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Maximizing Common Bean (*Phaseolus vulgaris* L.) Productivity Through Application of Organic and Inorganic Fertilizers in Alkaline Soil

Safiullah Habibi [1,*], Shafiqullah Aryan [2], Ali Yawar Seerat [1], Kalimullah Saighani [3] and Mohammad Daud Haidari [4]

[1] Faculty of Agriculture, Tokyo University of Agriculture and Technology (TUAT), Saiwai-cho 3-5-8, Fuchu City, Tokyo 183-8509, Japan; aliwarasi@gmail.com
[2] Faculty of Agriculture, Tokyo University of Agriculture, Sakuragaoka 1-1-1, Setagaya City, Tokyo 156-8502, Japan; shafiqaryan@gmail.com
[3] School of Biology, Biomedical Sciences Research Complex, University of St. Andrews, St Andrews KY16 9TS, UK; kamransaighani1@gmail.com
[4] Department of Soil Science and Irrigation, Faculty of Agriculture, Kabul University, Kabul 1001, Afghanistan; m.daud.haidari@gmail.com
* Correspondence: safiullahhabibi23@gmail.com

Abstract: Common beans are a vital source of protein, vitamins, and minerals. Increasing common beans productivity is crucial for improving food security and farmers' incomes globally. This study evaluated the growth and yield responses of common beans to integrated organic and inorganic fertilizers under field conditions at the Faculty of Agriculture, Kabul University. The trial was repeated over two consecutive growing seasons in 2020 and 2021, using a randomized complete block design with 18 treatments and three replications. The fertilizers used included urea (N) (0, 60, and 90 kg/ha), diammonium phosphate (D) (0, 50, and 100 kg/ha), and farmyard manure (O) (0 and 5000 kg/ha). The results show that integrated fertilizers, particularly O5000N60D50, O5000N60D100, O5000N90D50, and O5000N90D100, significantly increased growth and yield parameters. In 2020, the grain yield increased significantly ($p < 0.05$) by 75.6, 76.7, and 68.4% with the O5000N60D50, O5000N60D100, and O5000N90D100 treatments, respectively. In 2021, O5000N60D50, O5000N60D100, and O5000N90D50 showed significant yield increases of 94.7, 89.6, and 97.9%, respectively. The grain yield strongly correlated with the SPAD value (r = 0.84), number of pods per plant (r = 0.71), and number of seeds per pod (r = 0.66) in 2020, and it more strongly correlated with the SPAD value (r = 0.91), number of pods per plant (r = 0.77), and number of seeds per pod (r = 0.76) in 2021. A principal component analysis highlighted the effectiveness of organic–inorganic fertilizer combinations, particularly O5000N60D50, in enhancing productivity while potentially reducing inorganic fertilizer application. This study demonstrates that integrating organic and inorganic fertilizers enhances sustainable crop productivity and reduces negative environmental impacts, particularly in regions facing nutrient depletion and drought conditions.

Keywords: common bean; organic and inorganic fertilizers; yield; productivity; alkaline soil

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Academic Editor: Adriana Basile

Received: 10 December 2024
Revised: 15 March 2025
Accepted: 17 April 2025
Published: 1 May 2025

Citation: Habibi, S.; Aryan, S.; Seerat, A.Y.; Saighani, K.; Haidari, M.D. Maximizing Common Bean (*Phaseolus vulgaris* L.) Productivity Through Application of Organic and Inorganic Fertilizers in Alkaline Soil. *Appl. Biosci.* **2025**, *4*, 22. https://doi.org/10.3390/applbiosci4020022

1. Introduction

Common beans (*Phaseolus vulgaris* L.) are one of the world's main staple crops [1], which are widely cultivated and consumed [2–4] because of their high quality and nutritional value. Common beans provide valuable nutritional food containing high-quality protein, fiber, and other essential components [4–7]. In addition to their nutritional value, common beans are vital for income generation, boosting soil fertility, and animal feeding [8]. Moreover, farmers prefer common bean cultivation because of its early maturity, nutritional qualities, and better adaptation to various climates and soil conditions than other legumes [9]. Common beans, as members of leguminous crops, can contribute to soil fertility improvement through biological nitrogen fixation (BNF) by rhizobial microsymbiont in the plant root nodules [10–12]. BNF is a significant process in mitigating synthetic nitrogen fertilizer pollution, in which nitrogen can easily leach and cause soil degradation, soil acidification, depletion of organic matter, and global warming while conserving a sustainable agroecosystem [13–15]. This process supplies 200 million tons of N annually to aquatic and terrestrial ecosystem [16]. Incorporating legumes into cereal rotation effectively promotes plant growth [17] through soil fertility improvement, alleviating the effects of climate change, restoring soil organic matter, and mitigating pest and disease problems [18,19].

The crop rotation of various beans has been revealed to be an effective way to improve soil conditions and strengthen wheat crop rotation [14,20]. Cultivated beans increase soil nutrient availability, improve soil productivity, and interrupt pest and disease cycles in crop rotation systems. Thus, they provide a productive system for the next crop planting [21].

Organic fertilizer applications can increase water-holding capacity, enhance physical and chemical properties, and improve soil structure, thereby improving soil health, fertility, and sustainable crop productivity [15,22–25]. Furthermore, adding organic fertilizer to soil provides a rich source of food for various microbial communities and influences their composition compared to without application [26]. In addition, farmers have greater access to organic materials than chemical fertilizers because of their low cost and local availability in different regions. Incorporating chemical fertilizers with various organic fertilizers is considered a practical approach to boosting soil fertility and increasing cereal crop yields in crop rotation systems [10,27]. Previous studies have indicated that the combined application of organic and inorganic fertilizers may have the potential to significantly enhance the growth and yield of various crops, such as soybean [28], maize [29], tomato [30], and maize–wheat, in a cropping system [31]. They highlight that the integration of chemical fertilizers and manures is beneficial for sustainable yield productivity through improving soil fertility.

Twenty years and frequent drought occurrences have adversely influenced food security and agriculture in Afghanistan [32,33]. Livestock and legume products are primary protein sources that enhance food security in Afghanistan [34]. Common bean is widely cultivated in various regions of Afghanistan and accounts for about 16% of cultivated legumes and 69,000 hectares of land in 2020 [35]. Common beans are extensively used in the country as the cheapest and most available protein source and as a poor man's meat [36].

