

Article

Revealing the Nexus between Fertilizer Composition and the Performance of Common Bean (*Phaseolus vulgaris* L.) Genotypes in the Himalayan Heartland of India

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Abstract: Gaining insight into the interplay between crucial fertilizers and their impact on crop characteristics is crucial for enhancing the agricultural output and promoting sustainable crop administration. The objective of this study was to assess the growth, productivity, and nutrient-use efficiency (NUE) of common bean genotypes with varying levels of NPK. In the RCBD field study, three genotypes of common bean were cultivated—SKUA-WB-5000/1446 (V₁), SKUA-WB-5002/185 (V₂), and SKUA-WB-5003/1492 (V₃)—together with six combinations of NPK (N₂:P₂O₅:K₂O kg ha^{−1}). The findings indicated that the height of the plants had a positive correlation with elevated NPK levels subsequent to the maximum point in NPK 10-20-10. The V₁ genotype exhibited superior growth and productive traits, particularly with regard to its higher seed index and much greater quantity of pods plant^{−1}. This indicates that the V₁ genotype may be a suitable choice for cultivating common beans and highlights the importance of adjusting nutrient levels to ensure sustainable crop management. This study suggests applying 30-60-30 NPK kg ha^{−1} of fertilizer for genotypes V₁ and V₃, while genotype V₂ should receive 40-80-40 NPK kg ha^{−1} under rainfed circumstances.

Keywords: *Phaseolus vulgaris* L.; genotypes; growth; NPK; nutrient-use efficiency (NUE); productivity; sustainability

1. Introduction

The common bean (*Phaseolus vulgaris* L.), a member of the Fabaceae family, is a popular grain legume representing a significant source of protein, fiber, minerals, and vitamins [1]. *Phaseolus vulgaris* L., also known as the new world crop, is a plant that evolved 7000 years ago in two distinct regions of the North and South American continents [2,3]. This dry bean, often referred to as rajmash or rajma in India, is native to southern Mexico and

Central America [4,5]. The common bean is an annual crop with minor differences in growth habit, crop duration, pod size, shape, and color of pods and seeds, grown in a mixture of agro-climatic regions [6]. The crop is grown in humid, tropical, and subtropical climates up to 2000 m above sea level with 500 to 1500 mL of annual rainfall [7–9]. It is widely consumed for its edible seeds and pods and is inexpensive in many countries. It has multiple health benefits, including cholesterol and coronary heart disease management, as well as reducing blood sugar levels in diabetic people [10,11]. The common bean is the primary staple food for more than 200 million people in sub-Saharan Africa, making it a grain that humankind depends upon [12].

The common bean is grown worldwide over 29.39 million ha^{−1} with a production of 26.83 million tons (t) [13]. Myanmar, India, Brazil, the USA, Tanzania, China, and Mexico are the top dry bean producers [14]. *Phaseolus vulgaris* L. is grown on 9.47 million ha^{−1} in India, with a production of 3.90 million t and a productivity of 0.41 t ha^{−1} [13]. India's leading agricultural producing regions are Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, Maharashtra, the Nilgiri and Palani Hills of Tamil Nadu, parts of the Western Ghats of Kerala, the Chickmagalur Hills of Karnataka, and the Darjeeling Hills of West Bengal. Pulses are often cultivated in the rainfed Kurewa regions of Jammu and Kashmir, either as a mono- or as an intercrop with maize under a low-input system, producing low yields. The districts of Baramulla, Bandipora, and Kupwara in the Kashmir Valley have the potential for rajmash cultivation [15]. Common bean varieties vary in seed size, shape, and color. People mainly prefer local bean varieties such as Kashmiri, Bhaderwah, Harshil, Munsiyari, Auli, Barot, Chamba rajmash, and Kinnauree [16]. Farmers typically prefer kidney-shaped plain red seed coats over cuboidal and cylindrical seed coat shapes and other seed coat colors in the Kashmir Valley.

The crop growth and yield depend on sufficient amounts of mineral nutrients, and the primary nutrients, nitrogen (N), phosphorus (P), and potassium (K), are essential for increased productivity. The application of these nutrients plays a vital role in shaping the quantitative and qualitative characteristics of the common bean. *Phaseolus vulgaris* L. has reasonable prospects of N-fixation but has been reported less compared to other legumes [17,18]. Legume plants have a symbiotic relationship with rhizobia bacteria for the fixation of atmospheric N in the host plant. However, N-fixation is a high-energy-consuming process compared to artificial N supply to soil [19].

N in the soil is affected by the high temperature of the soil surface, drought stress, soil reaction (pH), and deficiency of phosphorus and other nutrients. The limitations on crop growth are caused mainly by the low availability of nutrients in the soil, which is affected by abiotic stress and, particularly, soil moisture. N supply to the common bean affects the photosynthesis, leaf area, number and size of pods, nodules, water-use efficiency, and yield [20–22]. N availability is crucial for optimizing the growth and yield of the common bean. It directly affects several key aspects of plant development and productivity. Firstly, adequate N levels enhance photosynthesis, thereby boosting the plant's ability to produce energy and grow efficiently. Additionally, N supports the expansion of leaf area, which is essential for capturing more sunlight and maximizing photosynthetic activity. Moreover, N plays a pivotal role in the formation and development of pods and nodules. It contributes to the formation of larger and more numerous pods, thereby increasing the yield potential. In leguminous plants like common beans, N also facilitates the formation of nodules on roots, where symbiotic N-fixing bacteria reside. This symbiosis allows the plant to convert atmospheric N into a form that can be utilized for growth, further enhancing nutrient availability. Furthermore, N availability improves water-use efficiency in plants, helping them to better manage water resources and tolerate periods of water stress. Ultimately, the cumulative effect of an optimized nitrogen supply results in an increased overall yield of common bean crops, making it a critical factor in agronomic management and genotype selection [20–22]. During genotype selection for common beans, increasing the protein levels in grains involves choosing plants that efficiently accumulate essential nutrients like N, P, and K. This process includes selecting genotypes with traits

that enhance nutrient uptake and utilization. Agronomists apply balanced fertilization and optimize field management to ensure plants receive adequate nutrients throughout their growth. Post-harvest techniques then maintain grain quality. Through rigorous evaluation, breeders identify genotypes that consistently produce high-protein grains, aiming to enhance the nutritional quality in cultivated beans [23].

P is the second major nutrient that impacts common bean growth, nodulation, and root development. It is responsible for plant metabolic processes such as transpiration, photosynthesis, and amino acid synthesis [24–26]. P also increases root growth, promotes adequate nodulation, and supports rhizobia in biological N-fixation [27–29]. The energy-consuming nodulation and N-fixation processes depend on sugars transported downward from the host plant's branches; in this regard, P is necessary for the synthesis of helpful energy as well as the production and translocation of sugars. P deficiency in the soil causes a reduction in leaf area, affects plant growth, and lowers dry matter accumulation [30]. Also, P deficiency affects how well UV light is absorbed, which lowers photosynthesis and inhibits the production of buds and flowers [31]. K plays a crucial role in most biochemical and physiological processes affecting plant growth. It contributes significantly to cell osmotic concentrations and the maintenance of stomata guard cell turgor, increases the photosynthesis rate and biomass production, and increases yields [32,33]. Additionally, it helps in enzyme activation and cell formation, reduces excessive intake of sodium (Na) from the soil, increases carbon (C) assimilation, translocates organic and inorganic nutrients from the soil, and effectively increases the yield quality [34–36].

Recently, breeders have identified some promising genotypes of the common bean in the Kashmir Valley. Agronomic interference is required to evaluate the optimum utilization of primary nutrients—N, P, and K—to realize the yield potential of these genotypes. Common beans are a critical source of protein and essential nutrients, making them indispensable for food security and nutrition, especially in regions like the Himalayas. This study's objective was to evaluate the effects of varying levels of primary nutrients (NPK) on the growth, yield, and nutrient-use efficiency of newly identified common bean genotypes in the temperate Himalayas. Emphasizing the identification of the most favorable agricultural conditions, this research aimed to enhance both the quality and yield of common beans. In doing so, we sought to promote sustainable development in the Himalayan region, ensuring that agricultural practices contribute to ensuring the long-term ecological balance and economic growth. This approach is vital for maximizing the potential of common bean genotypes, thereby supporting the region's agricultural output and sustainability.

2. Materials and Methods

2.1. Experimental Site Description

A field experiment was conducted during the autumn season (Kharif) of 2020 at the Agronomic Research Farm in the Faculty of Agriculture, SKUAST Kashmir, Wadura, Sopore. The experimental site lies at 34°21' North latitude, 74°23' East longitude, and at the height of 1590 m above mean sea level. The weather conditions during the crop growing period from May 2020 to August 2020 (19th–32nd SMW) are shown in Figure 1. The weekly mean minimum temperature ranged between 8.3 and 17.8 °C, with a mean value of 12.8 °C, and the weekly mean maximum temperature ranged between 22.7 and 33.9 °C, with a mean value of 29.5 °C. During the crop period, 146.2 mm of rain was recorded. The rainfall was almost uniformly distributed during the crop period. The rainfall was higher in May and the first fortnight of June. The weekly mean maximum relative humidity (RH I) ranged between 73.6 and 83.1%, with a mean value of 79.3%, and the weekly mean minimum relative humidity (RH II) ranged between 45.3 and 66.7%, with a mean value of 55.5%. A cold temperate climate prevails in this locality, with subzero winter temperatures and mild summer temperatures. The common bean cultivated in this region has a 100–110-day growth cycle. Composite soil samples at 0–15 cm depth were taken for initial soil analysis. The soil samples were air-dried, powdered, and passed through a 2 mm mesh sieve. The samples were subsequently submitted to a series of

mechanical and chemical tests. Regarding soil reactivity (pH), the soil was neutral, with medium levels of soil organic carbon (SOC), accessible N, P, and K. The physical and physicochemical properties of the experimental soil are presented in Table 1.

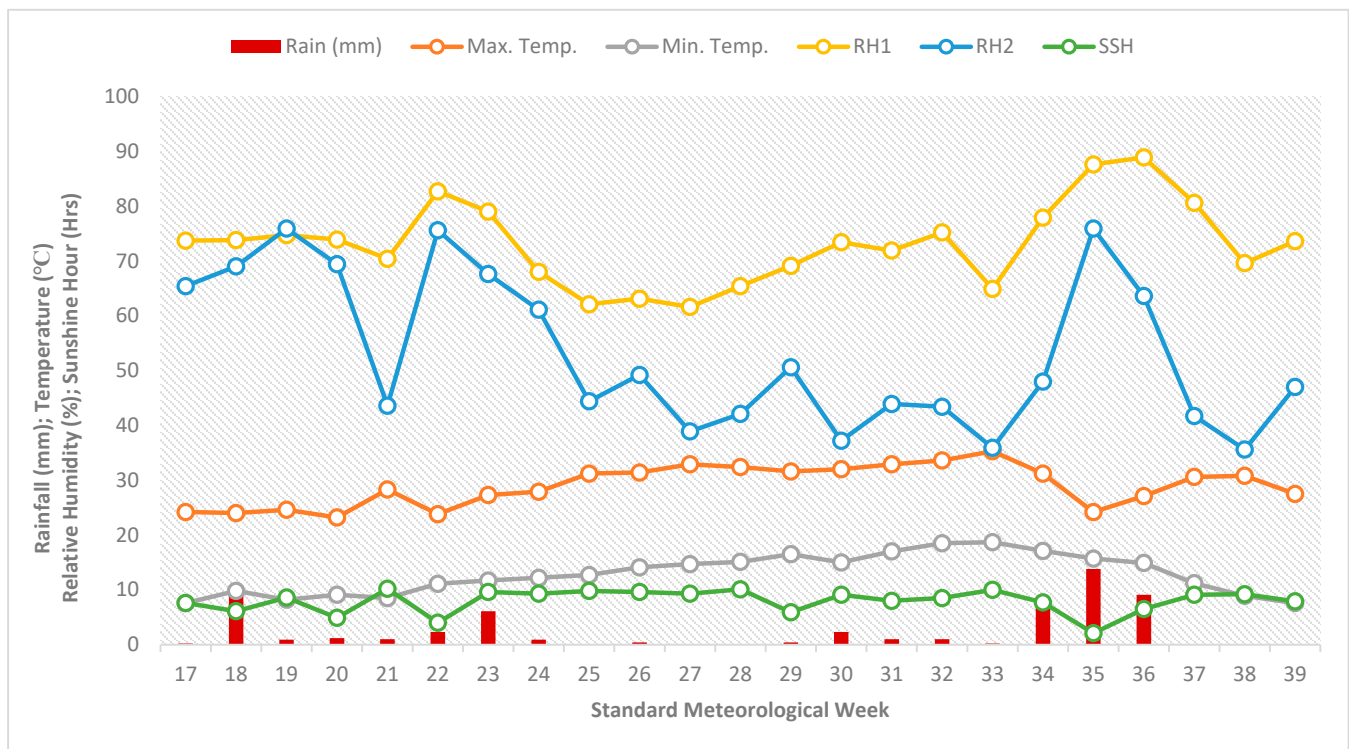


Figure 1. Weekly weather parameters during crop period of *Kharif* season in 2020 (18). RH I = relative humidity (%), RH II = relative humidity (%), SSH = sunshine hours (Hrs).

Table 1. Initial soil status of experimental field.

