^d\) |
| 2019 × SCF75 + FC25 | 24.8 ± 0.2\(^d\) | 10.0 ± 0.1\(^e\) | 29.9 ± 0.3\(^d\) |
| 2019 × SCF75 + FC25 + C\(_L\) | 31.4 ± 0.2\(^c\) | 15.3 ± 0.1\(^c\) | 39.4 ± 0.3\(^c\) |
| 2019 × SCF75 + FC25 + C\(_L\)B | 39.5 ± 0.3\(^b\) | 19.4 ± 0.2\(^b\) | 49.3 ± 0.4\(^b\) |
| 2020 × SCF100       | 29.4 ± 0.3\(^c\) | 13.2 ± 0.1\(^d\) | 37.4 ± 0.4\(^c\) |
| 2020 × SCF75 + FC25 | 29.3 ± 0.2\(^c\) | 12.9 ± 0.1\(^d\) | 36.8 ± 0.3\(^c\) |
| 2020 × SCF75 + FC25 + C\(_L\) | 38.4 ± 0.3\(^b\) | 19.6 ± 0.2\(^b\) | 48.3 ± 0.4\(^b\) |
| 2020 × SCF75 + FC25 + C\(_L\)B | 46.6 ± 0.4\(^a\) | 24.1 ± 0.2\(^a\) | 59.6 ± 0.4\(^a\) |

** and * indicate, respectively, differences at \(p \leq 0.05\) and \(p \leq 0.01\) probability level, respectively, and ns indicates not significant difference. Mean values with different letters in each column are significant (\(p \leq 0.05\)). SCF100 = chemical fertilizers applied to the soil at full recommended NPK doses; SCF75 = chemical fertilizers applied to the soil at 75% of recommended NPK doses; FC25 = chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses; C\(_L\) = 1.2 kg leguminous compost m\(^{-2}\); and C\(_L\)B = biocompost; leguminous compost (1.2 kg per m\(^{-2}\)) containing bacteria.

Table 4. Response of growth and productivity of *Phaseolus vulgaris* plants to growing season (2019 and 2020) and different fertilization strategies applied to virgin sandy soil.

| Source of Variation | Growth Parameters | Yield Parameters |
|---------------------|-------------------|-----------------|
|                     | Shoot FW (g Plant\(^{-1}\)) | Shoot DW (g Plant\(^{-1}\)) | Green Pod Weight (ton ha\(^{-1}\)) | Dry Seed Weight (ton ha\(^{-1}\)) |
| Season (S)          | *                 | *               | *                | *                    |
| 2019                | 18.3 ± 1.7\(^b\) | 2.25 ± 2.1\(^b\) | 2.62 ± 0.28\(^b\) | 0.67 ± 0.07\(^b\) |
| 2020                | 22.1 ± 2.2\(^a\) | 2.60 ± 2.6\(^a\) | 3.00 ± 0.30\(^a\) | 0.86 ± 0.09\(^a\) |
| Fertilization (F)   | **                | *               | *                | **                   |
| SCF100              | 15.3 ± 1.4\(^d\) | 1.95 ± 2.1\(^d\) | 2.16 ± 0.23\(^d\) | 0.52 ± 0.06\(^d\) |
| SCF75 + FCP25       | 17.9 ± 1.9\(^c\) | 2.22 ± 2.1\(^c\) | 2.62 ± 0.26\(^c\) | 0.63 ± 0.07\(^c\) |
| SCF75 + FCP25 + C\(_L\) | 21.6 ± 2.1\(^b\) | 2.59 ± 2.6\(^b\) | 3.07 ± 0.32\(^b\) | 0.83 ± 0.08\(^b\) |
| SCF75 + FCP25 + C\(_L\)B | 26.1 ± 2.5\(^a\) | 2.95 ± 2.8\(^a\) | 3.39 ± 0.34\(^a\) | 1.09 ± 0.11\(^a\) |
| S × F               | **                | *               | *                | **                   |
| 2019 × SCF100       | 14.2 ± 1.3\(^c\) | 1.79 ± 1.8\(^c\) | 1.96 ± 0.21\(^c\) | 0.46 ± 0.05\(^c\) |
| 2019 × SCF75 + FCP25 | 16.6 ± 1.7\(^d\) | 2.09 ± 1.9\(^d\) | 2.41 ± 0.25\(^d\) | 0.55 ± 0.05\(^d\) |
| 2019 × SCF75 + FCP25 + C\(_L\) | 19.0 ± 1.8\(^c\) | 2.36 ± 2.2\(^c\) | 2.90 ± 0.31\(^c\) | 0.72 ± 0.07\(^c\) |
| 2019 × SCF75 + FCP25 + C\(_L\)B | 23.4 ± 2.1\(^b\) | 2.75 ± 2.5\(^b\) | 3.19 ± 0.34\(^b\) | 0.96 ± 0.10\(^b\) |
Table 4. Cont.