Therefore, increasing common bean productivity is necessary to provide adequate protein for poor Afghan households, alleviate poverty in Afghanistan, and increase farmers' incomes in rural areas. As primary inputs, inorganic fertilizers are applied to enhance the growth and yield of common beans. However, the excessive application of chemical compounds, including fertilizers, is a primary concern related to environmental pollution in Afghanistan [37,38], especially river and groundwater contamination [39]. Furthermore, the availability of chemical fertilizers is limited for some farmers due to their high costs [10] and unstable markets [40]. Therefore, the combined use of organic and inorganic fertilizers might be suitable for reducing chemical fertilizer applications and moving toward a sustainable and sound agroecosystem [30,31,41] in the country. This study is significant as it explores the integration of organic and inorganic fertilizers to enhance common bean productivity in Afghanistan, where reliance on costly inorganic fertilizers poses a significant environmental challenge [42,43]. The findings could provide sustainable, cost-effective solutions for smallholder farmers, improving soil health, boosting yields, and reducing environmental degradation. The research also has broader implications for regions facing similar agricultural challenges, contributing to the development of sustainable farming practices worldwide.

The objectives of this study were (1) to evaluate the impact of integrating organic (farmyard manure) and inorganic (urea and diammonium phosphate (DAP)) fertilizers on the growth and yield of common bean and (2) to find the most optimal integrated rates of applied fertilizers for improving sustainable common bean productivity in Afghanistan.

2. Materials and Methods

2.1. Experimental Design and Site Description

A field trial was conducted over two consecutive years, with the first experiment in 2020 and the second in 2021. Both experiments were carried out in the research field of the faculty of Agriculture at Kabul University, Kabul, Afghanistan (Figure 1). It was located at coordinates N 34.517175 and E 69.139377, at an altitude of 1789 m above sea level, as mentioned in our recently published study [28].

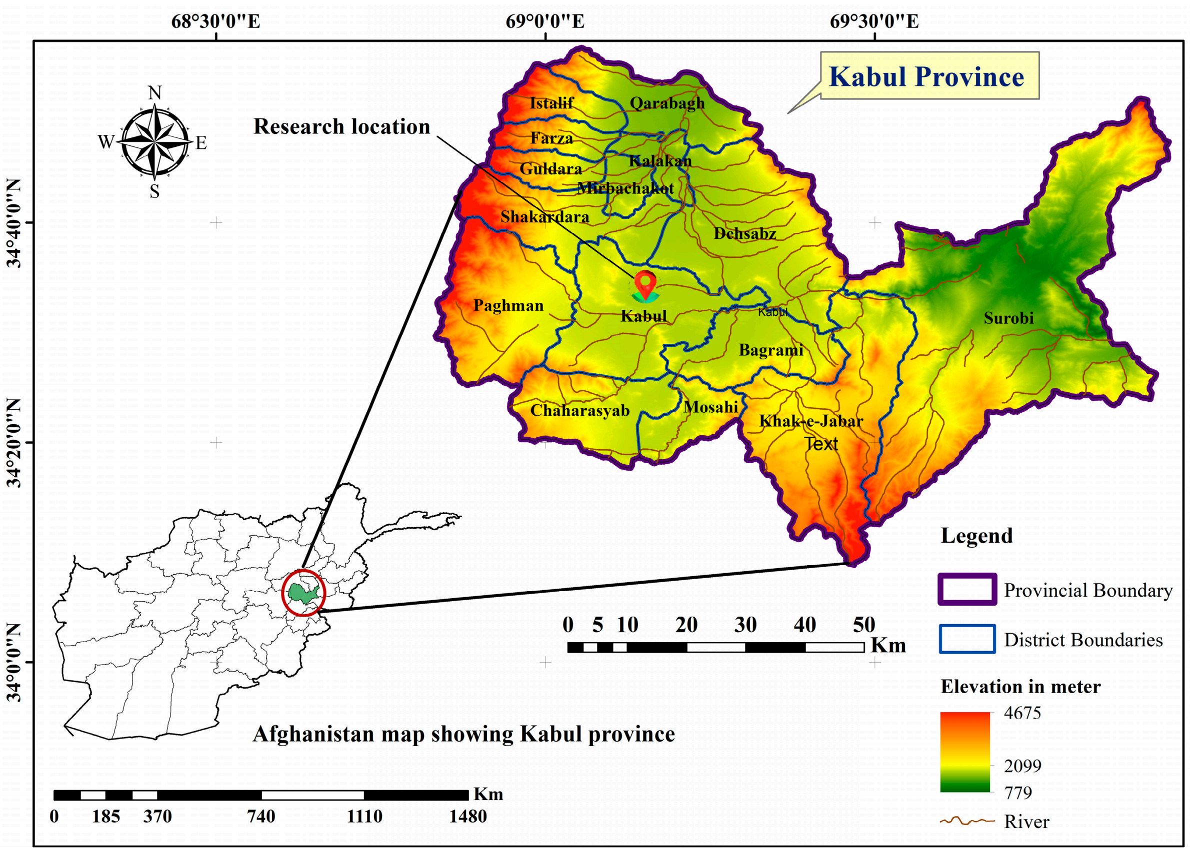

Figure 1. Afghanistan map and research site location in Kabul province.

The climate in Kabul is arid and semi-arid, and cultivated crops frequently acquire irrigation. The soil's characteristics indicated a pH of 8.2, calcareous soil, low organic matter, and a silty loam soil texture at a depth of 0–30 cm (Table 1).

The experiments were conducted from May 3 to August 30 in 2020, and from May 5 to September 10, in 2021. The research was carried out using a Randomized Complete Block Design (RCBD) consisting of eighteen treatments with various levels of fertilizers and three replications. Each plot was 2 m × 2 m in size. The land was plowed and leveled using a

240 Massey Ferguson tractor. The first irrigation was applied to specify the water border and suitable placement of the seed in the plot.

Prior to cultivation, a seed germination test was conducted to assess seed germination viability. A local common bean variety (Capsuli) was cultivated using an inter-row spacing of 70 cm and 10 cm between the plants (intra-row spacing), with 180,000 plants per ha. Well-decomposed organic fertilizer was added to the plot two weeks before the planting and mixed with the soil surface.

Table 1. Physical and chemical characteristics of the field soil used for common bean cultivation.

Soil Characteristics	Amount
pH	8.2
EC (dS/cm)	17.8
Organic matter (%)	0.7
Nitrogen (ppm)	8.9
Phosphorus (ppm)	8.7
Potassium (ppm)	73.2
Calcium carbonate ($CaCO_3$, %)	15.1
Sulfur (ppm)	7.1
Magnesium (ppm)	11.2
Soil texture	Silty loam

Eighteen treatment combinations were designed and implemented to optimize fertilization practices for common bean production. These treatments involved varying the amounts and combinations of chemical fertilizers to assess their impact on crop yield and overall productivity. The urea fertilizer (N), containing 46% nitrogen, was applied at rates of 0, 60, and 90 kg/ha, while DAP (used as 'D' in the treatment combinations), containing 18% nitrogen and 46% phosphorus, was applied at rates of 0, 50, and 100 kg/ha. Farmyard manure (O) was also used at 0 and 5000 kg/ha. Nitrogen fertilizer was applied twice during the crop's growth, as follows: 70% at the cultivation stage and 30% during the flowering stage. All phosphorus fertilizer was applied during cultivation. Although common beans are nitrogen-fixing legumes, additional nitrogen supplementation was required because of the low organic matter content and alkaline nature of the soil in Kabul [28]. During the growing season, weeds were regularly removed after two weeks using hand hoeing. The cultivated plants were irrigated according to their water requirements. The integration of various fertilizers in eighteen treatments is shown in Table 2.