Particular	Value	Rating	Method
Physical characteristics			
Soil texture	Sand 19.5%	Silty–clayey loam	[37]
	Silt 50.0%		
	Clay 28.5%		
Bulk density	1.33 Mg m ^{−3}		[38]
Physico-chemical characteristics			
pH	6.8	Normal	[39]
Electrical conductivity	0.07 dS m ^{−1}	Normal	[39]
Organic C	0.74%	Medium	[40]
Available N	275.5 kg ha ^{−1}	Medium	[41]
Available P	17.5 kg ha ^{−1}	Medium	[42]
Available K	174.2 kg ha ^{−1}	Medium	[39]

2.2. Design of Experiment and Experimental Duration

A factorial randomized complete block design (RCBD) with two factors and three replications was used for the experiment (Figure S1). The first factor had three genotypes of the common bean, i.e., SKUA-WB-5000/1446 (V_1), SKUA-WB-5002/185 (V_2), and SKUA-WB-5003/1492 (V_3), and the second was composed of six levels of primary nutrient (N,

P, and K) combinations, that is, $N_0P_0K_0$, $N_{10}P_{20}K_{10}$, $N_{20}P_{40}K_{20}$, $N_{30}P_{60}K_{30}$, $N_{40}P_{80}K_{40}$, and $N_{50}P_{100}K_{50}$, respectively. There were eighteen treatment combinations, each of which was assigned to a gross plot area of $2.7\text{ m} \times 2.8\text{ m}$. The crop was raised at a spacing of $30\text{ cm} \times 10\text{ cm}$. The details of the treatments are shown in Table S1.

The SKUA-WB-5000/1446 (V_1) genotype is regarded as a naval bean, also known as mangalore beans or simply sundal. They are small, oval, and slightly curved legumes, typically brown, black, or mottled in color. These beans are rich in protein, dietary fiber, and essential vitamins like B-complex, as well as minerals such as iron (Fe), calcium (Ca), and magnesium (Mg). They thrive in tropical and subtropical climates, preferring well-drained, loamy soils and requiring regular watering, particularly during flowering and pod development. With a growth cycle that spans 70–90 days from planting to harvest, they are a staple in Indian cuisine, especially in dishes like sundal, a seasoned bean salad often prepared during festivals. Generally resistant to pests and diseases, they are adaptable to diverse agricultural settings, making them a versatile and nutritious food source. The SKUA-WB-5002/185 (V_2) genotype is commonly known as red kidney beans, more commonly known as rajma in India. They are large, kidney-shaped beans with a deep red color and a smooth, glossy surface. Renowned for their high protein and dietary fiber contents, they are also rich in vitamins B-complex, particularly folate, and minerals like Fe, Mg, and potassium (K). These beans grow well in temperate climates, favoring well-drained, fertile soils with a pH between 6.0 and 7.0. With a growth cycle of 90–120 days, they require consistent moisture but do not tolerate waterlogging. Rajma is a culinary staple in North India, commonly used in the popular spiced curry dish also called rajma, typically served with rice. While these beans are prone to pests like aphids and diseases such as bean mosaic virus, proper crop management can mitigate these issues. Different cultivars offer variations in size, growth duration, and pest resistance. The SKUA-WB-5003/1492 (V_3) genotype typically constitutes purple beans that are slender, elongated legumes distinguished by their striking deep purple pods, which turn green when cooked. They are moderate in protein and high in dietary fiber, vitamins A, C, and K, folate, Fe, and antioxidants like anthocyanins. These beans thrive in temperate to tropical climates, requiring a warm growing season and well-drained, fertile soils. They need regular watering, especially during flowering and pod development, with a growth cycle of 60–70 days. Purple beans are versatile in the kitchen, often steamed, stir-fried, or used in salads, adding color and nutritional value to meals. Although susceptible to pests such as aphids and bean beetles, and diseases like rust and powdery mildew, proper crop rotation and spacing can reduce these risks. Their unique color and health benefits are making them increasingly popular in Indian markets and home gardens. The selection of these three genotypes for this study in Kashmir, India, was driven by their diverse nutritional profiles, agronomic adaptability, cultural and culinary significance, potential for agricultural innovation, and the specific research goals. Each bean type offers unique nutrients, addressing various dietary needs, and their different climate and soil requirements allowed for a comprehensive study of their adaptability to the temperate conditions of Kashmir. These beans are integral to Indian cuisine, particularly in India, making them relevant for local agricultural and dietary practices. Studying these beans can lead to improvements in yield, sustainability, and economic opportunities for farmers. Additionally, our research aimed to achieve crop improvement, enhance nutritional security, and promote sustainable farming practices in the region. Figure S2 shows the 3 genotypes of the common bean evaluated in the present study.

Figure S3 provides an overview of the experimental field. This experiment was conducted over a single vegetative season to obtain preliminary data on the growth and NUE of common bean genotypes under different NPK levels. Conducting the study over one year allowed for a controlled assessment of the genotypes' responses to the nutrient treatments within the specific climatic and environmental conditions of that season. While this provides valuable initial insights, it is acknowledged that agricultural experiments can be influenced by year-to-year variability in the weather, pest pressure, and other factors.

Therefore, further multi-seasonal studies are recommended to validate these findings and ensure their robustness and applicability across different growing conditions.

2.3. Biometric Analysis

- Plant height: 5 randomly selected plants per net plot were tagged, and their heights were recorded every 30 days, measured from the ground surface to the growing tip. Average height data in centimeters per plot were used to express plant height across the experimental area.
- Leaf area: Leaf area observations were also conducted at 30-day intervals from sowing. In a 0.5 m × 0.5 m quadrant outside each net plot, all plants were cut at ground level, and their leaves were separated. Total leaf area was measured using the Easy Leaf Area software from the University of California, USA, version 4.1 [43]. Leaf area was calculated as follows: Leaf area = (Green pixel count) × (Calibration area/Red pixel count). The leaf area index (LAI) was then estimated by dividing the total leaf area by the ground area of the sample quadrant.
- Dry matter accumulation: After leaf area observations, we used the same plant samples to estimate dry matter accumulation (DMA). These samples were oven-dried (60–65 °C) until reaching a constant weight, and then the total dry matter per quadrant was divided by the number of plants in that quadrant to calculate DMA, expressed as grams per plant (g plant^{−1}).
- Crop growth analysis: The traits of crop growth analysis—mean crop growth rate (mean CGR), mean relative growth rate (mean RGR), and mean net assimilation rate (mean NAR)—were estimated based on DMA and the leaf area produced per unit area.

The mean CGR (g m^{−2} ground area day^{−1}), mean RGR (mg g^{−1} dry matter day^{−1}), and mean NAR (g m^{−2} leaf area day^{−1}) were ascertained with the following formulas [44]:

$$\text{CGR} = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{\text{GA}} \quad (1)$$

$$\text{RGR} = \frac{\log W_2 - \log W_1}{t_2 - t_1} \quad (2)$$

$$\text{NAR} = \left(\frac{W_2 - W_1}{\text{LA}_2 - \text{LA}_1} \right) \times \left(\frac{\log \text{LA}_2 - \log \text{LA}_1}{t_2 - t_1} \right) \quad (3)$$

where W_1 and W_2 are the dry weights (g) of plants at times t_1 and t_2 , respectively, GA is the ground area (m²), and LA_1 and LA_2 are the leaf areas (m²) at t_1 and t_2 , respectively.

- Nodulation: Three carefully uprooted plants, preserving soil and minimizing nodule loss, had their roots washed in a sieve. Pink effective nodules were counted, air-dried, and weighed using a laboratory digital scale.
- Days to different phenological stages: We recorded the days needed to reach key phenological stages, like 50% emergence, 50% flowering, and 50% maturity, for each plot. Each stage was marked when half of the plants in the plot reached it.

2.4. Post-Harvest Determination

- Number of pods plant^{−1}: At harvest, 5 plants were chosen randomly from the net plot area of each plot in the experimental region. The total number of pods was counted, and the average was calculated to ascertain the number of pods plant^{−1}.
- Number of seeds pod^{−1}: All of the seeds were separated from the pods. The total number of seeds and the average number of seeds per pod^{−1} were calculated.
- Seed index: Each net plot area had seed samples from bulk products, and the weight of 100 seeds was computed and expressed in grams (g).
- Seed and stover yields: The biomass harvested from the net plot area of each plot of the experimental area was sun-dried and weighed (biological yield) before threshing. The seeds obtained from the net plot area of each plot were thoroughly cleaned, sun-dried, and weighed. The net plot seed yield was expressed in t ha^{−1}. The rest of the parts

after threshing the biomass from each plot constituted the stover yield. The net plot stover yield was expressed in $t\ ha^{-1}$.

- Harvest index: Total biological yields ($t\ ha^{-1}$) recorded from each net plot area were used to compute the harvest index (HI). The HI was calculated by multiplying the seed yield (economic yield) by the overall biological yield (percentage yield) [45]:

$$\text{Harvest index(\%)} = \frac{\text{Seed yield}}{\text{Biological yield}} \times 100 \quad (4)$$

2.5. Plant Chemical Analysis

Seed and stover samples from each plot were sun-dried and then packed in tagged paper bags. These samples were dried in an electric oven at 60–65 °C for 36 h until they reached a consistent weight. These samples were processed using a mechanical grinder after they had dried in the oven. Nutrient uptake ($kg\ ha^{-1}$) was calculated by using the following expression:

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \% \text{ Nutrient in seed or stover} \times \text{Seed or stover yield (kg ha}^{-1}\text{)} \quad (5)$$

$$\text{Total uptake of a nutrient by crop (kg ha}^{-1}\text{)} = \text{Uptake in seed} + \text{Uptake in stover} \quad (6)$$

- N content and uptake: The N content was determined by the modified micro-Kjeldahl method [37]. The N uptakes by seeds and stovers were estimated by multiplying the N content (percent) by their respective yields.
- P content and uptake: The vanado-molybdo-phosphoric yellow color method was used to detect P in seeds and stovers [39]. The P uptake by the crop was calculated by multiplying the P content in seeds and stovers by their corresponding yields.
- K content and uptake: A flame photometer was used to determine the K content. The percent K concentration was multiplied by the relative yields to calculate the K uptake levels in seeds and straw.

2.6. Post-Harvest Soil Chemical Analysis and Nutrient-Use Efficiency (NUE)

After the crop was harvested, soil samples were obtained from all plots in the experimental area and analyzed for soil pH, electrical conductivity (EC), soil organic carbon (SOC), available N, available P, and available K using the procedures described in Table 1.

The NUE of applied NPK fertilizers was calculated for each genotype and NPK level using partial factor productivity (PFP), agronomic efficiency (AE), apparent recovery efficiency (ARE), and physiological efficiency (PE). Those parameters were calculated [46] as follows:

$$\text{Agronomic efficiency} = \text{Physiological efficiency} \times \text{Apparent recovery efficiency} \quad (7)$$

$$\text{Partial factor productivity (kg seed yield/NPK applied)} = \frac{Y_T}{PF} \quad (8)$$

$$\text{Agronomic efficiency (kg yield increase/NPK applied)} = \frac{(Y_T - Y_0)}{PF} \quad (9)$$

$$\text{Apparent recovery efficiency (kg increase in NPK uptake/NPK applied)} = \frac{(U_T - U_0)}{PF} \quad (10)$$

$$\text{Physiological efficiency (kg yield increase/increase in NPK uptake)} = \frac{(Y_T - Y_0)}{(U_T - U_0)} \quad (11)$$

where PF = amount of NPK applied ($kg\ ha^{-1}$); Y_T = crop yield with NPK-treated plot ($kg\ ha^{-1}$); Y_0 = crop yield in control plot ($kg\ ha^{-1}$); U_T = total NPK uptake in NPK-treated plot ($kg\ ha^{-1}$); and U_0 = total NPK uptake in control plot ($kg\ ha^{-1}$).

2.7. Statistical Analysis

The data collected for various observations were statistically evaluated using the method proposed by [47]. In this study, two key statistical tests were employed to analyze the data: a two-way ANOVA and Student's *t*-test. The two-way ANOVA was selected to assess the effects of different levels of NPK fertilizer and various common bean genotypes on growth, yield, and nutrient-use efficiency. Following the ANOVA, Student's *t*-test was used for pairwise comparisons between treatment means when significant differences were identified. By integrating these statistical analyses, the study implemented a rigorous evaluation of the data, allowing for the identification of significant differences and the determination of optimal NPK levels for different common bean genotypes in the temperate Himalayan region. The experimental data analysis was conducted using Excel 2016 and SPSS version 26.0 [48].

3. Results

3.1. Biometric and Crop Growth Traits

The data in Table 2 indicate that plant heights were not significantly influenced by the main effect of common bean genotypes at 30 and 90 days after sowing (DAS). However, at 60 DAS, plant heights were significantly higher for the genotypes SKUA-WB-5002/185 (V₂) and SKUA-WB-5003/1492 (V₃) (Figure 2). Regardless of the genotype, plant heights were significantly influenced at all stages of observations due to the varying levels of NPK applied. Plant heights increased with higher NPK levels, but beyond N₁₀P₂₀K₁₀, no significant increase in plant height was observed at any stage of observation (Figure 2).

Table 2. Plant height and LAI of common bean as influenced by genotypes and NPK levels.