| Source of Variation | Growth Parameters | Yield Parameters |
|---------------------|-------------------|-----------------|
|                     | Shoot FW          | Shoot DW        | Green Pod Weight | Dry Seed Weight |
|                     | (g Plant⁻¹)       | (g Plant⁻¹)     | (ton ha⁻¹)       | (ton ha⁻¹)      |
| 2020 × S_CF100      | 16.4 ± 1.5 d      | 2.11 ± 2.3 d    | 2.36 ± 0.25 d    | 0.57 ± 0.07 d   |
| 2020 × S_CF100 + F_CF25 | 19.1 ± 2.0 c    | 2.34 ± 2.3 c    | 2.83 ± 0.27 c    | 0.69 ± 0.08 c   |
| 2020 × S_CF75 + F_CF25 + C_L | 24.2 ± 2.3 b   | 2.81 ± 2.9 b    | 3.24 ± 0.32 b    | 0.94 ± 0.08 b   |
| 2020 × S_CF75 + F_CF25 + C_L_B | 28.7 ± 2.8 a   | 3.14 ± 3.0 a    | 3.58 ± 0.34 a    | 1.22 ± 0.11 a   |

** and * indicate, respectively, differences at p ≤ 0.05 and p ≤ 0.01 probability level, respectively. Mean values with different letters in each column are significant (p ≤ 0.05). S_CF100 = chemical fertilizers applied to the soil at full recommended NPK doses, S_CF150 = chemical fertilizers applied at 75% of recommended NPK doses, F_CF25 = chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses, C_L = 1.2 kg leguminous compost m⁻², and C_L_B = bio-compost; leguminous compost (1.2 kg m⁻²) containing bacteria.

Table 5. Response of nutritional contents of *Phaseolus vulgaris* plants to growing season (2019 and 2020) and different fertilization strategies applied to virgin sandy soil.

| Source of Variation | Macronutrient Contents (mg g⁻¹ DW) | Micronutrient Contents (mg kg⁻¹ DW) |
|---------------------|-----------------------------------|-----------------------------------|
|                     | N | P | K | Fe | Mn | Zn |
| Season (S)          |   |   |   |    |    |    |
| 2019                | 21.1 ± 0.5 b | 1.93 ± 0.05 b | 24.0 ± 0.6 b | 274 ± 14 b | 180 ± 7 b | 126 ± 4 b |
| 2020                | 25.3 ± 0.8 a | 2.42 ± 0.07 a | 27.8 ± 0.8 a | 322 ± 17 a | 223 ± 9 a | 151 ± 5 a |
| Fertilization (F)   |   |   |   |    |    |    |
| S_CF100             | 16.9 ± 0.5 d | 1.47 ± 0.04 d | 19.4 ± 0.5 d | 221 ± 12 d | 144 ± 6 d | 100 ± 4 d |
| S_CF75 + F_CF25     | 20.9 ± 0.6 c | 1.89 ± 0.05 c | 23.6 ± 0.6 c | 265 ± 14 c | 176 ± 7 c | 127 ± 5 c |
| S_CF75 + F_CF25 + C_L | 25.6 ± 0.7 b | 2.43 ± 0.07 b | 28.1 ± 0.7 b | 327 ± 17 b | 222 ± 9 b | 152 ± 5 b |
| S_CF75 + F_CF25 + C_L_B | 29.3 ± 0.8 a | 2.92 ± 0.09 a | 32.6 ± 0.9 a | 378 ± 21 a | 264 ± 10 a | 176 ± 6 a |
| S × F               |   |   |   |    |    |    |
| 2019 × S_CF100      | 15.2 ± 0.4 c | 1.22 ± 0.03 c | 17.8 ± 0.3 c | 198 ± 10 c | 128 ± 5 c | 89 ± 3 c |
| 2019 × S_CF75 + F_CF25 | 18.4 ± 0.5 d | 1.68 ± 0.04 d | 21.1 ± 0.5 d | 239 ± 12 d | 156 ± 6 d | 112 ± 4 d |
| 2019 × S_CF75 + F_CF25 + C_L | 23.1 ± 0.5 c | 2.14 ± 0.06 c | 26.4 ± 0.6 c | 298 ± 15 c | 192 ± 8 c | 136 ± 4 c |
| 2019 × S_CF75 + F_CF25 + C_L_B | 27.6 ± 0.6 b | 2.67 ± 0.08 b | 30.6 ± 0.8 b | 360 ± 20 b | 244 ± 9 b | 165 ± 5 b |
| 2020 × S_CF100      | 18.6 ± 0.6 d | 1.72 ± 0.05 d | 20.9 ± 0.6 d | 244 ± 14 d | 160 ± 7 d | 110 ± 4 d |
| 2020 × S_CF75 + F_CF25 | 23.4 ± 0.7 c | 2.10 ± 0.05 c | 26.0 ± 0.6 c | 290 ± 16 c | 196 ± 7 c | 141 ± 5 c |
| 2020 × S_CF75 + F_CF25 + C_L | 28.0 ± 0.9 b | 2.71 ± 0.07 b | 29.8 ± 0.8 b | 356 ± 18 b | 251 ± 9 b | 168 ± 5 b |
| 2020 × S_CF75 + F_CF25 + C_L_B | 31.0 ± 0.9 a | 3.16 ± 0.09 a | 34.6 ± 1.0 a | 396 ± 20 a | 284 ± 11 a | 186 ± 7 a |

** and * indicate, respectively, differences at p ≤ 0.05 and p ≤ 0.01 probability level, respectively. Mean values with different letters in each column are significant (p ≤ 0.05). S_CF100 = chemical fertilizers applied to the soil at full recommended NPK doses, S_CF150 = chemical fertilizers applied at 75% of recommended NPK doses, F_CF25 = chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses, C_L = 1.2 kg leguminous compost m⁻², and C_L_B = bio-compost; leguminous compost (1.2 kg m⁻²) containing bacteria.