Additionally, the climate conditions, including precipitation, reference evapotranspiration (ETo), temperature and growing degree days (GDD), are shown in Figure 2. The GDD for common bean was determined, as described by Aryan et al. [44], using the following formula:

$$\mathrm{GDD} = \sum((\mathrm{Tmax} + \mathrm{Tmin})/2 - \mathrm{T_b})$$

The T_b (T base) value was used at 10 °C, as reported in previous studies [45,46] for bean crops.

Table 2. Description of treatments and the results of various organic and inorganic fertilizers' effects on cultivated common bean growth attributes. Highlighted bold numbers indicate effective treatment combinations of different fertilizers on growth attribute parameters.

Organic Manure (kg/ha)	Urea (kg/ha)	DAP (kg/ha)	Plant Height (cm)		Number of Leaves		Number of Branches		SPAD Value	
			2020	2021	2020	2021	2020	2021	2020	2021
0	0	0	39.2 ± 2.5 b [†]	42.7 ± 2.5 b	18.3 ± 2.6 b	19.3 ± 1.5 b	3.9 ± 1.3 b	3.5 ± 0.6 b	30.5 ± 1.7 d	29.7 ± 1.5 c
		50	42.2 ± 3.1 ab	43.1 ± 3.9 b	20.3 ± 1.5 b	20.2 ± 1.3 b	4.7 ± 0.6 ab	3.8 ± 0.7 b	35.0 ± 2.6 bcd	37.3 ± 2.1 b
		100	40.1 ± 2.6 ab	43.7 ± 5.1 ab	19.2 ± 2.1 b	20.7 ± 0.8 ab	4.8 ± 1.5 ab	3.7 ± 0.5 b	36.3 ± 1.9 abcd	37.6 ± 1.5 ab
	60	0	40.0 ± 2.2 ab	43.6 ± 5.3 ab	19.8 ± 3.7 b	20.1 ± 1.8 b	4.7 ± 1.7 ab	4.4 ± 0.5 ab	36.2 ± 2.5 abcd	37.0 ± 0.6 b
		50	43.5 ± 4.5 ab	44.6 ± 4.1 ab	20.2 ± 0.8 b	23.1 ± 2.3 ab	5.1 ± 1.8 ab	4.6 ± 1.1 ab	36.9 ± 2.6 abc	39.0 ± 1.1 ab
		100	44.7 ± 4.6 ab	45.0 ± 1.5 ab	20.1 ± 0.9 b	22.3 ± 1.5 ab	5.4 ± 0.7 ab	4.9 ± 0.9 ab	38.0 ± 2.0 abc	39.3 ± 1.5 ab
	90	0	42.7 ± 0.6 ab	43.7 ± 4.5 ab	20.0 ± 1.0 b	22.1 ± 1.7 ab	5.6 ± 1.8 ab	3.8 ± 1.1 b	38.3 ± 2.1 abc	39.2 ± 2.1 ab
		50	42.1 ± 2.1 ab	43.2 ± 1.9 b	21.2 ± 1.5 b	21.7 ± 2.7 ab	5.3 ± 0.6 ab	4.3 ± 1.2 ab	39.1 ± 2.3 abc	40.3 ± 1.5 ab
		100	43.3 ± 5.2 ab	45.2 ± 6.6 ab	21.2 ± 1.5 b	23.4 ± 1.2 ab	5.3 ± 0.6 ab	4.8 ± 0.5 ab	39.6 ± 2.5 abc	41.6 ± 1.0 ab
5000	0	0	41.5 ± 4.1 ab	43.6 ± 2.1 ab	21.1 ± 2.1 b	20.3 ± 1.1 ab	4.7 ± 0.8 ab	4.3 ± 0.9 ab	37.0 ± 1.2 abcd	37.7 ± 1.0 ab
		50	41.3 ± 2.0 ab	45.7 ± 3.8 ab	21.3 ± 2.1 b	21.3 ± 1.2 ab	4.8 ± 1.1 ab	4.2 ± 0.6 ab	33.7 ± 1.0 cd	37.3 ± 2.3 b
		100	43.6 ± 2.1 ab	44.1 ± 5.4 ab	21.2 ± 2.6 b	22.3 ± 1.2 ab	5.1 ± 0.2 ab	4.9 ± 0.7 ab	37.0 ± 1.6 abcd	38.6 ± 1.0 ab
	60	0	42.4 ± 3.2 ab	44.3 ± 4.6 ab	21.3 ± 3.5 b	21.7 ± 1.5 ab	5.4 ± 1.4 ab	4.5 ± 1.1 ab	40.1 ± 2.5 abc	39.0 ± 2.6 ab
		50	**46.6 ± 2.5 [‡] a**	**45.5 ± 3.2 ab**	**22.3 ± 1.5 ab**	**23.3 ± 1.1 ab**	**6.4 ± 1.3 a**	**5.3 ± 0.5 a**	**40.9 ± 2.6 abc**	**42.1 ± 2.5 ab**
		100	**44.7 ± 1.4 a**	**45.1 ± 5.1 ab**	**21.9 ± 1.1 ab**	**21.3 ± 1.2 ab**	**5.4 ± 0.8 ab**	**4.6 ± 0.6 ab**	**41.2 ± 1.5 ab**	**41.3 ± 2.1 ab**
	90	0	45.2 ± 9.1 ab	44.4 ± 3.5 ab	21.2 ± 2.6 b	22.7 ± 2.5 ab	5.1 ± 1.9 ab	4.8 ± 0.8 ab	40.9 ± 1.5 abc	41.3 ± 1.5 ab
		50	**44.7 ± 4.9 ab**	**47.1 ± 2.2 a**	**23.8 ± 1.4 a**	**25.1 ± 2.0 a**	**6.1 ± 1.2 a**	**5.5 ± 0.6 a**	**41.3 ± 2.1 ab**	**42.6 ± 0.6 a**
		100	**44.7 ± 4.6 ab**	**45.3 ± 4.7 ab**	**22.3 ± 1.1 ab**	**23.3 ± 2.6 ab**	**5.3 ± 1.7 ab**	**4.7 ± 0.6 ab**	**41.9 ± 1.5 a**	**42.0 ± 1.7 ab**

[†] The letters show differences among treatments according to Tukey's HSD at a 5% level. [‡] Highlighted bold numbers indicate effective treatment combinations of different fertilizers on growth attribute parameters of the common bean crop.