Treatment	Plant Height (cm)			Leaf Area Index (LAI)		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
Genotype						
SKUA-WB-5000/1446 (V ₁)	10.9	29	30.2	0.73	1.65	0.196
SKUA-WB-5002/185 (V ₂)	11.4	30.8	31.8	0.72	1.52	0.197
SKUA-WB-5003/1492 (V ₃)	11.3	31	31.7	0.72	1.64	0.195
SEM (±)	0.24	0.59	0.68	0.01	0.03	0.003
LSD ($p \leq 0.05$)	NS	1.7	NS	NS	0.07	NS
NPK level (N:P₂O₅:K₂O kg ha⁻¹)						
N ₀ P ₀ K ₀	10.9	29	29.7	0.67	1.43	0.181
N ₁₀ P ₂₀ K ₁₀	11.1	30	31	0.73	1.55	0.185
N ₂₀ P ₄₀ K ₂₀	11.4	30.8	32.2	0.75	1.68	0.207
N ₃₀ P ₆₀ K ₃₀	11.6	31.6	32.9	0.77	1.81	0.215
N ₄₀ P ₈₀ K ₄₀	11.9	32.3	33.7	0.77	1.87	0.219
N ₅₀ P ₁₀₀ K ₅₀	10.9	29	29.7	0.67	1.43	0.181
SEM (±)	0.34	0.83	0.96	0.01	0.04	0.005
LSD ($p \leq 0.05$)	1	2.4	2.8	0.03	0.1	0.013

Similar to plant height, the LAI was not significantly influenced by the main effect of common bean genotypes at 30 and 90 DAS (Table 2). However, at 60 DAS, the LAI was significantly higher for genotypes SKUA-WB-5000/1446 (V₁) and SKUA-WB-5003/1492 (V₃) (Figure 3). Regardless of the genotype, the LAI was significantly influenced at all stages of observation by the varying levels of NPK applied (Figure 3). The LAI increased with higher NPK levels, but beyond N₃₀P₆₀K₃₀, no significant increase in the LAI was

observed at any stage except for at 60 DAS, when the levels of $N_{40}P_{80}K_{40}$ and $N_{50}P_{100}K_{50}$ were found to be similar.

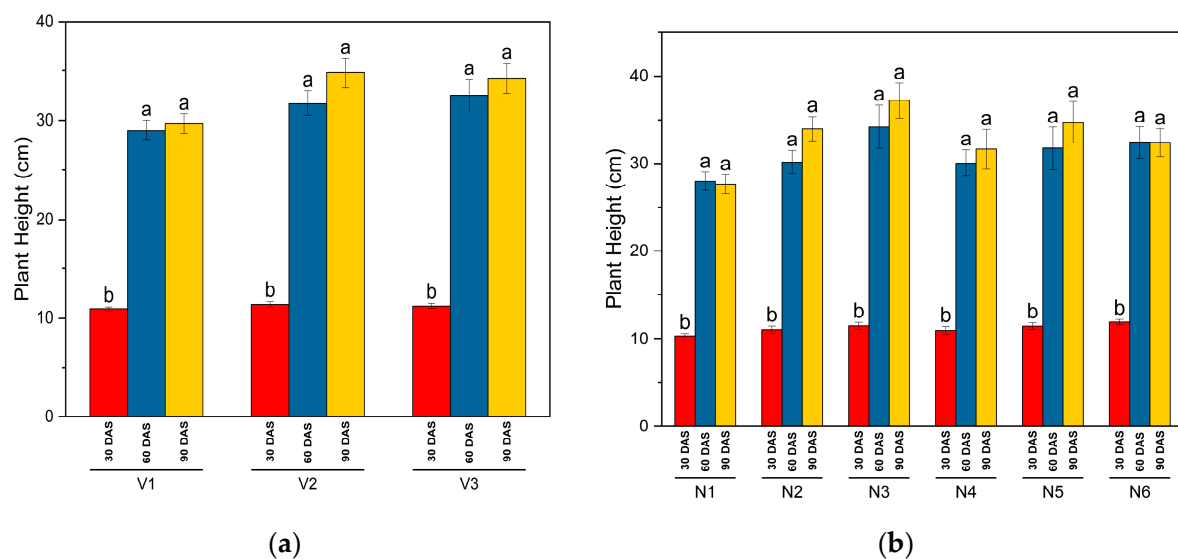


Figure 2. Plant height (cm) as influenced by genotypes (a) of common bean and NPK levels (b). Different letters (a, b) and error bars indicate Tukey's HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

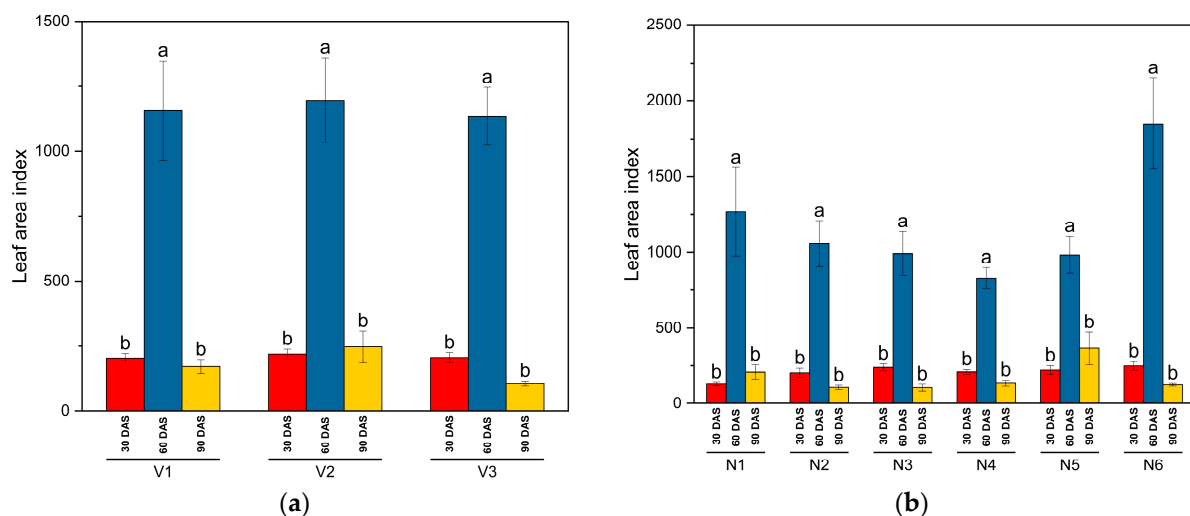


Figure 3. Leaf area index as influenced by genotypes (a) of common bean and NPK levels (b). Different letters (a, b) and error bars indicate Tukey's HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

Regardless of the NPK level applied, the DMA per plant of the common bean genotype was significantly higher with V_1 , followed by V_3 , at all stages of observation (Table 3 and Figure 4). Regardless of the genotype, the DMA was significantly higher at the maximum level of NPK applied ($N_{50}P_{100}K_{50}$) at 60 DAS and 90 DAS. For genotype V_1 , the DMA did not increase significantly beyond $N_{30}P_{60}K_{30}$, and for genotype V_3 , it did not increase significantly beyond $N_{40}P_{80}K_{40}$. In the case of genotype V_2 , a significantly higher DMA was observed only at the NPK level of $N_{50}P_{100}K_{50}$ (Figure 4). The effective nodule count and total nodule weight did not vary significantly among the different genotypes (Table 3). However, regardless of the genotype of common bean, the effective nodule count was notably higher at the NPK level of $N_{50}P_{100}K_{50}$. In contrast, the total nodule weight did

not show a significant increase beyond $N_{30}P_{60}K_{30}$. Neither parameter of nodulation was significantly affected by the genotype of the common bean or the NPK level applied.

Table 3. Main effects of genotypes and NPK levels on dry matter accumulation (DMA) and nodulation of the common bean.

Treatment	DMA (g Plant ⁻¹)			Nodulation	
	30 DAS	60 DAS	90 DAS	Effective Nodule Count (No. Plant ⁻¹)	Nodule Weight (mg Plant ⁻¹)
Genotype					
SKUA-WB-5000/1446 (V ₁)	2.13	11.95	16.55	26.6	1213
SKUA-WB-5002/185 (V ₂)	1.66	10.14	15.18	25.5	1145
SKUA-WB-5003/1492 (V ₃)	1.95	10.83	15.78	25.9	1209
SEM (±)	0.03	0.15	0.19	0.4	23
LSD ($p \leq 0.05$)	0.08	0.43	0.54	NS	NS
NPK level (N:P₂O₅:K₂O kg ha⁻¹)					
N ₀ P ₀ K ₀	1.38	7.03	9.7	20.7	1114
N ₁₀ P ₂₀ K ₁₀	1.7	9.63	13.74	23.7	1164
N ₂₀ P ₄₀ K ₂₀	1.87	10.76	15.47	25.2	1176
N ₃₀ P ₆₀ K ₃₀	2.02	11.75	17.12	27.2	1187
N ₄₀ P ₈₀ K ₄₀	2.22	13.02	19.02	28.9	1224
N ₅₀ P ₁₀₀ K ₅₀	2.31	13.64	19.96	30.4	1269
SEM (±)	0.04	0.21	0.26	0.6	32
LSD ($p \leq 0.05$)	0.12	0.6	0.76	1.8	92

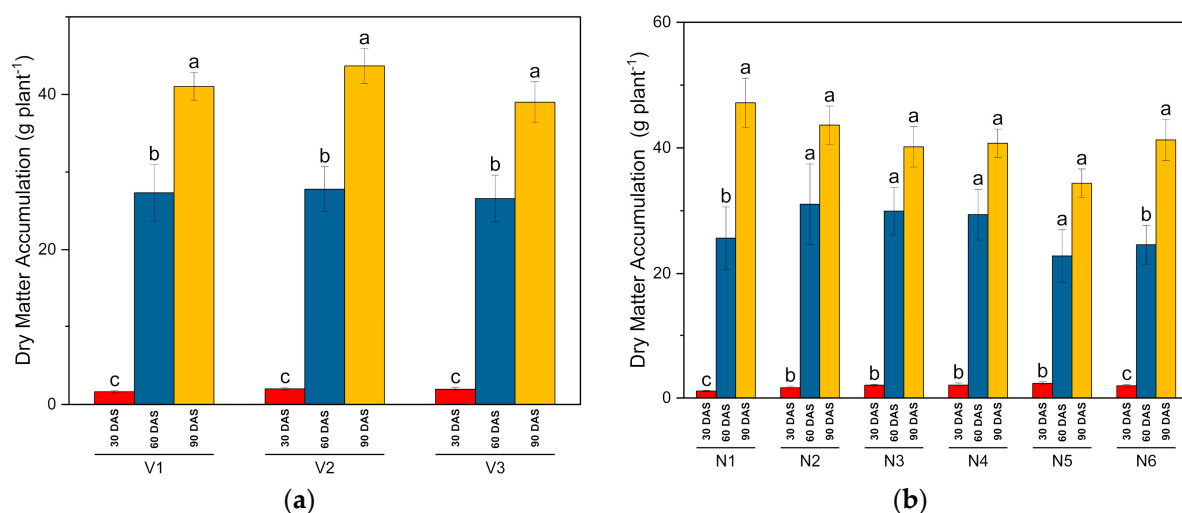


Figure 4. Dry matter accumulation as influenced by genotypes (a) of common bean and NPK levels (b). Different letters (a–c) and error bars indicate Tukey's HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

The mean CGR of the common bean was influenced by NPK levels during the growth intervals of 0–30 and 30–60 DAS, as shown in Table 4. Genotype V₁ exhibited the highest mean CGR, followed by genotype V₃, during these intervals (Figure 5). However, during the 60–90 DAS interval, the mean CGR did not vary significantly among the genotypes. Across all genotypes of common bean, the mean CGR was significantly increased with the application of all NPK levels throughout all intervals studied; nevertheless, there was

no significant increase beyond $N_{40}P_{80}K_{40}$ (Figure 5). Among the genotypes of common bean, the mean RGR varied across all growth intervals, as detailed in Table 4. Specifically, genotype V_1 exhibited the highest mean RGR during the 0–30 DAS period. Meanwhile, genotype V_2 showed the highest mean RGR during both the 30–60 DAS and 60–90 DAS intervals (Figure 6). Regardless of the genotype, the mean RGR did not show a significant increase beyond the $N_{40}P_{80}K_{40}$ level during the 0–30 DAS period (Figure 6). Similarly, during the last growth interval (60–90 DAS), the mean RGR did not significantly exceed the level of $N_{10}P_{20}K_{10}$.

Table 4. Main effects of genotypes of common bean and NPK levels on growth analysis traits.