Table 6. Response of photosynthetic parameters, relative water content, and osmoprotectant contents of *Phaseolus vulgaris* plants to growing season (2019 and 2020) and different fertilization strategies applied to virgin sandy soil.

| Source of Variation | Photosynthetic Parameters | Leaf Relative Water Content (RWC) and Osmoprotectant Contents |
|---------------------|---------------------------|---------------------------------------------------------------|
|                     | TChl Content (g kg⁻¹ FW) | Fv/Fm (%) | PI (%) | RWC (%) | Proline (µg g⁻¹ DW) | TS Sugars (mg g⁻¹ DW) |
| Season (S)          |                           |           |        |         |                     |                     |
| 2019                | 1.76 ± 0.03 b             | 0.77 ± 0.02 b | 13.7 ± 0.3 b | 65.0 ± 2.3 b | 160 ± 5 b | 18.0 ± 0.4 b |
| 2020                | 2.14 ± 0.04 a             | 0.83 ± 0.03 a | 15.9 ± 0.4 a | 73.8 ± 2.5 a | 185 ± 6 a | 22.4 ± 0.5 a |
| Fertilization (F)   |                           |           |        |         |                     |                     |
| S_CF100             | 1.30 ± 0.03 d             | 0.71 ± 0.02 d | 11.5 ± 0.3 d | 56.7 ± 2.1 d | 136 ± 4 d | 14.2 ± 0.4 d |
| S_CF75 + F_CF25     | 1.69 ± 0.03 c             | 0.76 ± 0.02 c | 13.4 ± 0.4 c | 64.5 ± 2.3 c | 163 ± 5 c | 18.0 ± 0.5 c |
| S_CF75 + F_CF25 + C_L | 2.17 ± 0.04 b             | 0.83 ± 0.03 b | 15.9 ± 0.4 b | 74.0 ± 2.5 b | 183 ± 7 b | 22.1 ± 0.5 b |
| S_CF75 + F_CF25 + C_L_B | 2.65 ± 0.05 a             | 0.89 ± 0.03 a | 18.5 ± 0.4 a | 82.3 ± 2.9 a | 205 ± 7 a | 26.4 ± 0.6 a |
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Table 1. Bars with a different letter indicate significant difference between treatments at two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Figure 3.

| Source of Variation | Photosynthetic Parameters | Leaf Relative Water Content (RWC) and Osmoprotectant Contents |
|---------------------|---------------------------|---------------------------------------------------------------|
|                     | TChl Content (g kg⁻¹ FW) | Fv/Fm | PI (%) | RWC (%) | Proline (μg g⁻¹ DW) | TS Sugars (mg g⁻¹ DW) |
|                     |                          |       |        |         |                   |                   |
| S × F               |                          |       |        |         |                   |                   |
| 2019 × SCF100       | 1.12 ± 0.02 e             | 0.68 ± 0.01 e       | 10.4 ± 0.2 f       | 52.4 ± 1.9 d       | 125 ± 3 d         | 12.4 ± 0.3 e       |
| 2019 × SCF75 + FCF25| 1.52 ± 0.02 d             | 0.73 ± 0.02 d       | 12.4 ± 0.3 e       | 60.2 ± 2.1 c       | 148 ± 4 d         | 15.8 ± 0.4 d       |
| 2019 × SCF75 + FCF25 + C_L| 1.97 ± 0.03 c | 0.79 ± 0.02 c       | 14.9 ± 0.3 c       | 69.6 ± 2.4 b       | 176 ± 6 c         | 19.6 ± 0.4 c       |
| 2019 × SCF75 + FCF25 + C_LB| 2.44 ± 0.04 b | 0.86 ± 0.02 b       | 17.2 ± 0.4 b       | 77.8 ± 2.9 a       | 192 ± 6 bc        | 24.0 ± 0.5 b       |
| 2020 × SCF100       | 1.48 ± 0.03 de            | 0.74 ± 0.02 d       | 12.6 ± 0.3 de      | 61.0 ± 2.2 c       | 147 ± 5 d         | 16.0 ± 0.4 d       |
| 2020 × SCF75 + FCF25| 1.86 ± 0.03 cd            | 0.79 ± 0.02 c       | 14.4 ± 0.4 cd      | 68.8 ± 2.5 b       | 178 ± 5 c         | 20.2 ± 0.5 c       |
| 2020 × SCF75 + FCF25 + C_L| 2.37 ± 0.04 b | 0.87 ± 0.03 b       | 16.9 ± 0.4 b       | 78.4 ± 2.6 a       | 196 ± 7 ab        | 24.6 ± 0.5 b       |
| 2020 × SCF75 + FCF25 + C_LB| 2.86 ± 0.05 a | 0.92 ± 0.03 a       | 19.8 ± 0.4 a       | 86.8 ± 2.8 a       | 218 ± 7 a         | 28.8 ± 0.6 a       |