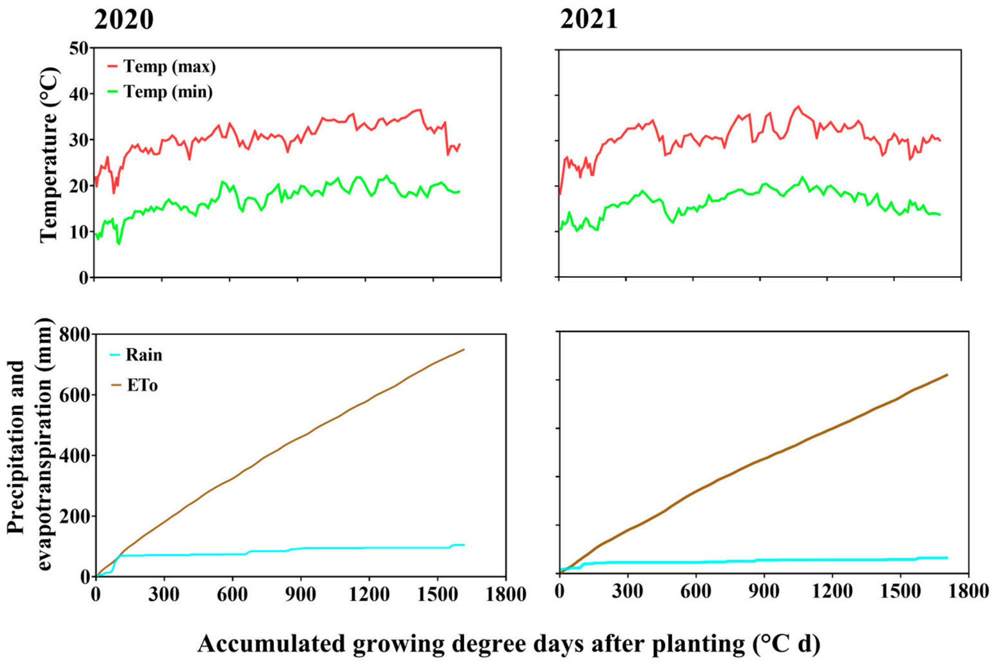

Figure 2. Details of precipitation, temperature, reference evapotranspiration (ETo), and growing degree days (GDD) for common bean in the research field at Kabul University [47].

2.2. Data Collection

Fifteen plants per treatment were selected to measure various growth and yield parameters. The growth attributes, including plant height (cm), the number of leaves, and branches per plant, were recorded 60 days after cultivation. The soil plant analysis development (SPAD) value was measured with a SPAD value meter (SPAD—502 Plus; Spectrum Technologies, Aurora, IL, USA) on the third trifoliate leaf before the flowering stage to evaluate the chlorophyll content of the crops' leaves. The yield components, such as the number of pods per plant, the number of seeds per pod, the 100-seed weight, and grain yield, were measured after the maturation of pods and were gradually recorded until the end of the harvest.

2.3. Statistical Analysis

The data for various growth and yield parameters were statistically analyzed using a two-way analysis of variance (ANOVA), a correlation matrix, and principal component analysis (PCA) in the R language (version 3.6.1). A Tukey post hoc test was performed at a 5% significance level to compare treatment means and identify the most effective treatments for future field applications.

3. Results

3.1. Impact of Combined Fertilizers on Growth Attributes

Generally, the fertilizers' application significantly ($p < 0.05$) improved the growth response parameters like plant height, the number of leaves and branches, and SPAD value. In 2020, the plant height ranged from 39.2 to 44.7 cm, and maximum significant differences of 18.8% and 14.0% were observed through the applications of three integrated types of fertilizer treatments (O5000N60D50 and O5000N60D100) compared with the non-fertilized treatment (O0N0D0) (Table 2). In 2021, the treatment of O5000N90D50 exhibited a considerable plant height increase of 10.3% among the treatments, with a variation of 42.7 to 47.1 cm (Table 2).

The applications of the O5000N90D50 treatment resulted in a significant increase in leaf number, by 30.0% compared with the negative control for two years (2020–2021). In both years, the variation in leaf numbers between the integrated organic and inorganic fertilizer treatments was higher than for a single inorganic fertilizer combination (Table 2).

The number of branches significantly increased through the application of different fertilizer treatments. The highest branch number values were obtained in 2020, with applications of O5000N60D50 and O5000N90D50 treatments at 64.1% and 56.4%, respectively. Moreover, in 2021, the same trend of significant results related to the O5000N60D50 and O5000N90D50 treatments was observed at 35.8% and 41.0%, respectively.

The SPAD values in 2020 varied among the treatments from 30.5 to 41.9, while in 2021, they ranged from 29.7 to 42.6. A gradual increase in SPAD values was observed with the increasing amounts of various combinations of organic and inorganic fertilizers during the two consecutive years (2020–2021) (Table 2). Among the treatments, the highest SPAD value in 2020 was recorded in the treatment O5000N90D100 at 37.4%, followed by O5000N90D50 at 35.4% and O5000N60D100 at 35.0%. In 2021, the treatment O5000N90D50 showed the highest value (39.7%). Notably, adding organic fertilizer significantly improved common bean growth parameters over the two growth seasons.

3.2. Effect of Integrated Fertilizers on Yield and Yield Components

The number of pods per plant over two years significantly varied through applying different fertilizers, ranging from 55.6 to 87.0 in 2020. The maximum values (56.4%, 41.9%) were observed in the O5000N60D50 and O5000N90D50 treatments compared to the negative control (Table 3). In 2021, numerous treatments of organic and inorganic fertilizers exhibited considerable enhancement in the number of pods per plant. The O5000N90D100 treatment displayed the maximum number of pods per plant (54.9%) among the four treatments with the highest number.

In 2020, the number of seeds per pod significantly increased with the application of O5000N60D100, reaching a value of 46.6% compared to the unfertilized treatment. Likewise, in 2021, the treatments O5000N60D50 and O5000N60D100 showed a considerable increase of 42.4% and 39.3% in the number of seeds per pod, respectively. In addition, substantial increases of 33.3% and 36.3 were observed with O5000N90D50 and O5000N90D100 treatments compared to the control (Table 3).

In both years, the weight of 100 seeds varied from 45.8–51.5 g in 2020 and 44.1–51.3 g in 2021. Significant increases in the weight of 100 seeds were observed in many treatments (Table 3), with maximum values of 13.7% and 16.3% noted with the O5000N90D50 treatment in 2020 and 2021, respectively.

The yields over two years (2020 and 2021) significantly ($p < 0.05$) varied among the treatments (Figure 3). In 2020, the application of inorganic fertilizers, such as O0N60D50, O0N60D100, and O0N90D100, resulted in significant increases of 47.5%, 58.3%, and 58.5%, respectively.