Treatment	Mean CGR ($\text{g m}^{-2} \text{Day}^{-1}$)			Mean RGR ($\text{mg g}^{-1} \text{Day}^{-1}$)			Mean NAR ($\text{g m}^{-2} \text{Day}^{-1}$)		
	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS
Genotype									
SKUA-WB-5000/1446 (V_1)	2.37	10.91	5.11	24.53	57.33	10.75	17.39	9.61	7.42
SKUA-WB-5002/185 (V_2)	1.85	9.42	5.6	16.56	59.74	13.41	13.79	8.73	8.57
SKUA-WB-5003/1492 (V_3)	2.17	9.86	5.5	21.73	56.93	12.31	16.09	8.77	7.98
SEM ($\pm$)	0.03	0.16	0.15	0.49	0.68	0.33	0.25	0.18	0.23
LSD ($p \leq 0.05$)	0.09	0.47	NS	1.4	1.95	0.95	0.72	0.51	0.66
NPK levels ($\text{N:P}_2\text{O}_5\text{:K}_2\text{O kg ha}^{-1}$)									
$N_0P_0K_0$	1.53	6.28	2.97	10.67	54.23	10.79	12.55	6.92	5.65
$N_{10}P_{20}K_{10}$	1.89	8.81	4.57	17.37	57.98	11.89	14.97	8.79	7.54
$N_{20}P_{40}K_{20}$	2.08	9.88	5.23	20.47	58.48	12.22	15.37	9.08	8.18
$N_{30}P_{60}K_{30}$	2.24	10.82	5.96	22.97	58.91	12.66	16.18	9.39	8.53
$N_{40}P_{80}K_{40}$	2.47	12	6.66	26.35	59.12	12.68	17.43	9.89	8.91
$N_{50}P_{100}K_{50}$	2.56	12.59	7.02	27.8	59.28	12.71	18.05	10.15	9.13
SEM ($\pm$)	0.05	0.23	0.21	0.69	0.96	0.47	0.36	0.25	0.33
LSD ($p \leq 0.05$)	0.13	0.67	0.61	1.98	2.75	1.35	1.02	0.72	0.94

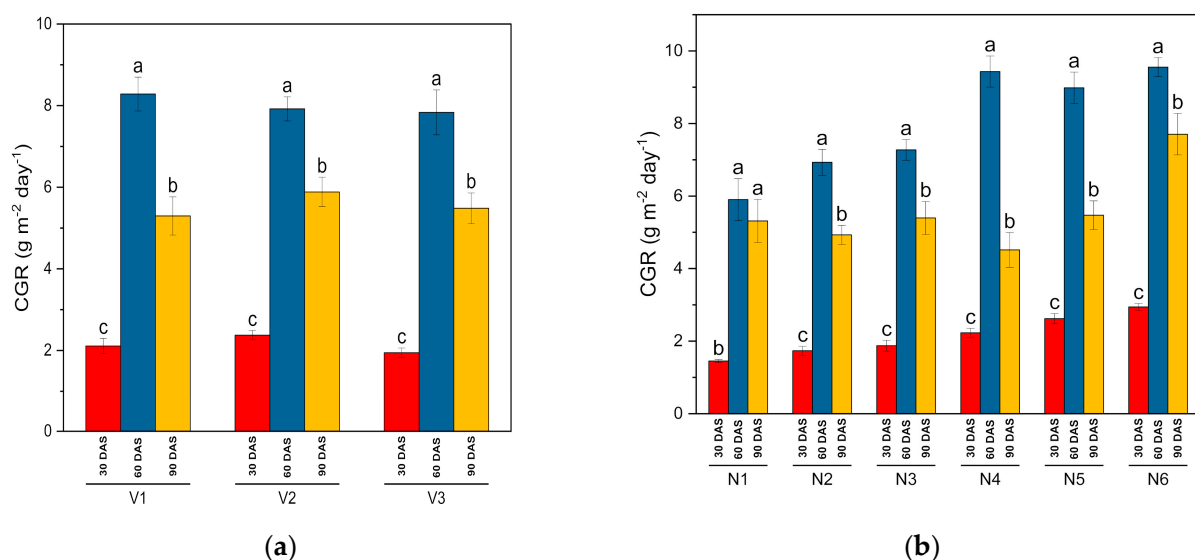


Figure 5. Mean CGR of common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a–c) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

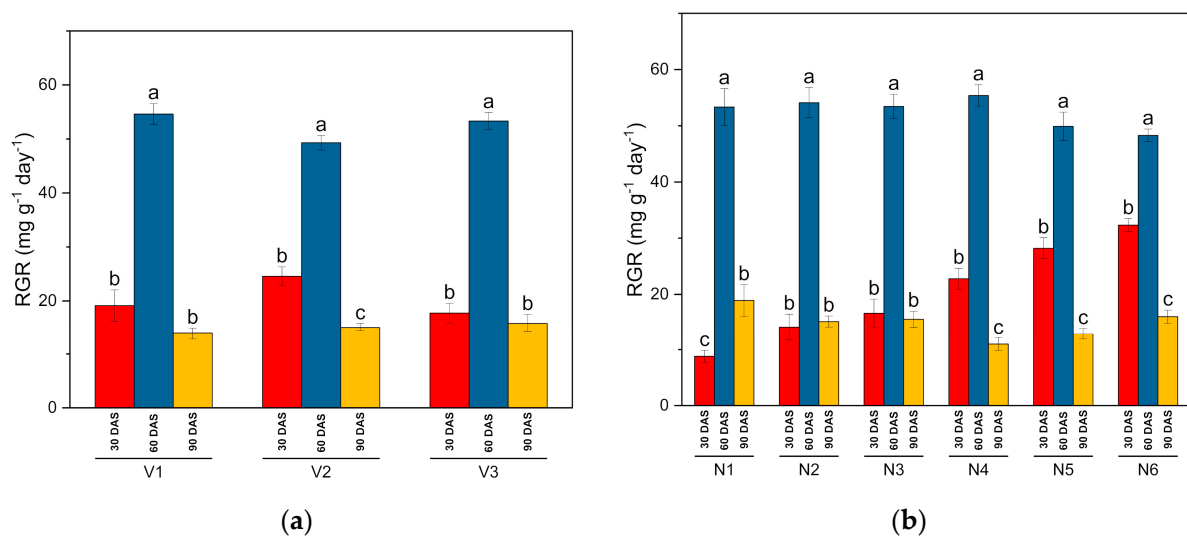


Figure 6. Mean RGR of common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a–c) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

The mean NAR was higher during the 0–30 DAS period and declined in the later growth intervals, as shown in Table 4. Both the genotypes and NPK levels influenced this trend. Genotype V₁ exhibited a significantly higher mean NAR during the 0–30 DAS and 30–60 DAS intervals. In contrast, genotypes V₂ and V₃ had significantly higher mean NAR during the 60–90 DAS interval (Figure 7). Regardless of the genotype, the mean NAR increased with higher levels of NPK. However, the increase was not significant beyond the N₄₀P₈₀K₄₀ level during the 0–30 DAS and 30–60 DAS intervals. In the later growth interval of 60–90 DAS, the mean NAR did not significantly increase beyond the N₃₀P₆₀K₃₀ level (Figure 7).

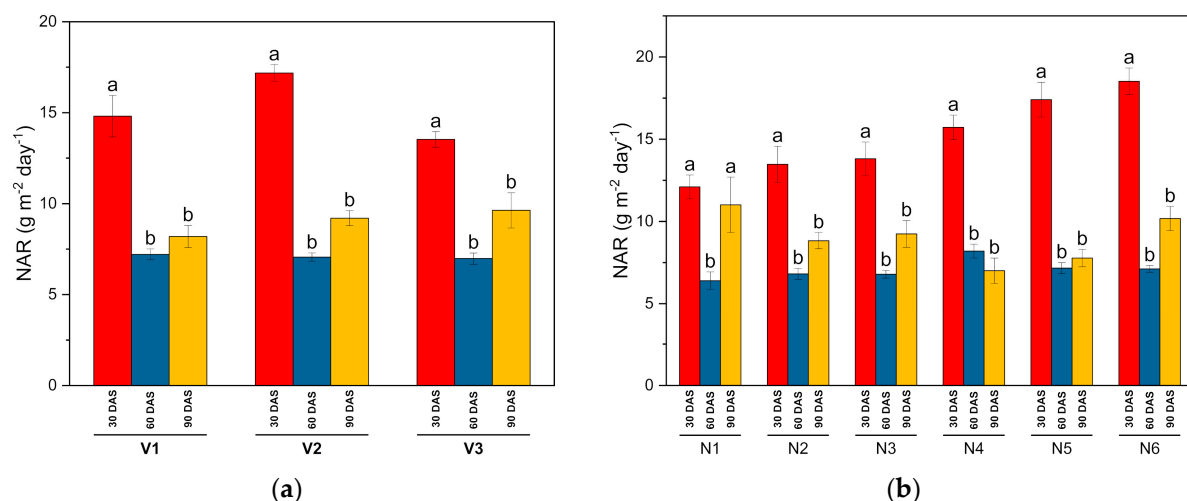


Figure 7. Mean NAR of common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a, b) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

3.2. Phenological Development, Yield Characteristics, Harvest Index and Nutrient Content and Uptake

The days to 50% emergence, 50% flowering, and 50% pod development differed significantly among common bean genotypes, as shown in Table S2. Genotype V₃ exhibited significantly fewer days to 50% emergence. In terms of the days to 50% flowering and

50% pod development, genotype V₁ was significantly earlier. There were no significant differences among genotypes in reaching 50% maturity. Regardless of genotype, an increase in NPK level caused a delay in reaching each phenological stage. The days to 50% emergence increased significantly starting from the N₃₀P₆₀K₃₀ level. Similarly, the days to 50% flowering, 50% pod development, and 50% maturity increased significantly starting from the N₁₀P₂₀K₁₀ level. The genotype of the common bean and the applied NPK level had a substantial impact on the number of pods plant^{−1}, the number of seeds pod^{−1}, and the seed index (Table 5). Regardless of the NPK level, the number of pods plant^{−1} and the seed index were significantly influenced by the common bean genotype. Genotype V₁ produced the highest number of pods plant^{−1}, followed by V₃ and V₂ (Figure 8). The yield attribute of genotype V₃ was comparable to that of V₁, and genotype V₂ was comparable to V₃. Additionally, genotype V₁ had a significantly higher seed index than both genotypes V₃ and V₂. The number of seeds pod^{−1} did not vary significantly among the genotypes. Across all genotypes, these yield characteristics were significantly influenced by the applied NPK levels (Figure 8). The pods plant^{−1} and the number of seeds pod^{−1} did not increase significantly beyond the N₃₀P₆₀K₃₀ treatment. However, the seed index achieved with N₄₀P₈₀K₄₀ was comparable to that obtained with N₅₀P₁₀₀K₅₀.

Table 5. Main effects of genotypes and NPK levels on yield characteristics and yield parameters of the common bean.

Treatment	No. of Pods Plant ^{−1}	No. of Seeds Pod ^{−1}	Seed Index (g)	Seed Yield (t ha ^{−1})	Stover Yield (t ha ^{−1})	Biological Yield (t ha ^{−1})	Harvest Index (%)
Genotype							
SKUA-WB-5000/1446 (V ₁)	8.02	3.84	39.47	2.36	3.66	6.03	38.9
SKUA-WB-5002/185 (V ₂)	7.53	3.71	36.82	1.97	3.49	5.46	35.7
SKUA-WB-5003/1492 (V ₃)	7.82	3.86	37.23	2.34	3.62	5.95	39.1
SEM (±)	0.11	0.06	0.26	0.03	0.04	0.06	0.3
LSD ($p \leq 0.05$)	0.31	NS	0.75	0.08	0.13	0.18	0.9
NPK level (N:P₂O₅:K₂O kg ha^{−1})							
N ₀ P ₀ K ₀	6.62	3.32	35	1.54	3.33	4.87	31.5
N ₁₀ P ₂₀ K ₁₀	7.58	3.34	36.63	1.94	3.48	5.41	35.6
N ₂₀ P ₄₀ K ₂₀	7.9	3.87	37.3	2.24	3.54	5.78	38.6
N ₃₀ P ₆₀ K ₃₀	8.08	4	38.44	2.43	3.64	6.07	40
N ₄₀ P ₈₀ K ₄₀	8.13	4.11	39.66	2.55	3.74	6.3	40.5
N ₅₀ P ₁₀₀ K ₅₀	8.44	4.16	40.02	2.64	3.81	6.45	40.9
SEM (±)	0.15	0.09	0.37	0.04	0.06	0.09	0.42
LSD ($p \leq 0.05$)	0.44	0.25	1.05	0.11	0.18	0.26	1.2

The data of the main effects on the yield parameters are presented in Table 5. The main effects of the common bean genotypes were that the seed yield, stover yield, biological yield, and HI were significantly higher in genotypes V₁ and V₃ (Figures 9 and 10). Regardless of the genotype, the seed yield and biological yield did not increase significantly beyond the N₄₀P₈₀K₄₀ level (Figures 9 and 10). Meanwhile, the stover yield and HI did not increase significantly beyond the N₃₀P₆₀K₃₀ level.

We found that variations in the N content (%), P content, and K content in seeds and stovers were not significant among the genotypes. Regardless of genotype, the contents of these nutrients in seeds and stovers increased significantly with higher levels of NPK application (Table S3). However, the N and P contents in seeds did not increase significantly beyond the N₃₀P₆₀K₃₀ level, while the K content did not increase significantly beyond the N₄₀P₈₀K₄₀ level. In stovers, the N and K contents did not increase significantly beyond

$N_{40}P_{80}K_{40}$ and $N_{30}P_{60}K_{30}$, respectively. The P content in stovers was significantly higher with $N_{50}P_{100}K_{50}$. Regardless of the NPK level applied, the levels of N, P, and K uptake in seeds and the whole plant (seeds and stovers) were significantly higher in genotypes V_1 and V_3 (Figure 11). However, the uptake of N and K in stovers did not vary among the common bean genotypes. Regardless of the genotype, the uptake of P and K in seeds, stovers, and the whole plant did not significantly increase beyond $N_{40}P_{80}K_{40}$ (Figure 11). N uptake in seeds and stovers did not increase significantly beyond $N_{40}P_{80}K_{40}$, although the total uptake in the whole plant was significantly higher at $N_{50}P_{100}K_{50}$ (Table 6).