** and * indicate, respectively, differences at p ≤ 0.05 and p ≤ 0.01 probability level, respectively. Mean values with different letters in each column are significant (p ≤ 0.05). TChl = total chlorophylls, Fv/Fm = chlorophyll fluorescence, PI = performance index, SCF100 = chemical fertilizers applied to the soil at full recommended NPK doses, SCF75 = chemical fertilizers applied to the soil at 75% of recommended NPK doses, FCF25 = chemical fertilizers applied as foliar sprays at 25% of recommended NPK doses, C_L = 1.2 kg leguminous compost m⁻², and C_LB = biocompost; leguminous compost (1.2 kg m⁻²) containing bacteria.

Figure 1. Response of cation exchange capacity to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at p ≤ 0.05.

Figure 2. Response of soil organic C content to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at p ≤ 0.05.
**Figure 3.** Response of soil enzyme activities (cellulase) to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$.

**Figure 4.** Response of soil enzyme activities (invertase) to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$.

**Figure 5.** Response of soil enzyme activities (urease) to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$. 
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Figure 6. Response of soil enzyme activities (catalase) to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$.

Figure 7. Response of leaf nonenzymatic antioxidants contents (ascorbic acid—AsA) of Phaseolus vulgaris plants to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$.

Figure 8. Response of leaf nonenzymatic antioxidants contents (glutathione—GSH) of Phaseolus vulgaris plants to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at $p \leq 0.05$. 

$\text{GSH content (nmol glutathione g}^{-1} \text{FW)}$  
$\text{AsA content (μmol ascorbate g}^{-1} \text{FW)}$  
$\text{Catalase (μmol d}^{-1} \text{g}^{-1} \text{FW)}$  
$\text{Urease (μg d}^{-1} \text{g}^{-1} \text{FW)}$  
$\text{Invertase (μmol d}^{-1} \text{g}^{-1} \text{FW)}$
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Figure 9. Response of leaf enzyme activity (superoxide dismutase—SOD) of Phaseolus vulgaris plants to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at \( p \leq 0.05 \).

Figure 10. Response of leaf enzyme activity (catalase—CAT) of Phaseolus vulgaris plants to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at \( p \leq 0.05 \).

Figure 11. Response of leaf enzyme activity (guaiacol peroxidase—GPD) of Phaseolus vulgaris plants to different fertilization strategies applied in two seasons (2019 and 2020) to sandy soil. Abbreviations of fertilization treatments are explained in Table 1. Bars with a different letter indicate significant difference between treatments at \( p \leq 0.05 \).
In the 2020 growing season, there were significant ($p \leq 0.05$) increases in available N at 18.5%, K at 21.3%, Fe at 31.9%, Mn at 45.7%, and Zn at 42.3% compared to those obtained in the 2019 growing season (Table 3). The data in Figures 1–6 display that the cation exchange capacity (CEC), organic C content, cellulose, invertase, urease, and catalase activities of the tested soil were significantly increased in the 2020 growing season compared to those achieved in the 2019 season. As shown in Table 4, shoot fresh and dry weights, and green pods and dry seed weights of *Phaseolus vulgaris* plants were significantly ($p \leq 0.05$) increased by 20.8, 15.6, 14.5, and 28.4%, respectively, in the 2020 season compared to those gained in the 2019 season. The plant nutrient contents represented the same behavior of the soil nutrient contents, since N, P, K, Fe, Mn, and Zn contents were significantly ($p \leq 0.05$) increased by 19.9, 25.4, 15.8, 17.5, 23.9, and 19.8% in the 2020 growing season compared to those collected in the 2019 season (Table 5). The data in Table 6 and Figures 7–12 revealed that the physiobiochemical attributes (e.g., total chlorophyll content, Fv/Fm, PSII performance index, leaf relative water content, proline content, total soluble sugar content, ascorbate content, glutathione content, protein content, and leaf enzymatic activity of guaiacol peroxidase, catalase, and superoxide dismutase) of *Phaseolus vulgaris* plants were significantly elevated in the 2020 season compared to those determined in the 2019 season. The total chlorophyll content, Fv/Fm, PSII performance index, leaf relative water content, proline content, total soluble sugar contents were increased by 21.6, 7.8, 16.1, 13.5, 15.6, and 24.4%, respectively. Besides this, the contents of ascorbate, glutathione, and protein, as well as the activities of guaiacol peroxidase, catalase, and superoxide dismutase, were increased by 39.3, 19.4, 27.9, 31.3, 24.5, and 12.2, respectively.

### 3.3. Response of Soil Chemical Properties and Plant Performances to Different Fertilization Strategies

Some fertilization strategies (sub-main factor) were applied to the nutrient-deficient virgin sandy soil tested in this study, and they positively influenced the soil chemical properties, soil and plant contents of essential nutrients and activities of various enzymes, plant growth and productivity, and plant physiobiochemistry (Tables 3–6 and Figures 1–12).