Of the organic combination, the O5000N60D50, O5000N60D100, and O5000N90D100 treatments recorded the highest significant increases of 75.6%, 76.7%, and 65.9%, respectively.

Of the inorganic fertilizer combinations (except O0N60D100), the other treatments showed considerable increases in yield parameters. The highest results (79.9% and 80.4%) were observed with the O0N90D50 and O0N90D100 treatments, respectively (Figure 3). For the integrated organic and inorganic fertilizer treatments, O5000N60D50, O5000N60D100, and O5000N90D50 showed significant results at 96.1%, 89.6% and 97.9%, respectively. The statistical analysis revealed significant differences among treatments, with O5000N60D50 consistently showing superior results in growth and yield parameters.

Table 3. Description of the treatments and the results of various organic and inorganic fertilizers' effects on the yield parameters. Highlighted bold numbers demonstrate the effective treatment of different fertilizers in relation to enhancing yield parameters.

Organic Manure (kg/ha)	**Urea (kg/ha)**	**DAP (kg/ha)**	**Number of Pods/Plants**		**Number of Seeds/Pods**		**100-Seeds Weight (g)**	
			2020	**2021**	**2020**	**2021**	**2020**	**2021**
0	0	0	55.6 ± 5.1 c	44.6 ± 5.2 c	3.0 ± 0.1 b	3.3 ± 0.4 b	45.8 ± 1.9 b	44.1 ± 2.6 b
		50	59.7 ± 3.5 abc	46.8 ± 6.8 bc	3.5 ± 0.3 ab	3.4 ± 0.4 b	47.1 ± 1.5 ab	46.1 ± 1.5 ab
		100	63.3 ± 9.8 abc	57.7 ± 2.7 abc	3.6 ± 0.4 ab	3.7 ± 0.2 ab	47.7 ± 2.3 ab	46.0 ± 1.2 ab
	60	0	59.1 ± 1.5 bc	52.8 ± 10.5 abc	3.3 ± 0.9 ab	4.3 ± 0.9 ab	48.1 ± 3.2 ab	46.4 ± 2.5 ab
		50	66.1 ± 11.9 abc	61.2 ± 5.7 abc	3.5 ± 0.2 ab	4.3 ± 0.5 ab	49.0 ± 3.2 ab	47.2 ± 3.2 ab
		100	64.7 ± 11.1 abc	64.3 ± 4.5 abc	3.5 ± 0.2 ab	3.9 ± 0.3 ab	48.9 ± 3.1 ab	46.4 ± 2.1 ab
	90	0	65.1 ± 10.5 abc	65.1 ± 11.3 abc	3.5 ± 0.3 ab	4.2 ± 0.2 ab	49.2 ± 4.3 ab	46.3 ± 3.1 ab
		50	65.0 ± 7.6 abc	68.3 ± 7.2 a	3.6 ± 0.3 ab	3.8 ± 0.2 ab	49.3 ± 6.1 ab	45.6 ± 1.5 ab
		100	64.4 ± 3.7 abc	68.1 ± 3.3 a	4.0 ± 0.8 ab	4.3 ± 0.1 ab	48.6 ± 3.3 ab	45.3 ± 2.1 ab
5000	0	0	68.3 ± 15.3 abc	62.6 ± 4.6 abc	3.1 ± 0.3 b	3.5 ± 0.9 b	48.2 ± 2.1 ab	48.2 ± 2.1 ab
		50	63.7 ± 8.1 abc	55.4 ± 4.9 abc	3.5 ± 0.1 ab	3.9 ± 0.6 b	49.2 ± 1.2 ab	46.7 ± 2.5 ab
		100	72.5 ± 5.5 abc	60.6 ± 8.3 abc	3.8 ± 0.1 ab	4.0 ± 0.2 ab	49.3 ± 0.7 ab	48.3 ± 2.5 ab
	60	0	66.4 ± 7.2 abc	55.4 ± 4.9 abc	4.1 ± 0.3 ab	4.4 ± 0.8 ab	48.2 ± 3.1 ab	46.7 ± 3.5 ab
		50	**87.0 ± 2.6 a**	**66.3 ± 5.5 ab**	**4.1 ± 0.2 ab**	**4.7 ± 0.4 a**	**51.1 ± 1.4 a**	**51.2 ± 1.4 ab**
		100	76.7 ± 5.7 abc	62.7 ± 5.5 abc	**4.4 ± 0.1 a**	**4.6 ± 0.3 a**	**50.8 ± 1.1 a**	**51.3 ± 1.0 a**
	90	0	69.1 ± 5.8 abc	61.6 ± 6.6 abc	4.0 ± 1.0 ab	4.3 ± 0.2 ab	50.1 ± 5.3 ab	46.6 ± 1.5 ab
		50	**78.9 ± 6.6 ab**	**68.8 ± 10.1 a**	**3.9 ± 0.2 ab**	**4.4 ± 0.3 ab**	**52.1 ± 1.7 a**	**51.3 ± 1.9 a**
		100	77.2 ± 9.3 abc	**69.1 ± 5.0 a**	**4.2 ± 0.3 ab**	**4.5 ± 0.7 ab**	**51.5 ± 2.1 a**	**51.3 ± 1.5 a**

† The letters show differences among treatments according to Tukey's HSD at a 5% level. ‡ Highlighted bold numbers indicate effective treatment combinations of different fertilizers on growth attribute parameters of the common bean crop.