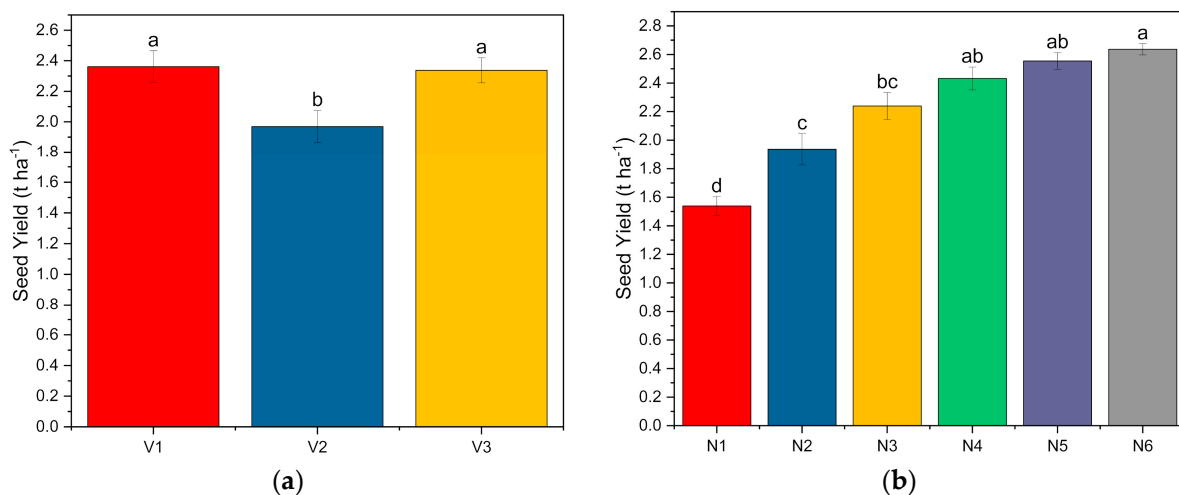


Figure 8. Seed yield of common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a–d) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

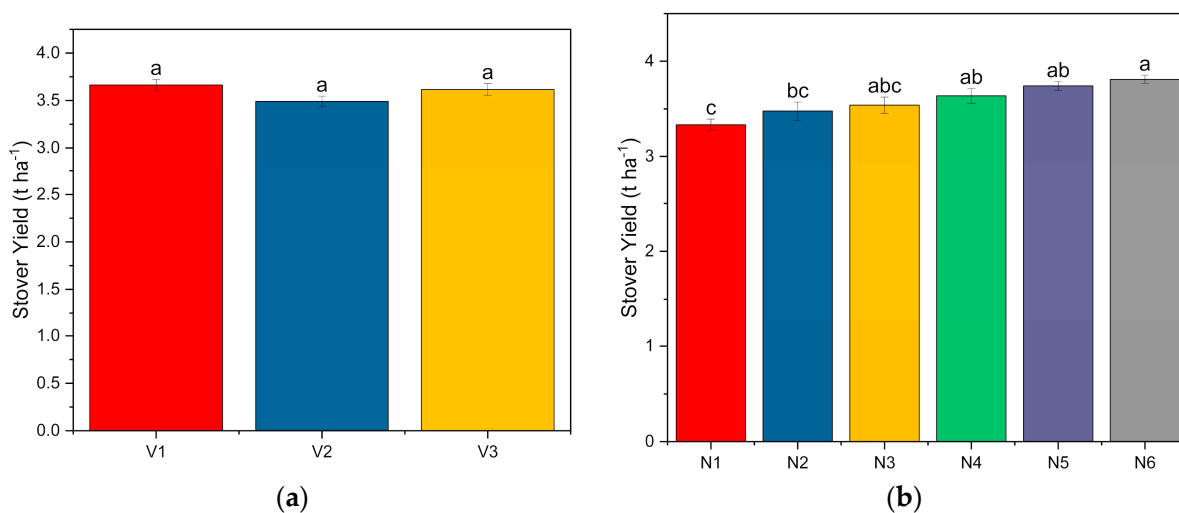


Figure 9. Stover yield of the common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a–c) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

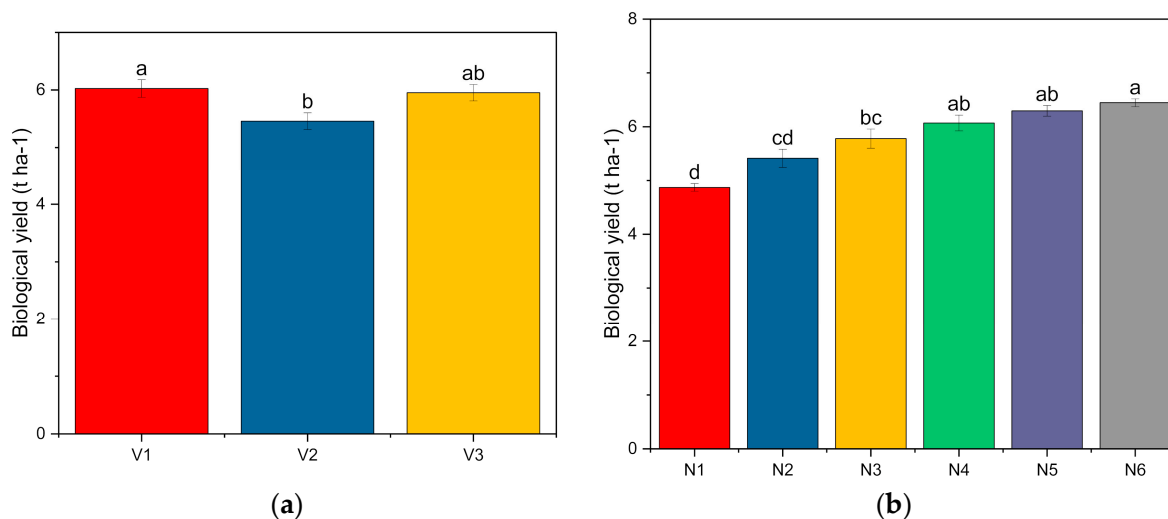


Figure 10. Biological yield of common bean as influenced by genotypes (a) and NPK levels (b). Different letters (a–d) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

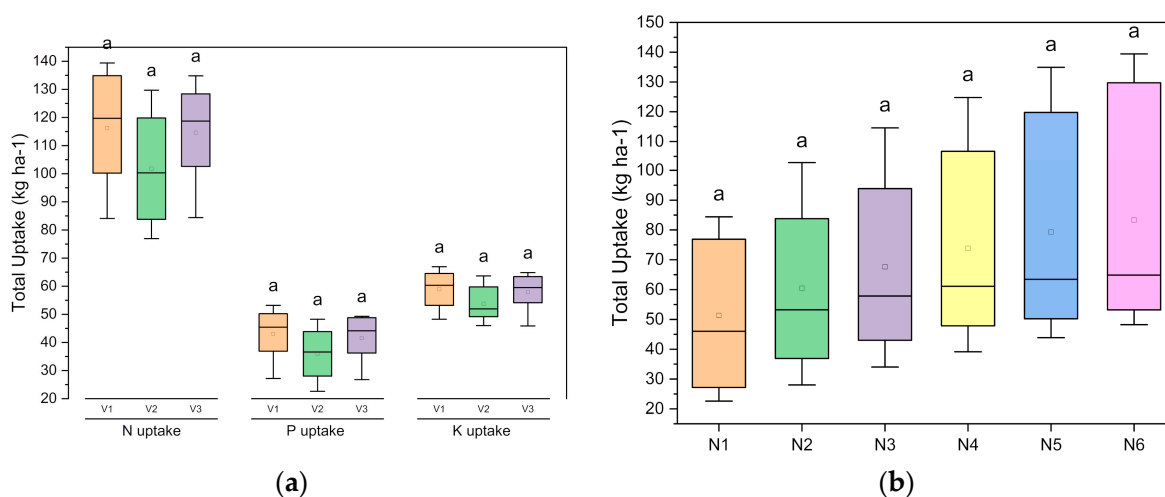


Figure 11. Total uptake of nutrients by common bean crop as influenced by genotypes (a) and NPK levels (b). Different letters (a) and error bars indicate Tukey’s HSD post hoc analysis, with two-way ANOVA (analysis of variance) at $p = 0.05$.

Table 6. Main effects of genotypes and NPK levels on nutrient uptake by the common bean crop.

Treatments	N Uptake (kg N ha ⁻¹)			P Uptake (kg P ₂ O ₅ ha ⁻¹)			K Uptake (kg K ₂ O ha ⁻¹)		
	Seed	Stover	Total	Seed	Stover	Total	Seed	Stover	Total
Genotype									
SKUA-WB-5000/1446 (V ₁)	67.3	49.1	116.4	34.85	8.21	43.06	15.7	43.2	58.93
SKUA-WB-5002/185 (V ₂)	55.4	46.39	101.8	28.47	7.52	35.99	13	40.79	53.75
SKUA-WB-5003/1492 (V ₃)	66.5	48.1	114.6	33.7	7.88	41.58	15.6	42.29	57.87
SEM (±)	1.06	0.9	1.29	0.59	0.15	0.68	0.31	0.74	0.81
LSD ($p \leq 0.05$)	3.06	NS	3.7	1.69	0.42	1.96	0.89	NS	2.32

Table 6. Cont.

Treatments	N Uptake (kg N ha ⁻¹)			P Uptake (kg P ₂ O ₅ ha ⁻¹)			K Uptake (kg K ₂ O ha ⁻¹)		
	Seed	Stover	Total	Seed	Stover	Total	Seed	Stover	Total
NPK level (N:P₂O₅:K₂O kg ha⁻¹)									
N ₀ P ₀ K ₀	41.3	40.51	81.8	20.17	5.37	25.54	9.4	37.32	46.72
N ₁₀ P ₂₀ K ₁₀	52.4	43.12	95.6	27.24	6.48	33.72	12.3	39.91	52.18
N ₂₀ P ₄₀ K ₂₀	62.7	45.02	107.7	32.34	7.55	39.89	14.5	40.87	55.36
N ₃₀ P ₆₀ K ₃₀	69.5	48.55	118.1	36.1	8.12	44.22	16.2	42.99	59.14
N ₄₀ P ₈₀ K ₄₀	74.1	53.55	127.7	38.33	9.32	47.64	17.6	45.02	62.57
N ₅₀ P ₁₀₀ K ₅₀	78.2	56.43	134.7	39.87	10.38	50.25	18.7	46.45	65.13
SEM (±)	1.5	1.27	1.82	0.83	0.21	0.96	0.44	1.05	1.14
LSD ($p \leq 0.05$)	4.32	3.66	5.2	2.39	0.59	2.77	1.26	3.03	3.28

3.3. Soil Properties and Nutrient-Use Efficiency

The soil reaction, EC, and SOC were not significantly affected by the main effects of the genotype and NPK level applied (Table S4). However, regardless of genotype, the main effects of the NPK levels applied at N₅₀P₁₀₀K₅₀ significantly increased the soil reaction and EC. SOC did not increase significantly beyond the NPK level of N₄₀P₈₀K₄₀. Regardless of the NPK level applied, the available N, P, and K in the soil did not vary significantly among the common bean genotypes (Table S4). When studying the main effects of the applied NPK, we found that the treatments of N₃₀P₆₀K₃₀ and N₄₀P₈₀K₄₀ were comparable for available N and K. These nutrients did not increase above the levels of N₄₀P₈₀K₄₀. Meanwhile, the available P in the soil did not increase above N₃₀P₆₀K₃₀. The NUE of the applied NPK, measured through the PFP, AE, ARE, and PE, is summarized in Table 7. Across all NPK levels, genotypes V₁ and V₃ exhibited higher PFP, AE, and ARE, while genotype V₂ had the highest PE. Genotype V₁ showed the greatest AE for the applied NPK, with genotype V₃ following. Similarly, ARE was highest in genotypes V₁ and V₃. Genotype V₂ had the highest PE, with genotype V₃ showing the lowest. NUE parameters, including PFP, AE, ARE, and PE, were higher at lower NPK application levels. These efficiency metrics were calculated for each genotype. For genotype V₂, AER increased with higher NPK levels, peaking at N₄₀P₈₀K₄₀. Genotype V₁ displayed a relatively higher NUE at N₃₀P₆₀K₃₀ and N₄₀P₈₀K₄₀, followed by genotypes V₃ and V₂.

Table 7. Nutrient-use efficiency (NUE) as influenced by genotypes of the common bean and NPK levels.

Treatment	PFP	AE	ARE	PE
	(kg Seed kg ⁻¹ NPK Applied)			
Genotype				
SKUA-WB-5000/1446 (V ₁)	26.9	8.7	0.63	13.45
SKUA-WB-5002/185 (V ₂)	21.5	6.3	0.44	14.37
SKUA-WB-5003/1492 (V ₃)	27.1	7.8	0.64	11.85
SEM (±)	-	-	-	-
LSD (<i>p</i> ≤ 0.05)	-	-	-	-

Table 7. Cont.

Treatment	PFP	AE	ARE	PE
	(kg Seed kg ⁻¹ NPK Applied)			
NPK level (N:P ₂ O ₅ :K ₂ O kg ha ⁻¹)				
N ₀ P ₀ K ₀	-	-	-	-
N ₁₀ P ₂₀ K ₁₀	48.4	9.9	0.68	14.28
N ₂₀ P ₄₀ K ₂₀	28.0	8.8	0.61	14.89
N ₃₀ P ₆₀ K ₃₀	20.3	7.4	0.56	13.40
N ₄₀ P ₈₀ K ₄₀	16.0	6.3	0.52	12.13
N ₅₀ P ₁₀₀ K ₅₀	13.2	5.5	0.48	11.41
SEM (±)	-	-	-	-
LSD (<i>p</i> ≤ 0.05)	-	-	-	-

4. Discussion

This study has examined the plant height, LAI, DMA, and nodulation as growth metrics for different genotypes of common bean (SKUA-WB-5000/1446 (V₁), SKUA-WB-5002/185 (V₂), and SKUA-WB-5003/1492 (V₃)) under various NPK treatments. The results revealed that NPK levels significantly influenced these growth metrics, particularly at 60 DAS. Genotypes V₂ and V₃ exhibited significantly higher plant heights compared to V₁, with increases observed up to N₁₀P₂₀K₁₀. For LAI, genotypes V₁ and V₃ showed higher values, with significant improvements up to N₃₀P₆₀K₃₀. Genotype V₁ had the highest DMA at all observation stages, followed by V₃, with significant increases noted up to N₅₀P₁₀₀K₅₀ at later growth stages. The interaction between genotypes and NPK levels showed that, at 60 DAS, plant height and LAI did not vary significantly across different NPK levels, except that LAI for V₁ and V₃ did not increase significantly beyond N₃₀P₆₀K₃₀. For DMA, V₁ and V₃ did not show significant increases beyond N₃₀P₆₀K₃₀ and N₄₀P₈₀K₄₀, respectively. Genotype V₂ did not exhibit a significant increase in LAI beyond N₄₀P₈₀K₄₀ at 60 DAS, while DMA continued to increase significantly up to N₅₀P₁₀₀K₅₀ at all growth stages.