All blended fertilization strategies used in this study significantly increased the chemical properties of the tested soil, soil and plant contents of essential nutrients and activities of various enzymes, plant growth and productivity, and the plant physiobiochemistry, excluding some exceptions recorded by $S_{CF75} + F_{CF25}$ treatment compared to control ($S_{CF100} = $ chemical fertilizers applied to the soil at full recommended NPK doses). Among all fertilization strategies, the $S_{CF75} + F_{CF25} + C_{LB}$ was the best treatment. It conferred ($p \leq 0.05$) significant increases in soil content of available N, Mn, and Zn by 56.7, 61.3, and
50.9%, respectively (Table 3), and soil cellulase and urease activities by 80.1 and 54.5%, respectively (Figures 3 and 5), compared to control. Besides this, it awarded highly significant ($p \leq 0.01$) increases in soil content of available P, K, and Fe by 84.7, 58.9, and 82.6%, respectively (Table 3), and soil CEC, organic C content, and invertase and catalase activities by 83.0, 100.4, 104.3, and 89.7%, respectively (Figures 4 and 6), compared to control. For *Phaseolus vulgaris* plant, the best treatment ($S_{CF75} + F_{CF25} + C_LB$) also conferred highly significant ($p \leq 0.01$) increases in shoot fresh weight and dry seed weight by 70.6 and 109.6%, respectively (Table 4), contents of P, Mn, Zn, total chlorophylls, proline, soluble sugars, and ascorbate by 98.6, 83.3, 76.0, 103.8, 50.7, 85.9, and 83.3%, respectively (Figures 7 and 12), and activities of superoxide dismutase, catalase, and guaiacol peroxidase by 93.7, 84.6, and 79.7%, respectively (Figures 9–11), compared to control. It contributed significant ($p \leq 0.05$) increases in shoot dry weight and green pods weight by 51.3 and 56.9%, respectively (Table 4), contents of N, K, Fe, glutathione, and protein by 73.4, 68.0, 71.0, 61.6, and 36.0%, respectively (Table 5; Figures 8 and 12), and in Fv/Fm, performance index, and relative water content by 25.4, 60.9, and 45.1%, respectively (Table 6), compared to control ($S_{CF100}$).

### 3.4. Response of Soil Chemical Properties and Plant Performances to the Interaction between Growing Season and Different Fertilization Strategies

The interaction between growing season and fertilization strategies and their influences on the chemical properties of the tested soil, soil and plant contents of essential nutrients and activities of various enzymes, plant growth and productivity, and plant physiobiocchemistry under nutrient-deficient virgin sandy soil conditions are shown in Tables 3–6 and Figures 1–12.

Among all interactions, the application of 2019 × $S_{CF100}$ (control) or 2019 × $S_{CF75} + F_{CF25}$ collected the lowest findings of all determined soil and plant parameters. However, 2020 × $S_{CF75} + F_{CF25} + C_LB$ was the best interaction treatment, which conferred significant ($p \leq 0.05$) or highly significant ($p \leq 0.01$) increases in all tested soil and plant parameters. It conferred ($p \leq 0.05$) significant increases in soil content of available N, Mn, and Zn by 82.0, 149.1, and 120.7%, respectively (Table 3), and soil cellulase and urease activities by 104.6 and 115.0%, respectively (Figures 3 and 5), compared to control. Besides, it contributed highly significant ($p \leq 0.01$) increases in soil content of available P, K, and Fe by 131.7, 91.0, and 131.5%, respectively (Table 3), and soil CEC, organic C content, and invertase and catalase activities by 124.8, 256.9, 179.1, and 127.5%, respectively (Figures 4–6), compared to control. For *Phaseolus vulgaris* plant, the best interaction treatment (2020 × $S_{CF75} + F_{CF25} + C_LB$) also conferred highly significant ($p \leq 0.01$) increases in shoot fresh weight and dry seed weight by 102.1 and 165.2%, respectively (Table 4), contents of P, Mn, Zn, total chlorophylls, proline, soluble sugars, and ascorbate by 159.0, 121.9, 109.0, 155.4, 74.4, 132.3, and 124.3%, respectively (Tables 5 and 6; Figure 7), and activities of superoxide dismutase, catalase, and guaiacol peroxidase by 143.5, 136.4, and 130.3%, respectively (Figures 9–11), compared to control. It contributed significant ($p \leq 0.05$) increases in shoot dry weight and green pods weight by 75.4 and 82.7%, respectively (Table 4), contents of N, K, Fe, glutathione, and protein by 103.9, 94.4, 100.0, 87.7, and 51.4%, respectively (Table 5; Figures 8 and 12), and in Fv/Fm, performance index, and relative water content by 35.3, 90.4, and 65.6%, respectively (Table 6), compared to control ($S_{CF100}$).