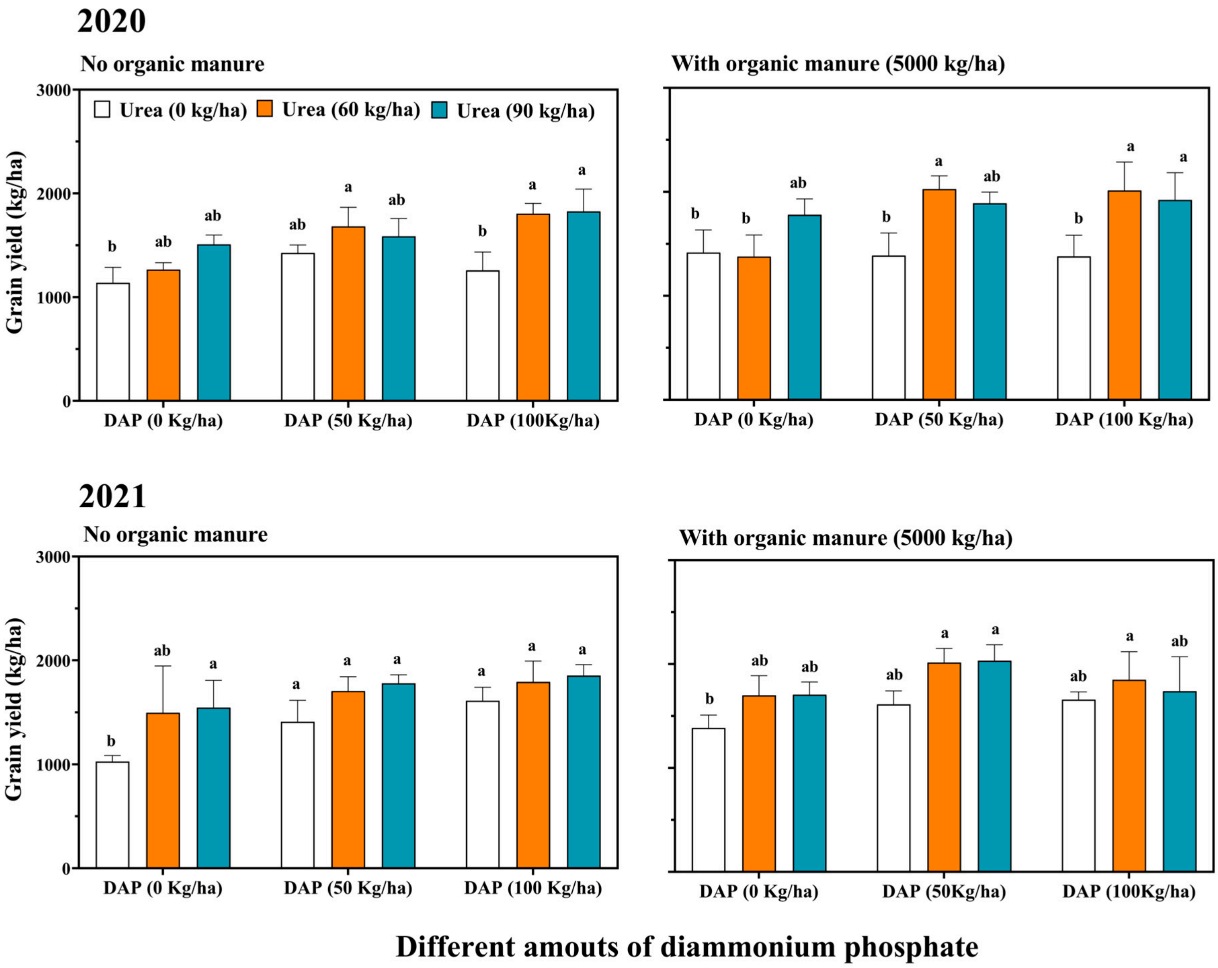

Figure 3. The effects of different fertilizer treatments on increasing common bean grain yield parameters over two years (2020 and 2021). The letters on the top of bars show differences among treatments according to Tukey's HSD at a 5% level. The DAP indicates diammonium phosphate.

3.3. Correlations of Growth and Yield Parameters

The growth and yield parameters showed a great correlation among the increased parameters (Figure 4). In 2020, the number of leaves revealed a positive correlation (r = 0.65) with the number of branches. Similarly, the number of branches showed close correlations with the number of pods (r = 0.77) and 100 seed weight (r = 0.78). Moreover, the SPAD value correlated highly with plant height (r = 0.80) and grain yield (r = 0.84). In 2021, the number of leaves indicated a strong relationship with the number of branches (r = 0.78), SPAD value (r = 0.80), and number of pods per plant (r = 0.78). Likewise, the grain yield had a positive correlation with the number of leaves (r = 0.75), SPAD value (r = 0.91), number of pods per plant (r = 0.77), and number of seeds per pod (r = 0.76).

The principal component analysis was conducted to evaluate the relationship among the treatments, growth and grain yield parameters (Figure 5). In 2020, it was found that adding organic fertilizer with inorganic fertilizer highly influenced the growth and yield parameters and grouping of the treatments. The effects were more visible in the leaf numbers, SPAD, 100-seed weight, number of pods per plant, and number of seeds per pod (Figure 5) under organic fertilization. The increasing growth and yield parameters were effectively influenced by applying the O5000N60D50, O5000N60D100, O5000N90D50, and O5000N90D100 treatments. In 2021, similar results for the organic fertilizer effects were observed in the correlation of treatments and parameters, as well as effective treatments (Figure 5). The O5000N60D50 treatment contains low nitrogen and phosphorus rates compared to other effective treatments, showing the same effect on the growth and yield parameters. However, the effects on growth and yield parameters varied over two consecutive growth seasons. A strong positive correlation was observed between SPAD values and grain yield (e.g., r = 0.84–0.91), highlighting the importance of nitrogen availability in improving productivity.

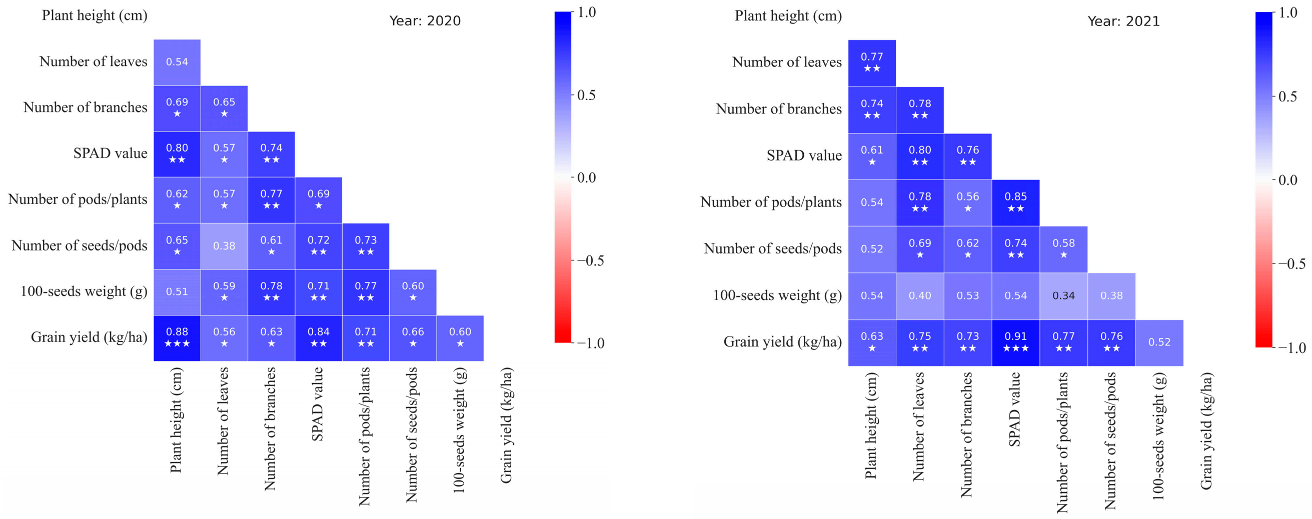

Figure 4. Correlation matrix of growth attributes and yield parameters for the cultivated common bean crop. The symbols *, **, and *** in the correlation matrix indicate $p < 0.05$, $p < 0.01$, and $p < 0.001$ values, respectively.