The genotypes' influences on the growth parameters were due to their genetic characteristics. Plant nutrients (NPK) play significant roles in controlling plant height, LAI, and DMA with varying intensity among the crop genotypes. The beneficial effects of N, P, and K could be attributed to the fact that the essential primary nutrients are directly engaged in plant metabolism actions such as photosynthesis, nutrient storage, and transportation, all of which contribute to plant growth and development [49]. Leguminous crops have a symbiotic nodulation process; hence, they respond well to NPK application. However, the significant response to these growth parameters varied at different levels of NPK application, which might be due to inherent soil fertility status and genetic characteristic differences among common bean genotypes. Several studies have also reported on the growth parameters of the common bean as influenced by varying levels of NPK application. A considerably increased plant height of the bean crop was observed with fertilizer levels ranging at 25–120 kg N, 60–75 kg P, and 30–50 kg K ha⁻¹ in different studies [50–52]. Ayub et al. [53] reported that applying P and K fertilizers in the ratio of 70:70 kg ha⁻¹ increased the plant height. A significant increase in leaf area at 150 kg N and 75 kg P₂O₅ ha⁻¹ was reported by Kakon et al. [54]. The maximum DMA in beans was reported with fertilizer levels at 80:75:30 kg NPK ha⁻¹ [50] and 120:60:45 kg NPK ha⁻¹ [50].

Differences in the effective nodule count and total nodule weight were not significant among the genotypes. However, NPK levels greatly influenced the effective nodule count and total nodule weight. The effective nodule count was significantly higher at N₅₀P₁₀₀K₅₀, while the total nodule weight was not increased dramatically beyond N₃₀P₆₀K₃₀. Many reports suggest that the common bean is a poor N-fixer compared to other legumes. Therefore, the crop is more responsive to N than other legumes [55,56]. N is recommended in

legumes with a low soil N status (less than 34 kg N ha⁻¹) to avoid manifest deficiency symptoms [57]. However, the common bean also exhibited nodulation in hilly conditions as the soil contained suitable *Rhizobium* strains. In these conditions, the nodulation was affected by the application of more N irrespective of the genotype as nitrogenous activity declined with applied N, decreasing the sink strength and reducing the quantity of photo-assimilate partitioned to nodules [58]. Common bean genotypes had a substantial impact on whether the nodule number and nodule weight responded well to NPK application from 30:60:30 to 50:100:20 kg ha⁻¹ of N:P:K [27,59].

Based on the DMA and leaf area throughout a 30-day growth interval, crop growth analysis traits such as the mean CGR, RGR, and NAR were determined. Irrespective of NPK levels, genotype V₁ showed the marked maximum mean CGR, followed by genotype V₃, during the growth intervals of 0–30 and 30–60 DAS. The maximum mean RGR was logged with genotype V₁ during 0–30 DAS, while for genotype V₂, we logged a higher mean RGR during 30–60 and 60–90 DAS. A significantly higher mean NAR was computed with genotype V₁ during 0–30 DAS and 30–60 DAS and with genotypes V₂ and V₃ during the growth interval of 60–90 DAS. Irrespective of the common bean genotype, the mean CGR was significantly increased with the application of all NPK levels during all the growth intervals. However, it was not increased considerably above the level of N₄₀P₈₀K₄₀. The mean RGR was not significantly increased above N₄₀P₈₀K₄₀ and N₁₀P₂₀K₁₀ during the early growth interval (0–30 DAS) and later growth intervals (30–60 DAS and 60–90 DAS), respectively. The mean NAR was not increased significantly above N₄₀P₈₀K₄₀ during 0–30 DAS and 30–60 DAS. At 60–90 DAS, the mean NAR was not raised above N₃₀P₆₀K₃₀. Variability in how genetic features and NPK impacted the leaf area and dry matter production per unit area per unit time were blamed for the disparities in growth analysis traits. Earlier researchers also reported variation in crop growth traits due to plant nutrients in crops like the cluster bean, moth bean [60,61], and green gram [62].

The influence of the NPK level on phenological development phases such as the days to 50% emergence, days to 50% flowering, days to 50% pod development, and days to 50% maturity was investigated among genotypes. Significant earliness in the days to 50% emergence was noted with genotype V₃. Meanwhile, significantly earliness of the days to 50% flowering and 50% pod development was seen in the genotype V₁. No significant differences were observed among the genotypes in the days to 50% maturity. The growth and development of common bean genotypes differed with fertility levels. Earliness of phenological development phases occurred at lower levels of NPK application, and with each successive increase in NPK level, these phases were delayed. Irrespective of the genotype, 50% emergence was observed in about 12 days below N₃₀P₆₀K₃₀ and increased significantly beyond that level. The days to 50% flowering, 50% pod development, and 50% maturity were increased considerably from N₁₀P₂₀K₁₀.

Varietal differences in early germination and seedling emergence occur in response to low temperature and soil moisture tolerance. De Ron et al. [63] reported that the rate of emergence in bean genotypes was greatly reduced by a cool temperature. Beruktawit et al. [64] reported that differences in the days to flowering among common bean cultivars suggested a high percentage of seed germination when there was a balanced supply of N, P, and K. However, a lack of P and K with a high N supply resulted in limited germination ability. A delay in flowering might occur because an excessive collection of N promotes luxuriant and succulent vegetative growth, dominating the reproductive phase. Marschner [65] suggested that the nutrients taken up were used for increased cell division and synthesis of carbohydrates, which will predominantly be partitioned to the vegetative sink of the plants, resulting in plants with a luxurious foliage growth and delayed in maturity. Tewari and Singh [66] reported that increased N levels resulted in more plant height but delayed blooming in beans. Dejene et al. [67] hypothesized that greater P application increased cytokinin production, resulting in early flowering.

Except for the number of seeds pod⁻¹, the yield characteristics—the number of pods plant⁻¹ and seed index—were significantly influenced by the common bean genotypes.

Both these yield characteristics were substantially higher with genotype V₁. An increased level of NPK resulted in a higher number of pods plant^{−1}, number of seeds pod^{−1}, and seed index. However, beyond the level of N₃₀P₆₀K₃₀, neither the number of pods plant^{−1} nor the number of seeds pod^{−1} grew appreciably. Meanwhile, the seed index obtained with N₄₀P₈₀K₄₀ was similar to that with N₅₀P₁₀₀K₅₀. The yield parameters—seed yield, stover yield, biological yield, and harvest index of the common bean—were significantly higher with genotypes V₁ and V₃. Irrespective of the genotype, the seed yield and biological yield were not significantly above the level of N₄₀P₈₀K₄₀. In comparison, the stover yield and harvest index were not significantly above the level of N₃₀P₆₀K₃₀. The harvest index in genotypes V₁ and V₂ was not significantly above the level of N₃₀P₆₀K₃₀. In the case of genotype V₃, the harvest index was not improved above the level of N₂₀P₄₀K₂₀. The yield characteristics are the crucial parameters that are supposed to play a role directly in achieving potential yield recovery in legumes. The number of pods plant^{−1} can positively correlate with nodulation and the crop yield [19]. Common bean cultivars vary in yield characteristics [27]. The application of 25:75:50 kg ha^{−1} of NPK in dolichos bean resulted in a significantly greater number of pods plant^{−1} [52]. Chekanai et al. [28] also reported that the application of N in the primary season increased the number of pods in the subsequent season. Similarly, Leal et al. [68] also suggested that the application of 120 kg N ha^{−1} increased the number of pods plant^{−1}. Elsewhere, the number of pods plant^{−1} increased with N and K application [69].

A considerable increase in the number of seeds pod^{−1} with N, P, and K applications was reported by Zebire and Gelgelo [70]. Sofi et al. [71] observed that number of seeds pod^{−1} was significantly increased up to 60 kg P₂O₅ ha^{−1}. The genotypes also created significant variation in the yield characteristics. Emam and Semida [72] reported that the seed index increased with K supply. Yin et al. [73] reported that the amounts of NPK for a higher seed index were 41.9 kg N ha^{−1}, 20.7 kg P₂O₅ ha^{−1}, and 66.50 kg K₂O ha^{−1}. The yield of a crop can be defined as the outcome and highly dependent on the vegetative growth, and numerically, it is the product of plant population and yield characteristics. In pulses, a higher vegetative growth may render a greater final yield. According to Sofi et al. [74], an increase in yield-attributing features among the diverse genotypes of the common bean resulted in increased seed production. The application of nutrients highly influences the yield parameters. A significant response in the seed yield of bean was observed with N application varied from 120 to 240 kg ha^{−1} and P application from 60 to 100 kg P₂O₅ ha^{−1} [66,75,76]. Shubhashree et al. [77] reported that the yield of rajmash was significantly higher at 80:75:30 kg N:P₂O₅:K₂O ha^{−1}.

The influence of NPK on the productivity of common beans is multifaceted, impacting several physiological and biochemical processes essential for plant growth and the yield. N is a crucial component of amino acids, proteins, and chlorophyll, all of which are vital for plant growth and development. An adequate N supply enhances photosynthesis by increasing the chlorophyll content, thereby improving the plant's ability to capture light energy and convert it into biomass [78]. Furthermore, N promotes leaf area expansion, providing a larger surface area for photosynthesis, which is critical for biomass accumulation and the yield [79]. P is essential for energy transfer within the plant, as it is a key component of ATP (adenosine triphosphate), which fuels various metabolic processes [80]. It plays a significant role in root development, enhancing the plant's ability to absorb water and nutrients from the soil [81]. Additionally, P is critical for the formation and development of flowers, seeds, and pods, directly affecting reproductive success and the yield [82]. P regulates the water-use efficiency and stomatal function, which are crucial for maintaining cellular turgor and controlling water loss, particularly under drought conditions [65]. It activates enzymes involved in photosynthesis, protein synthesis, and carbohydrate metabolism, thereby facilitating overall plant growth and productivity [32]. P also enhances the plant's ability to withstand biotic and abiotic stresses, contributing to more stable and higher yields [83]. The balanced application of NPK fertilizers ensures that common bean plants receive all essential macronutrients in appropriate proportions,

promoting optimal growth and development. The synergistic effects of combined NPK application can lead to enhanced root biomass, improved nutrient uptake, and better overall plant health [84]. For instance, N and P together can enhance root development more effectively than either nutrient alone, resulting in improved nutrient acquisition and growth [85]. Adequate NPK nutrition leads to increased biomass production, higher pod and seed counts, and improved seed quality, including a higher protein content [86]. N primarily influences vegetative growth and protein synthesis, P impacts reproductive development and energy transfer, and K improves stress tolerance and water-use efficiency. Collectively, these effects contribute to higher yields and better productivity of common beans. The influence of NPK on the productivity of common beans involves enhancing photosynthesis, energy transfer, nutrient uptake, water-use efficiency, and stress resistance, leading to improved growth, development, and yield [87–89]. Our findings revealed that the nutrient contents (N, P, and K) in genotypes V₁, V₂, and V₃ were on a par. However, the N, P, and K uptake levels in seeds and whole plants (seeds and stovers) were significantly higher with genotypes V₁ and V₃. The higher seed yield and total biomass obtained with genotypes V₁ and V₃ might have increased the uptake of these nutrients. Irrespective of the genotype, the contents of these nutrients in seeds and stovers increased significantly with the increasing levels of NPK applied. However, the N and P contents in the seeds were not increased significantly above the level of N₃₀P₆₀K₃₀, while the K content was not increased significantly above the level of N₄₀P₈₀K₄₀. Consequently, the uptake of these nutrients by crop was not significantly above the level of N₄₀P₈₀K₄₀. Increasing the application of nutrients leads to more available nutrients in the soil; consequently, the nutrient content and uptake increase [90]. Thus, when the nutrient application is increased, the nutrient uptake by the plants is also higher because of increased biomass production [91–93].

Irrespective of the nutrients applied, the soil reaction, EC, SOC, and available soil nutrients (N, P, and K) were not significantly affected among the common bean genotypes. These soil properties were found to be very stable and may not be varied considerably by varied genotypes in a short period of one crop cycle. The various levels of NPK had significant effects on soil properties. The level of N₅₀P₁₀₀K₅₀ had significantly higher values of soil reaction and EC. The SOC was not markedly increased beyond the level of N₄₀P₈₀K₄₀. The available NPK in soil was also not increased significantly above the level of N₃₀P₆₀K₃₀. SOC is an essential soil quality index, playing a significant role in affecting crop productivity [94]. The findings by Sharma and Verma [95] indicated that a build-up of SOC and available N, P, and K (over the control) occurred due to the inoculation of rajmash with *Rhizobium* and the application of organic manure and chemical fertilizers. The SOC and available NPK in the soil can be maintained at an optimum level or improved through fertility management by using inorganic fertilizers and organic manures, tillage methods, crop rotation, and other cropping system components. However, a report indicated that increasing the P levels did not impact the pH, SOC, or soil-available N [96]. Phosphorous fertilization in the common bean was expected to improve the cropping system performance, with well-documented P residual benefits to crop rotations [28]. Sofi et al. [71] noted no changes in pH, EC, SOC, or available NPK in the soil when growing various genotypes of the common bean and varying the phosphorus levels. The SOC levels were also measured at various P levels, but the percentage increase over a single season was near-negligible.