### 4. Discussion

Climate change, as one of the major challenges facing the world at present, has negatively affected agricultural lands. Furthermore, future changes in climatic events are expected to worsen [58], particularly in arid and semi-arid regions [59–63]. As a consequence, soils have lost much of their fertility, threatening the food security of the world [58,64–70]. Accordingly, to maintain sustainable agricultural development, virgin (unused) lands that can be cultivated with more organic and less chemical fertilization, are being, or should be, used to minimize pollutants to produce clean agricultural products free of pollution [71].
Sandy soils suffer from high permeability coupled with poor water retention, which results in the loss of many important nutrients due to poor ability to retain many important nutrients, besides, the competition of cations, and consequently the rapid leaching [1, 72–74]. Besides, if such soil was virgin, its suffering would have been greater. Therefore, it is necessary to improve the weaknesses of this soil by nourishing it with organic fertilizers, especially biocomposts, because they enhance microbial decomposition leading to humification of organic matter [75] in favor of the soil and plants growing on it.

The virgin sandy soil used in this study had very low water and nutrient holding capacity and a poor cation exchange capacity (CEC), making it impossible to rely on adding nitrogen, phosphorus, and potassium (NPK) fertilizers only, otherwise, these fertilizers are rapidly lost. Therefore, to minimize fertilizer nutrient loss, it is appropriate to add a portion of the recommended NPK fertilizer (about 25%) to the plant as a foliar spray in combination with adding another portion (about 75%) to the soil with the addition of an appropriate amount of organic (SCF75 + FCF25 + C1) or bio-organic fertilizer (SCF75 + FCF25 + C1B) as a required strategy for the sustainability and productivity of plants growing on the tested soil. From this point of view, the SCF75 + FCF25 treatment went beyond the control treatment and significantly increased soil physicochemical properties (Tables 2 and 3; Figures 1–6) and Phaseolus vulgaris plant growth, productivity, and physiobiochemical attributes (Tables 4–6; Figures 7–12). Enrichment of the SCF75 + FCF25 treatment with leguminous compost (C1L) at 1.2 kg per m² (SCF75 + FCF25 + C1L) increased the treatment efficiency, as it exceeded the SCF75 + FCF25 treatment, resulting in a significant increase in the tested soil and plant attributes (Tables 3–6; Figures 1–12). Moreover, enrichment of the C1L in the SCF75 + FCF25 + C1L treatment with bacteria (Bacillus subtilis) further increased the treatment efficiency, as the SCF75 + FCF25 + C1B treatment greatly exceeded the SCF75 + FCF25 + C1L treatment, resulting in a further significant improvement in soil and plant attributes (Tables 2–6; Figures 1–12).

Therefore, from our findings of the tested virgin sandy soil and Phaseolus vulgaris plant, the SCF75 + FCF25 + C1L B treatment was the best, with the best improvement results for the soil texture, pH, ECv, and CaCO3 content in both the 2019 and 2020 seasons (Tables 2–6; Figures 1–12). These improvements were attributed to the leguminous bio compost (C1L B), which provided soil characteristics, in addition to the NPK nutrients that the plant acquired through two pathways: roots and leaves. In addition, compared to all treatments, including the control, the SCF75 + FCF25 + C1B treatment significantly increased CEC, soil organic carbon (C) content, soil nutrient (N, P, K, Fe, Mn, and Zn) contents, and soil enzymes (e.g., cellulase, invertase, urease, and catalase) activities (Table 3 and Figures 1–6).

Soil pH was decreased with soil supplementation using C1B, which could be attributed to the increase in organic C content and soil enzyme activities (Figures 1–6), which led to the decomposition of the added organic matter (in C1B). Besides, organic acids and phytohormones (e.g., indole acetic acid and cytokinins) resulting from the activity of bacteria added to the compost, leading to an increase in biological activity [33, 76–78]. As obtained in this study (Table 2), a decrease in pH is reported with the combined use of biocompost and inorganic fertilizer [79]. This positive result is attributed to the production of organic acids due to biocompost decomposition followed by an increase in the salt content of the soil due to mineralization, which increases the EC of the soil. Sinha et al. [79] also reported that soil pH decreased while EC increased, due to biocompost application, which also had a significant influence on soil organic C content and available nutrients (e.g., N, P, K, and S).

Furthermore, supplementing the soil with C1B enhanced the microbial decomposition that leads to an increase in soil organic matter and thus CEC (Figures 1–6). Buragohain et al. [75] found that the biocompost generates a large number of different bacteria that cause an increase in soil organic matter, which leads to improved crop growth. This subsequently results in increased exudations of plant roots and return of post-harvest residues, thus contributing to the organic content of the soil. They also documented that the observed high contribution of biocompost to soil organic C indicates more rebellious forms of soil organic C, thus resulting in enhanced soil C stabilization. Soil organic C
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... elevation is also observed following the application of biofertilizers (Bacillus megatherium and Bacillus mucilaginous), as per Wu et al. [80]. Increase of CEC after application of compost [21], and in particular bio compost, is an indication of a high accumulation of soil organic C pool along with low inorganic P and N. The decreased inorganic P and N following the application of bio compost contribute to building a soil environment where a desirable microbial composition is created to stabilize the soil organic carbon pool [75]. They also reported that the quality of organic matter and fertility of the soil is improved due to the increased humic/fulvic acid ratio due to the increased rate of humification, which helps to raise the stability of organic C as a result of bio compost supplementation to the soil [81].