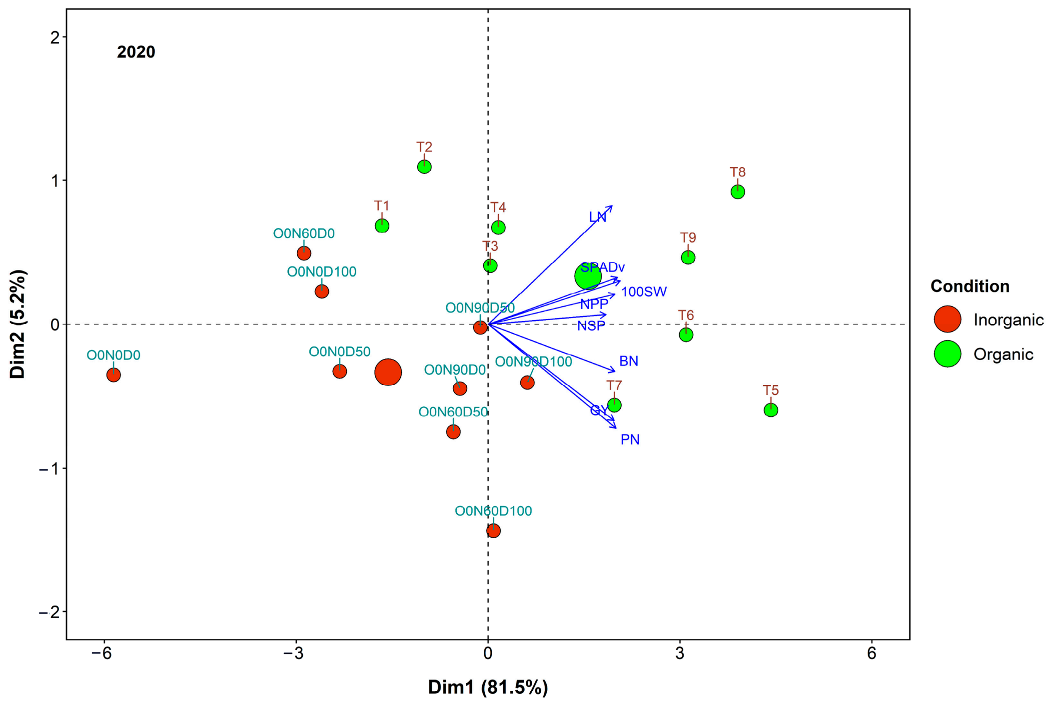

Figure 5. *Cont.*

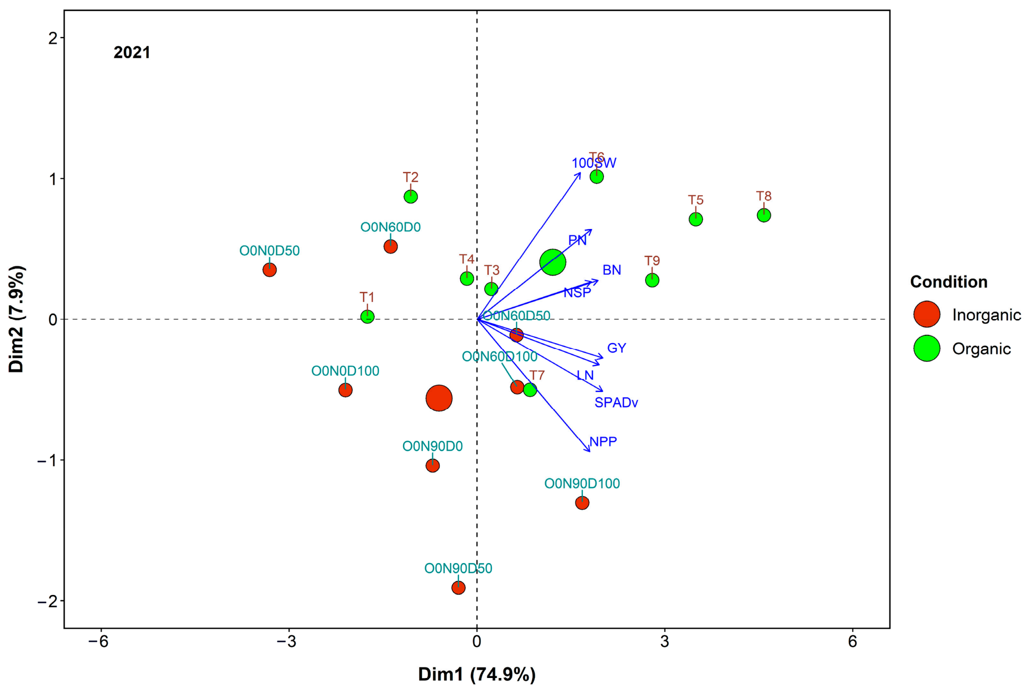

Figure 5. Principal component analysis of two years of experiments concerning the applied fertilizers' treatments, growth, and yield parameters. The letters of treatments in organic conditions present T1:O5000N0D0, T2:O5000N0D50, T3:O5000N0D100, T4:O5000N60D0, T5:O5000N60D50, T6:O5000N60D100, T7:O5000N90D0, T8:O5000N90D50, and T9:O5000N90D100. The growth attributes parameters are abbreviated as PH: plant height (cm), LN: leaf number, BN: branch number, SPADv: soil and plant analyzer development value, NPP: number of pods/plant, NSP: number of seeds/pod, 100SW: 100 seeds weight (g), GY: grain yield (Kg/ha).

4. Discussion

Plants require essential nutrients for optimal growth and yield, with nitrogen and phosphorus being major elements that play crucial roles in plant growth development. Furthermore, organic materials provide various crop nutrients and help maintain soil health [48]. Therefore, we evaluated the influence of integrated organic and inorganic fertilizers on common bean growth and yield. Our results show that the combined use of organic and inorganic fertilizers significantly affected growth and yield parameters, which might be due to the availability of both macro- and micronutrients for the plants. In 2020 and 2021, the maximum plant heights, leaf numbers per plant, and branch numbers per plant were observed in the mixed treatments of organic and inorganic fertilizers (O5000N60D50, O5000N60D100, and O5000N90D50). A similar positive influence of organic and inorganic fertilizers on plant height and branch numbers per plant in common beans was reported by Mohamed et al. [49], who found that the tallest plant, highest branch numbers per plant, and the heaviest fresh and dry weights in T4 (100% M-RDN) and salicylic acid at 150 ppm treatment over two growth seasons. Likewise, the highest plant height (38.9 cm) was reported in the combined treatment of organic and inorganic fertilizers (CM2 + NP1) [50]. The increase in common bean growth parameters could be attributed to the synergistic effects of combined organic and inorganic fertilizers.