Irrespective of the NPK level applied, PFP, AE, and ARE were found to be higher with genotypes V₁ and V₃. PE was found to be at its maximum with genotype V₂. The nutrient-use efficiency in terms of PFP, AE, ARE, and PE was higher at lower levels of NPK applied. AER in genotype V₂ increased with the NPK level, reaching a maximum at N₄₀P₈₀K₄₀. At N₃₀P₆₀K₃₀ and N₄₀P₈₀K₄₀, the genotype V₁ showed a relatively higher nutrient-use efficiency, followed by V₃ and V₂. The mineral sustenance law states that there will be a greater expansion in yield with the first addition of applied supplement and the yield increment will be lower with higher supplement rates [97]. In this study, the higher growth rates and yields of different genotypes suggested that the optimum application rates of NPK fertilizers were at N₃₀P₆₀K₃₀ and N₄₀P₈₀K₄₀. Akter et al. [98] reported that

increasing the nutrient-use efficiency helps reduce fertilizers' costs and control pollution. When lowering the application of N fertilizer, rhizobia will be free to fix atmospheric N. K fertilizer doses should be regulated to optimize crop growth and development. P fertilizer application should be stabilized to improve its utilization by plants. With precise, optimized fertilization, the utilization of these nutrients by crops can be increased, improving the crop fertilization efficacy, environmental protection, crop quality, and crop yield. Most of the N and P fertilizers available in the market have a use efficiency of <30% because of rapid volatilization into greenhouse gases or fixation in soil [73]. Therefore, it was previously suggested that fertilizer application in green gram should reduce N, increase K, and stabilize P. Dejene et al. [67] commented that common beans' P-use efficiency was associated with their variation in P uptake ability. In contrast, Ortiz-Monasterio et al. [99] reported that this mainly depended on root morphological characteristics. Leal et al. [68] reported that the agronomic, physiological, and recovery-use efficiencies of N application in some common bean cultivars stood out, which may have been due to better nodulation at lower rates of N application.

5. Conclusions

This study in the temperate Himalayan region of India provides valuable insights and recommendations from economic, agronomic, ecological, and sustainable perspectives, as well as considering nutritional value. The findings reveal that for common bean genotypes SKUA-WB-5000/1446 (V_1) and SKUA-WB-5003/1492 (V_3), the optimal nutrient levels are 30 kg N, 60 kg P_2O_5 , and 30 kg K_2O per ha^{-1} . Genotype SKUA-WB-5002/185 (V_2) thrive best with 40 kg N, 80 kg P_2O_5 , and 40 kg K_2O per ha^{-1} , to maximize productivity and nutrient utilization in rainfed conditions. Economically and agronomically, plant height increases gradually with NPK levels, but it did not show significant improvements beyond $N_{10}P_{20}K_{10}$. LAI exhibited significant increases at 60 DAS with V_1 and V_3 . Genotype V_1 demonstrated superior growth parameters and yield characteristics, including a greater numbers of pods per plant and higher seed index, which led to an increased seed yield, stover yield, biological yield, and harvest index. Additionally, V_1 exhibited a higher DMA per plant across the observation stages. Ecologically, genotypes V_1 and V_3 showed a greater nutrient uptake, particularly for N and P, and higher NUE. This indicates their potential for more sustainable nutrient management, reducing the need for excessive fertilizer application and minimizing the environmental impact. From a sustainability perspective, soil properties varied with genotypes and nutrient levels, underscoring the importance of tailored nutrient management strategies for optimizing crop performance and ensuring long-term soil health. Optimizing nutrient levels not only enhances the crop yield but also improves the nutritional quality of the common beans, contributing to better food security and dietary health in the region. In conclusion, this study emphasizes the significance of genotype-specific nutrient management practices to enhance productivity and sustainability in common bean farming in the temperate Himalayan region. The insights gathered contribute to advancing agricultural practices that balance economic profitability, ecological stewardship, and nutritional value, thereby supporting informed decision-making for farmers and stakeholders involved in crop production in similar agro-ecological contexts.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su16146234/s1>, Figure S1: Layout of the experimental field; Figure S2: Genotypes of the common bean evaluated in the experiment; Figure S3: Overview of the experimental field; Table S1: Details of the experimental treatments; Table S2: Main effects of genotypes and NPK levels on phenological development stages of the common bean; Table S3: Main effects of genotypes and NPK levels on nutrient contents in the common bean; Table S4: Main effects of genotypes of the common bean and NPK levels on soil properties.

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References

- Rodriguez, L.; Mendez, D.; Montecino, H.; Carrasco, B.; Arevalo, B.; Palomo, I.; Fuentes, E. Role of *Phaseolus vulgaris* L. in the prevention of cardiovascular diseases—Cardioprotective potential of bioactive compounds. *Plants* **2022**, *11*, 186. [CrossRef]
- Camara, C.R.; Urrea, C.A.; Schlegel, V. Pinto beans (*Phaseolus vulgaris* L.) as a functional food: Implications on human health. *Agriculture* **2013**, *3*, 90–111. [CrossRef]
- Celmeli, T.; Sari, H.; Canci, H.; Sari, D.; Adak, A.; Eker, T.; Toker, C. The nutritional content of common bean (*Phaseolus vulgaris* L.) landraces in comparison to modern varieties. *Agronomy* **2018**, *8*, 166. [CrossRef]
- Katoch, S.; Katoch, A.; Dhiman, S.; Sharma, P.; Rana, S.K.; Sharma, P.N. Recitation of R genes identified in common bean landrace KRC-5 and KRC-8 native to Himachal Pradesh against *Colletotrichum lindemuthianum* virulences. *Himachal J. Agric. Res.* **2019**, *45*, 51–56.
- Basavaraja, T.; Manjunatha, L.; Chandora, R.; Singh, M.; Rathod, S.; Dubey, V.; Singh, N.P. Assessment of phenotypic diversity and multi-locational screening against bean common mosaic virus (BCMV) disease resistance in dry bean (*Phaseolus vulgaris* L.) germplasm. *Plant Genet. Resour.* **2022**, *20*, 79–86. [CrossRef]
- Jan, S.; Rather, I.A.; Sofi, P.A.; Wani, M.A.; Sheikh, F.A.; Bhat, M.A.; Mir, R.R. Characterization of common bean (*Phaseolus vulgaris* L.) germplasm for morphological and seed nutrient traits from Western Himalayas. *Legume Sci.* **2021**, *3*, e86. [CrossRef]
- George, M.T.; Susan, N.M. Diversity of common bean (*Phaseolus vulgaris* L.) genotypes in iron and zinc contents under greenhouse conditions. *Afr. J. Agric. Res.* **2010**, *5*, 738–747.
- Souza, T.L.P.; Faleiro, F.G.; Dessaune, S.N.; Paula-Junior, T.J.D.; Moreira, M.A.; Barros, E.G.D. Breeding for common bean (*Phaseolus vulgaris* L.) rust resistance in Brazil. *Trop. Plant Pathol.* **2013**, *38*, 361–374. [CrossRef]
- Alemu, H. Review paper on breeding common bean (*Phaseolus vulgaris* L.) genotypes for acidic soil tolerance. *Int. J. Adv. Res. Publ.* **2017**, *1*, 39–46.
- Barrett, M.L.; Udani, J.K. A proprietary alpha-amylase inhibitor from white bean (*Phaseolus vulgaris*): A review of clinical studies on weight loss and glycemic control. *Nutr. J.* **2011**, *10*, 34. [CrossRef]
- Assefa, T.; Assibi Mahama, A.; Brown, A.V.; Cannon, E.K.; Rubyogo, J.C.; Rao, I.M.; Cannon, S.B. A review of breeding objectives, genomic resources, and marker-assisted methods in common bean (*Phaseolus vulgaris* L.). *Mol. Breed.* **2019**, *39*, 20. [CrossRef]
- Schmutz, J.; McClean, P.E.; Mamidi, S.; Wu, G.A.; Cannon, S.B.; Grimwood, J.; Jackson, S.A. A reference genome for common bean and genome-wide analysis of dual domestications. *Nat. Genet.* **2014**, *46*, 707–713. [CrossRef]
- FAOSTAT. Crops and Livestock Products. 2016. Available online: <https://www.fao.org/faostat/en/#data/QCL> (accessed on 1 January 2023).
- Siddiq, M.; Uebersax, M.A.; Siddiq, F. Global production, trade, processing, and nutritional profile of dry beans and other pulses. In *Dry Beans and Pulses: Production, Processing, and Nutrition*; John Wiley & Sons: Hoboken, NJ, USA, 2022; pp. 1–28. [CrossRef]
- Sheikh, F.A.; Khan, M.N.; Sofi, P.A.; Dar, Z.A.; Sofi, N.R.; Bhat, J.A.; Bhat, M.A. Farmers' Preference Ranking in Bush Type of Common Bean (*Phaseolus vulgaris* L.) in Kashmir—Participatory Varietal Selection. *Int. J. Pure Appl. Biosci.* **2017**, *5*, 712–719. [CrossRef]
- Rana, J.C.; Sharma, T.R.; Tyagi, R.K.; Chahota, R.K.; Gautam, N.K.; Singh, M.; Ojha, S.N. Characterisation of 4274 accessions of common bean (*Phaseolus vulgaris* L.) germplasm conserved in the Indian gene bank for phenological, morphological, and agricultural traits. *Euphytica* **2015**, *205*, 441–457. [CrossRef]
- Martinez-Romero, E. Diversity of *Rhizobium-Phaseolus vulgaris* symbiosis: Overview and perspectives. *Plant Soil* **2003**, *252*, 11–23. [CrossRef]
- Peoples, M.B.; Giller, K.E.; Jensen, E.S.; Herridge, D.F. Quantifying country-to-global scale nitrogen fixation for grain legumes: I. Reliance on nitrogen fixation of soybean, groundnut and pulses. *Plant Soil* **2021**, *469*, 1–14. [CrossRef]

19. Kumar, S.S.; Mahale, A.G.; Sultan, A.; Jadhav, S.C.; Ejaz, A.; Krishna, J.R.; Channa, T.K. Boosting Agricultural Production-Beneficial Biofertilizers. *Int. J. Curr. Microbiol. Appl. Sci.* **2021**, *10*, 646–662. [\[CrossRef\]](#)
20. Wilker, J.; Humphries, S.; Rosas-Sotomayor, J.C.; Gómez Cerna, M.; Torkamaneh, D.; Edwards, M.; Pauls, K.P. Genetic diversity, nitrogen fixation, and water use efficiency in a panel of Honduran common bean (*Phaseolus vulgaris* L.) landraces and modern genotypes. *Plants* **2020**, *9*, 1238. [\[CrossRef\]](#)
21. Lavrenko, S.O.; Lavrenko, N.M.; Maksymov, D.O.; Maksymov, M.V.; Didenko, N.O.; Islam, K.R. Variable tillage depth and chemical fertilization impact on irrigated common beans and soil physical properties. *Soil Tillage Res.* **2021**, *212*, 105024. [\[CrossRef\]](#)
22. dos Santos Sousa, W.; Soratto, R.P.; Peixoto, D.S.; Campos, T.S.; da Silva, M.B.; Souza, A.G.V.; Gitari, H.I. Effects of Rhizobium inoculum compared with mineral nitrogen fertilizer on nodulation and seed yield of common bean: A meta-analysis. *Agron. Sustain. Dev.* **2022**, *42*, 52. [\[CrossRef\]](#)
23. Fageria, N.K.; Melo, L.C.; de Oliveira, J. Nitrogen use efficiency in dry bean genotypes. *J. Plant Nutr.* **2013**, *36*, 2179–2190. [\[CrossRef\]](#)
24. Hawkesford, M.; Horst, W.; Kichey, T.; Lambers, H.; Schjoerring, J.; Möller, I.S.; White, P. Functions of macronutrients. In *Marschner's Mineral Nutrition of Higher Plants*; Academic Press: Cambridge, MA, USA, 2012; pp. 135–189. [\[CrossRef\]](#)
25. Singh, M.; Kumar, J.; Singh, S.; Singh, V.P.; Prasad, S.M. Roles of osmoprotectants in improving salinity and drought tolerance in plants: A review. *Rev. Environ. Sci. Bio/Technol.* **2015**, *14*, 407–426. [\[CrossRef\]](#)
26. Zeng, J.; Tu, Q.; Yu, X.; Qian, L.; Wang, C.; Shu, L.; He, Z. PCycDB: A comprehensive and accurate database for fast analysis of phosphorus cycling genes. *Microbiome* **2022**, *10*, 101. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Amanuel, A.; Amisalu, N.; Merkeb, G. Growth and yield of common bean (*Phaseolus vulgaris* L.) cultivars as influenced by rates of phosphorus at Jimma, Southwest Ethiopia. *J. Agric. Biotechnol. Sustain. Dev.* **2018**, *10*, 104–115. [\[CrossRef\]](#)
28. Chekanai, V.; Chikowo, R.; Vanlauwe, B. Response of common bean (*Phaseolus vulgaris* L.) to nitrogen, phosphorus and rhizobia inoculation across variable soils in Zimbabwe. *Agric. Ecosyst. Environ.* **2018**, *266*, 167–173. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Taliman, N.A.; Dong, Q.; Echigo, K.; Raboy, V.; Saneoka, H. Effect of phosphorus fertilization on the growth, photosynthesis, nitrogen fixation, mineral accumulation, seed yield, and seed quality of a soybean low-phytate line. *Plants* **2019**, *8*, 119. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Singh, S.K.; Reddy, V.R.; Fleisher, D.H.; Timlin, D.J. Phosphorus nutrition affects temperature response of soybean growth and canopy photosynthesis. *Front. Plant Sci.* **2018**, *9*, 1116. [\[CrossRef\]](#)
31. Waraich, E.A.; Ahmad, R.; Halim, A.; Aziz, T. Alleviation of temperature stress by nutrient management in crop plants: A review. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 221–244. [\[CrossRef\]](#)
32. Wang, M.; Zheng, Q.; Shen, Q.; Guo, S. The critical role of potassium in plant stress response. *Int. J. Mol. Sci.* **2013**, *14*, 7370–7390. [\[CrossRef\]](#)
33. Hasanuzzaman, M.; Bhuyan, M.B.; Nahar, K.; Hossain, M.S.; Mahmud, J.A.; Hossen, M.S.; Fujita, M. Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy* **2018**, *8*, 31. [\[CrossRef\]](#)
34. Wakeel, A.; Farooq, M.; Qadir, M.; Schubert, S. Potassium substitution by sodium in plants. *Crit. Rev. Plant Sci.* **2011**, *30*, 401–413. [\[CrossRef\]](#)
35. Dawood, M.G.; Abdelhamid, M.T.; Schmidhalter, U. Potassium fertiliser enhances the salt-tolerance of common bean (*Phaseolus vulgaris* L.). *J. Hortic. Sci. Biotechnol.* **2014**, *89*, 185–192. [\[CrossRef\]](#)
36. Dubey, R.S.; Srivastava, R.K.; Pessarakli, M. Physiological mechanisms of nitrogen absorption and assimilation in plants under stressful conditions. In *Handbook of Plant and Crop Physiology*; CRC Press: Boca Raton, FL, USA, 2021; pp. 579–616.
37. Piper, C.S. *Annual International Science Publication*; Asian Edition; University of Adelaide: Adelaide, Australia, 1966; p. 235.
38. Blake, G.R.; Hartge, K.H. Bulk density. In *Methods of soil structure and migration of colloidal materials soils*. *Soil Sci. Soc. Am. Proc.* **1986**, *26*, 297–300. [\[CrossRef\]](#)
39. Jackson, M.L. *Soil Chemical Analysis*; Prentice Hall of India Private Limited: New Delhi, India, 1967.
40. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [\[CrossRef\]](#)
41. Subbiah, B.; Asija, G.L. Alkaline permanganate method of available nitrogen determination. *Curr. Sci.* **1956**, *25*, 259–260.
42. Olsen, S.R.; Cole, C.V.; Watanabe, F.S.; Dean, L.A. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. In *USDA Circular 939*; U.S. Government Printing Office: Washington, DC, USA, 1954.
43. Easlon, H.M.; Bloom, A.J. Easy Leaf Area: Automated digital image analysis for rapid and accurate measurement of leaf area. *Appl. Plant Sci.* **2014**, *2*, 1400033. [\[CrossRef\]](#)
44. Watson, D.J. The physiological basis of variation in yield. *Adv. Agron.* **1952**, *4*, 101–145. [\[CrossRef\]](#)
45. Donald, C.M. In search of yield. *J. Aust. Inst. Agric. Sci.* **1962**, *28*, 171–178.
46. Sepat, S.; Bana, R.S.; Kumar, D.; Rana, K.S. A practical manual on principle and practices of managing soil and field crops. In *New Delhi Publication*; Division of Agronomy, IARI: New Delhi, India, 2013; p. 90.
47. Cochran, G.C.; Cox, M.M. *Experimental Designs*; Asia Publishing House: Bombay, India, 1963; pp. 293–316.
48. SPSS, *Statistical Package for the Social Sciences*, Version 26.0; IBM SPSS: Armonk, NY, USA, 2020.
49. Pandey, R. Mineral nutrition of plants. *Plant Biol. Biotechnol.* **2015**, 499–538. [\[CrossRef\]](#)
50. Kalmani, B.R.; Sunad, L.K.; Gopur, S.T. Studies on the effect of mother plant nutrition on crop growth, yield and quality of French bean. *Leg. Res.* **2002**, *19*, 34–41.