The buildup of available nutrients in nutrient-deficient soils, such as the soil tested in this study, can be attributed to the increased microbial proliferation due to the addition of organic manures, especially bio compost, which helps in mineralization as well as solubilization of native nutrients by complexation of nutrients by humic and fulvic acid contained in bio compost [79]. The results of this study indicated that the application of NPK fertilizers only was not effective in maintaining soil fertility (Tables 2 and 3; Figures 1–6). The nutrients available in the soil and soil organic C were preserved in the treatment containing bio compost. It has been reported by Sinha et al. [79] that soil fertility-contributing bulk density and pore spaces are improved effectively due to the accumulation of organic C content of the bio compost-treated soil. The beneficial influences of bio compost in improving the soil’s physical and chemical properties may be attributed to the improvement in the organic matter status of the soil treated with bio compost, which leads to the buildup of soil fertility for sustainable production of Phaseolus vulgaris. Sinha et al. [79] also explained that the use of bio compost greatly increases the soil microbial population, which utilizes the accumulated organic C as a source of energy, nutrients, and nourishment, which leads to the spread of microorganisms in the soil. This improved microbial community and activity due to the accumulation of organic matter by the application of bio compost help maintain soil fertility and productivity due to the faster decomposition rate and smooth mineralization of organic materials [79].

As shown in the data of this study, the combined use of bio compost and inorganic fertilizers (applied to both soil and plant leaves) effectively increased the uptake of nutrients, which reflected positively on the higher yield (Tables 4 and 5). Managing nutrients through organic and inorganic sources leads to more nutrient uptake. As of the effectively increased parameters due to the combined use of C1B and inorganic fertilizers, the soil organic C content and availability of nutrients (e.g., N, P, K, Fe, Mn, and Zn) in the tested virgin sandy soil may be attributed to the increased content of organic C and nutrients in the C1B and the beneficial advantages of inorganic nutrients. These nutrients are released from the compost into the soil through bacterial decomposition [82] present in C1B, which is activated by the added compost. Manirakiza and Seker [77] reported increased contents of soil nutrients and organic C which could be attributed to the compost’s richness in organic C and various nutrients. The release of nutrients from compost into the soil via the mineralization process can elucidate this result [77,83].

Compared to all other treatments, including the control, the SCF75 + CF25 + C1B treatment significantly increased soil enzymes (e.g., cellulase, invertase, urease, and catalase) activities, especially after adding C1B, indicating a potentially greater source of beneficial microbes. The increased activity of soil enzymes contributed to the release of more nutrients for microbial use [75]. Besides, the bacteria present in the C4B have desirable influences on increasing and stabilizing bacterial populations [84], which contributed along with the increased soil enzyme activities to repair limitations of the soil tested.

Macci et al. [85] and Buragohain et al. [75] demonstrated that compost and bio compost fertilizers increase soil quality due to enhancements of soil properties related to physicochemistry and biochemistry. This positive finding is confirmed by the results obtained for the tested virgin sandy soil, which reflected positively in the growth, productivity, and physiobiochemical indices of Phaseolus vulgaris plants (Tables 4–6; Figures 7–12). The
increased availability of nutrients to the plants as a result of the improved physicochemical properties of the tested soil under supplementation of biocompost contributed to the increase in growth and physiobiochemical indices, and thus the productivity of *P. vulgaris* plants. As reported in [86], compost enriched with many bacterial strains (e.g., *Bacillus, Rhizobium, Azotobacter, Azospirillum, Bradyrhizobium, Acetobacter*, and *Pseudomonas*) has been reported to improve yields of different crops in some defective soils. Furthermore, it has been explained by Sinha et al. [79] that the immediate and rapid supply of nutrients through an inorganic source for plant growth and a steady supply of nutrients by organics, especially biocompost, throughout the growth period leads to an increase in plant yield due to integrated use of organic and inorganic nutrients. The biocompost releases nutrients after decomposition and mineralization that will increase the availability of nutrients at a later stage and improve physical, chemical, and biological properties of soil, resulting in improved soil fertility and absorption of nutrients by the plant. The integrated use of organic nutrient sources with inorganic fertilizers has been shown to increase the potential of organic fertilizers [79].

The growth and yield trend after two consecutive trial years of *P. vulgaris* plants showed that reducing 25% of the recommended NPK fertilizer dose of soil addition for use in foliar spraying along with the application of biocompost resulted in a progressive increase in the growth and yield of *P. vulgaris* plants (Table 4). Thus, the $S_{CF75} + F_{CF25} + C_{LB}$ treatment represented the highest sustainability for a period of two seasons (2019 and 2020). Allocating 25% of the NPK fertilizers to foliar spray conferred the opportunity to reduce the inorganic minerals added to the soil along with the use of $C_{LB}$ to conserve the soil while increasing its fertility (Tables 2 and 3; Figures 1–6). Besides, it increased the efficiency of the growing *P. vulgaris* plants in sandy soil to obtain all their nutritional needs, especially in the presence of $C_{LB}$ that facilitates nutrient uptake. Foliar spraying with NPK nutrients has become a concern of scientists for its dynamic application to increase plant growth and yield [17,87] (Tables 2–6; Figures 1–12).