The SPAD value increased across the treatments, ranging from 29.7 to 42.6 when organic and inorganic fertilizers were used over two consecutive years (2020–2021). Previous studies have reported similar trends in SPAD value increments for beans [51] and other crops [52,53] when mixed organic and inorganic fertilizers were applied. However, the chlorophyll contents of different common bean genotypes varied depending on the specific treatment of organic and inorganic fertilizers [51]. The increase in SPAD value could be due to the increased availability of nutrients, particularly nitrogen [54], in the soil, which is crucial for plant health and can enhance leaf chlorophyll content.

The application of organic and inorganic fertilizers improved the yield and yield parameters. In 2020 and 2021, the O5000N60D50, O5000N60D100, and O5000N90D50 treatments showed a significantly higher number of pods per plant, seed per pod, and 100-seeds weight. These results are consistent with previous studies [49,50], and Mohamed et al. [49] reported that in both years (2020 and 2021), treatments T4 (100% M-RDN) and T3 (75% of M-RDN +25% O-RDN) with 150 ppm salicylic acid (SA) showed the highest 100-seed weight. Similarly, Ref. [50] found that the number of pods per plant was considerably increased in mixed treatments of organic manure and chemical fertilizers (CM1 + NP3). Moreover, Ref. [55] indicated a significant increase in pods per plant (40.83) when organic and inorganic fertilizers treatment (100% NPK + PM @ 5 t ha^{-1}) were combined. Integrating organic fertilizers with inorganic fertilizers for common bean yield components appears to be very effective and may influence plant growth in various ways [56–58]. Furthermore, organic fertilizers are not only crucial for sustainable crop productivity, but they also serve as a viable alternative for restoring degraded soil [59], improving soil physical and chemical properties [60,61], preserving diverse soil organisms [62], and mitigating the need for inorganic fertilizer application [63–65].

The grain yield significantly increased with the application of combined organic and inorganic fertilizer treatments. In 2020, the highest results were observed with the O5000N60D50, O5000N60D100, and O5000N90D100 treatments, while in 2021, the O5000N90D100 was replaced by the O5000N90D50 treatment. Interestingly, the O5000N60D50 treatment in both experiments (2020 and 2021), which contained lower nitrogen and phosphorus levels compared to the other effective treatments, resulted in the same grain yield. This may be attributed to the nutrient balance in this treatment, as excessive nitrogen disrupts microbial activity and suppresses nodulation in common bean [66,67], while increasing phosphorus does not mitigate the inhibitory effect of nitrogen on nodule formation [68]. Additionally, previous studies stated that organic fertilizers improve the efficiency of inorganic fertilizers by providing nutrients and improving soil quality, leading to better plant growth and yield [69,70].

Plants cannot utilize all applied nitrogen in the field, eventually leading to runoff and groundwater contamination [71,72] and environmental pollution [73,74].

Combining organic and inorganic fertilizers effectively boosts grain yield and reduces inorganic fertilizer usage. Mohamed et al. [49] reported similar findings, stating that organic treatment T3 (75% M-RDN+ 25% M-RDN) + 150 ppm SA improved common bean productivity by enhancing soil physical conditions, root aeration, water drainage, and nutrient exchange. Likewise, Tunc et al. [50] reported that a maximum grain yield (2742.1 kg ha^{-1}) was found in combined organic and inorganic fertilizers (CM1 + NP3). Furthermore, Ref. [75] indicated the highest economic value of 69,460 and 63,250 ETB from applying organic (compost) and inorganic (Triple Superphosphate) fertilizers.

The correlation matrix resulted in a positive correlation between grain yield and other growth and yield parameters, including plant height, SPAD value, and number of pods per plant in 2020, while in 2021, the correlation efficiency was found to be stronger with the number of leaves, SPAD value, number of pods per plant, and number of seeds per pods. Previous studies have confirmed the positive correlation between grain yield and several growth and yield parameters [76,77]. Moreover, SPAD values exhibited a strong, significant relationship with grain yield in both experiments (2020 and 2021), ranging from 0.84 to 0.91. This suggests that enhancing the SPAD value increases crop yield, as it reflects the nitrogen status of the crop through chlorophyll content in the leaves [78–81]. A similar trend of increasing SPAD value with various nitrogen levels has been observed in numerous crops and previous studies [52,69,82]. Furthermore, it has been reported that organic fertilizers increase leaf chlorophyll content [83], leaf area, and the number of branches, all of which commonly result in positive yield outcomes [51]. The positive outcomes observed in the growth and yield of common beans through the combined use of organic and inorganic fertilizers demonstrate the effectiveness of these treatments and underscore their transformative potential for sustainable agriculture. These findings align with global fertilizer policies by increasing organic matter application, efficiently using inorganic fertilizers, and reducing reliance on mineral fertilizers [42,84]. They also provide a valuable framework for developing agricultural policies for improving soil health, enhancing productivity, and addressing environmental challenges such as nutrient runoff and groundwater contamination.

5. Conclusions

In this study, various organic and inorganic fertilizers were integrated and applied to determine the most effective treatments for enhancing common bean productivity. Over two years of evaluation, treatments such as O5000N60D50, O5000N60D100, O5000N90D50, and O5000N90D100 significantly improved growth attributes and yield components. Notably, the O5000N60D50 treatment, with lower nitrogen and phosphorus levels, led to a remarkable 75.6% increase in grain yield in 2020 and 96.1% in 2021, demonstrating its potential for enhancing productivity while reducing dependency on inorganic fertilizer. The findings suggest that integrating organic and inorganic fertilizers can be a practical approach for improving crop yield, particularly in drought-prone and nutrient-depleted regions, and could cooperate to reduce costs, improve soil health, and mitigate environmental impacts. These practices offer a pathway to more sustainable and climate-resilient agriculture, especially for smallholder farmers facing high fertilizer costs and ecological challenges. Further research is required to explore the mechanisms of the synergistic effects of organic and inorganic fertilizers on common beans growth and yield using different soil types under various climatic conditions.

Author Contributions: Conceptualization, S.H., S.A. and M.D.H.; methodology, S.H., S.A., A.Y.S. and M.D.H.; software, S.H. and S.A.; validation, S.H., S.A., A.Y.S., K.S. and M.D.H.; formal analysis, S.H. and S.A.; investigation, S.H., S.A. and M.D.H.; resources, S.H., S.A. and M.D.H., data curation, S.H. and S.A.; writing—original draft preparation, S.H., S.A., K.S. and M.D.H.; writing—review and editing, S.H., S.A., A.Y.S., K.S. and M.D.H.; visualization, S.H. and S.A.; supervision, S.H., S.A. and M.D.H.; project administration, S.H., S.A. and M.D.H.; funding acquisition, S.H., S.A. and M.D.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflicts of interest.

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