As explained in [88], the increase in plant growth and productivity can be attributed to the positive influences of biocompost and its content of microorganisms in raising root surfaces, root distribution, water-use efficiency, and photosynthetic activity. These positive results directly affect the physiological processes and carbohydrate metabolism due to the high levels of nutrients and organic matter in the applied biocompost. Similarly, our data attributed the increases in growth and productivity of *P. vulgaris* plants to the application of $C_{LB}$, which contributed to improved phytoneutrient contents (Table 3), photosynthetic efficiency (chlorophyll content, chlorophyll fluorescence, and PSII performance index), and relative cellular water content (Table 4), as well as the plant’s antioxidant defense system; osmoprotectants (proline and sugars) and both enzymatic and nonenzymatic antioxidants (Table 6 and Figures 7–12).

The physicochemical properties and fertility of the virgin sandy soil, including the soil’s organic C content and organic acids, which were greatly improved by applying $C_{LB}$ (Tables 2 and 3; Figures 1–6), led to an increase in water retention in the soil [89], allowing *P. vulgaris* plants to absorb more water and nutrients, leading to increased relative cellular water content and different nutrient contents (Tables 4–6). Relative cellular water content indicates the water status in plants, reflecting the activity of plant metabolic processes, and is utilized as an indicator to distinguish between legumes with contrasting variations in drought tolerance [90]. The increased plant water and nutrient contents through the application of $S_{CF75} + F_{CF25} + C_{LB}$ played crucial roles in improving the efficiency of photosynthesis and the antioxidant defense system (Table 4 and Figures 7–12), which need water as a medium for their reactions to take place [22,91]. The $S_{CF75} + F_{CF25} + C_{LB}$ including $C_{LB}$ notably improved *P. vulgaris* plant water content due to the improved water uptake by roots and as a result of the accumulation of elemental K, free proline, and soluble sugars as osmoprotectant compounds [47,73]. Furthermore, the accumulation of ascorbate and glutathione with the $S_{CF75} + F_{CF25} + C_{LB}$ treatment contributed to the improved tissue water status and membrane integrity by reducing the activity of the
reactive oxygen species (ROS) [47,92,93]. It has been explained that the accumulation of K+*, free proline, and soluble sugars as osmolytes contributes to osmotic adjustment, which helps to maintain the cell turgor and stabilize the membranes by activation of antioxidant plant defense system [73,94–99]. This is also evident from improvement in antioxidant enzymes activities in this study (Figures 7–12), such as superoxide dismutase (SOD), catalase (CAT), and guaiacol peroxidase (GPOD), including leaf content of protein for the SCF75 + FC25 + C1B treatment in P. vulgaris plants grown under the tested conditions. Enhanced activities of assayed antioxidant enzymes with the SCF75 + FC25 + C1B treatment have been also associated with improved photosynthetic activity and carbohydrates supply to growing sink [73], which contributed towards increased growth and yield of P. vulgaris plants. This increase in P. vulgaris plant performance with the SCF75 + FC25 + C1B treatment is also associated with its influences on different physiological mechanisms and enzymes such as starch metabolism and glucose transport during photosynthesis and accumulation period [100]. All these findings were reflected, positively, in P. vulgaris plant growth and productivity (Table 4).

Soil application with C1B (compost + bacteria) can integrate conventional NPK fertilizers that should be applied to both soil and plant (foliar spray) in the cultivation of P. vulgaris and other crops using the defective sandy soils to improve plants’ efficiency for good production and minimize contamination of farmland and agricultural products achieving agricultural sustainability.

All results of the 2020 season notably exceeded those of the 2019 season in terms of all the attributes examined for soil physicochemical properties and P. vulgaris plant growth, yield, and physiobiochemistry (Tables 2–6; Figures 1–12). This may be attributed to the residual effects of the first year’s treatments, which provided the opportunity to liberate nutrients in excess amounts from the soil due to the elevated bacterial decomposition of the biocompost applied in the preceding season (2019), as well as the increased solubility of nutrients that contained in the biocompost.

5. Conclusions

The positive influences of leguminous biocompost in integration with reducing 25% of the recommended NPK fertilizers on soil fertility and physicochemical properties, as well as P. vulgaris plant growth, productivity, and physiobiochemical attributes, have been elucidated in a virgin sandy soil. Soil application with leguminous biocompost at a rate of 1.2 kg per m² + 75% of the recommended NPK fertilizer doses in integration with 25% of the recommended NPK fertilizer doses as a foliar spray for P. vulgaris plants resulted in significant improvements in soil fertility, physicochemical properties and plant physiobiochemical attributes, which were positively reflected in the plant growth and yield. These positive soil and plant results indicate the positive influences of biofertilizers as a supplementary fertilizer strategy for integrating soil application with NPK fertilizers, allocating a portion of mineral fertilizers for foliar spraying for sustainable agriculture using virgin sandy soils that can be used for the expansion of crop cultivation.

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