51. Kumar, M.; Sinha, K.K.; Sharma, R.R. Effect of organic manure, NPK and boron application on the productivity of French bean in sandy loam soil of north Bihar. *Indian J. Pulses Res.* **2004**, *17*, 42–44.
52. Kumar, E.S.; Channaveerswami, A.S.; Merwade, M.N.; Naik, V.R.; Krishna, A. Influence of Nipping and Hormonal Sprays on Growth and Seed Yield in Field Bean [*Lablab purpureus* (L.) Sweet] Genotypes. *Int. J. Econ. Plants* **2018**, *5*, 008–014. [\[CrossRef\]](#)
53. Ayub, M.; Nadeem, M.A.; Naeem, M.; Tahir, M.; Tariq, M.; Ahmad, W. Effect of different levels of P and K on growth, forage yield and quality of cluster bean (*Cyamopsis tetragonolobus* L.). *J. Anim. Plants Sci.* **2012**, *22*, 479–483.
54. Kakon, S.S.; Bhuiya, M.S.U.; Hossain, S.M.A.; Naher, Q.; Bhuiyan, M.D. Effect of nitrogen and phosphorus on growth and seed yield of French bean. *Bangladesh J. Agric. Res.* **2016**, *41*, 759–772. [\[CrossRef\]](#)
55. Amare, G.; Assaye, D.; Tuma, A. The response of haricot bean varieties to different rates of phosphorus at Arba Minch, Southern Ethiopia. *J. Agric. Biol. Sci.* **2014**, *9*, 344–350.
56. Soratto, R.P.; Perez, A.A.; Fernandes, A.M. Age of No-Till system and nitrogen management on common bean nutrition and yield. *Agron. J.* **2014**, *106*, 809–820. [\[CrossRef\]](#)
57. Dwivedi, Y.C.; Sharma, R.S.; Sengupata, S.K. Effect of phosphorus and potassium fertilization on grain yield of French bean (*Phaseolus vulgaris* L.). *Veg. Sci.* **1995**, *22*, 36–38.
58. Davis, J.G.; Brick, M.A. Colorado State University Extension. Fertilizing Dry Beans. Crop Series. Fact Sheet No. 0.539. Available online: <https://extension.colostate.edu/docs/pubs/crops/00539.pdf> (accessed on 1 January 2023).
59. Alemayehu, D.; Shumi, D. Response of faba bean (*Vicia faba* L.) to phosphorus nutrient application in Bore Highlands, Guji Zone, Southern Ethiopia. *Agric. Res. Technol.* **2018**, *17*, 107–114.
60. Talwar, H.S.; Soni, M.L.; Beniwal, R.K. Evaluation of crop physiological traits in clusterbean (*Cyamopsis tetragonoloba* L. Taub) and mothbean (*Vigna aconitifolia* Jacq. Marechal). *Arid Legumes Sustain. Agric. Trade* **2019**, *2*, 274.
61. Rawat, G.S.; Rajput, R.L.; Rawat, U. Response of Varying Levels of Organic Manure and PSB on the Productivity of Clusterbean *Cyamopsis tetragonoloba* Taub. *Bhartiya Krishi Anusandhan Patrika* **2010**, *24*, 71–73.
62. Bhattacharya, A. Mungbean seed yield IV. Effect of various physiological parameters during pre and post flowering periods. *Legume Res.-Int. J.* **2006**, *29*, 169–174.
63. De Ron, A.M.; Rodiño, A.P.; Santalla, M.; González, A.M.; Lema, M.J.; Martín, I.; Kigel, J. Seedling emergence and phenotypic response of common bean germplasm to different temperatures under controlled conditions and in open field. *Front. Plant Sci.* **2016**, *7*, 1087. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Beruktawit, M.; Tamada, T.; Nigussie, D. *Response of Common Bean (Phaseolus vulgaris L.) Cultivars with Different Growth Habits to Plant Density at Haramaya*; Haramaya University: Haramaya, Ethiopia, 2012.
65. Marschner, H. *Marschner's Mineral Nutrition of Higher Plants*; Academic Press: Cambridge, MA, USA, 2011.
66. Tewari, J.K.; Singh, S.S. Effect of nitrogen and phosphorus on growth and seed yield of French bean (*Phaseolus vulgaris* L.). *Veg. Sci.* **2000**, *27*, 172–175.
67. Dejene, T.; Tana, T.; Urage, E. Response of common bean (*Phaseolus vulgaris* L.) to application of lime and phosphorus on acidic soil of Areka, Southern Ethiopia. *J. Nat. Sci. Res.* **2016**, *6*, 90–100.
68. Leal, F.T.; Filla, V.A.; Bettiol, J.V.T.; Sandrini, F.D.O.T.; Mingotte, F.L.C.; Lemos, L.B. Use efficiency and responsivity to nitrogen of common bean cultivars. *Ciência E Agrotecnologia* **2019**, *43*, e004919. [\[CrossRef\]](#)
69. Kwizera, C.; Ong'or, B.T.I.; Kaboneka, S.; Nkeshimana, F.; Ahiboneye, N. Effects of Potassium Fertilizer on Bean growth and Yield parameters. *Int. J. Adv. Sci. Res. Eng.* **2019**, *5*, 1–7. [\[CrossRef\]](#)
70. Zebire, D.A.; Gelgelo, S. Effect of phosphorus fertilizer levels on growth and yield of haricot bean (*Phaseolus vulgaris* L.) in South Omo Zone, Ethiopia. *Agric. Sci. Dig.-A Res. J.* **2019**, *39*, 55–58. [\[CrossRef\]](#)
71. Sofi, P.A.; Rehman, K.; Gull, M.; Kumari, J.; Djanaguiraman, M.; Prasad, P.V.V. Integrating root architecture and physiological approaches for improving drought tolerance in common bean (*Phaseolus vulgaris* L.). *Plant Physiol. Rep.* **2021**, *26*, 4–22. [\[CrossRef\]](#)
72. Emam, S.M.; Semida, W.M. Foliar-applied Amcoton® and potassium thiosulphate enhances the growth and productivity of three faba beans varieties by improving photosynthetic efficiency. *Arch. Agric. Environ. Sci.* **2020**, *5*, 89–96. [\[CrossRef\]](#)
73. Yin, Z.; Guo, W.; Xiao, H.; Liang, J.; Hao, X.; Dong, N.; Yin, F. Nitrogen, phosphorus, and potassium fertilization to achieve expected yield and improve yield components of mung bean. *PLoS ONE* **2018**, *13*, e0206285. [\[CrossRef\]](#)
74. Sofi, P.; Zargar, M.Y.; Debouck, D.G.; Graner, A. Evaluation of common bean (*Phaseolus vulgaris* L) germplasm under temperate conditions of Kashmir Valley. *J. Phytol.* **2011**, *3*, 47–52.
75. Singh, A.K.; Singh, S.S. Effect of planting dates, nitrogen and phosphorus levels on yield contributing factors in french bean. *Legume Res.-Int. J.* **2000**, *23*, 33–36.
76. Veeresh, N.K. Response of French bean (*Phaseolus vulgaris* L.) to fertilizer levels in Northern Transitional Zone of Karnataka. Ph.D. Thesis, University of Agricultural Sciences Bangalore, Dharwad, Indian, 2004; pp. 37–79.
77. Shubhashree, K.S.; Alagundagi, S.C.; Hiremath, S.M.; Chittapur, B.M.; Hebsur, N.S.; Patil, B.C. Effect of nitrogen, phosphorus and potassium levels on growth, yield and economics of rajmash (*Phaseolus vulgaris*). *Karnataka J. Agric. Sci.* **2011**, *24*, 283–285.
78. Taiz, L.; Zeiger, E. *Plant Physiology*; Sinauer Associates Inc. Publisher: Sunderland, MA, USA, 2006.
79. Fageria, N.K.; Baligar, V.C.; Jones, C.A. *Growth and Mineral Nutrition of Field Crops*; CRC Press: Boca Raton, FL, USA, 2010.
80. Raghothama, K.G. Phosphate acquisition. *Annu. Rev. Plant Biol.* **1999**, *50*, 665–693. [\[CrossRef\]](#) [\[PubMed\]](#)
81. Vance, C.P.; Uhde-Stone, C.; Allan, D.L. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource. *New Phytol.* **2003**, *157*, 423–447. [\[CrossRef\]](#) [\[PubMed\]](#)

82. Grant, C.A.; Flaten, D.N.; Tomasiewicz, D.J.; Sheppard, S.C. The importance of early season phosphorus nutrition. *Can. J. Plant Sci.* **2001**, *81*, 211–224. [[CrossRef](#)]
83. Pettigrew, W.T. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. *Physiol. Plant.* **2008**, *133*, 670–681. [[CrossRef](#)]
84. Fageria, N.K.; Baligar, V.C. Enhancing nitrogen use efficiency in crop plants. *Adv. Agron.* **2005**, *88*, 97–185. [[CrossRef](#)]
85. Lynch, J.P.; Brown, K.M. Root strategies for phosphorus acquisition. In *The Ecophysiology of Plant-Phosphorus Interactions*; Springer: Dordrecht, The Netherlands, 2008; pp. 83–116. [[CrossRef](#)]
86. Sinclair, T.R.; Vadez, V. Physiological traits for crop yield improvement in low N and P environments. *Plant Soil* **2002**, *245*, 1–15. [[CrossRef](#)]
87. Ullah, H.; Santiago-Arenas, R.; Ferdous, Z.; Attia, A.; Datta, A. Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. *Adv. Agron.* **2019**, *156*, 109–157. [[CrossRef](#)]
88. Karavidas, I.; Ntatsi, G.; Vougeleka, V.; Karkanis, A.; Ntanasi, T.; Saitanis, C.; Savvas, D. Agronomic practices to increase the yield and quality of common bean (*Phaseolus vulgaris* L.): A systematic review. *Agronomy* **2022**, *12*, 271. [[CrossRef](#)]
89. Islam, M.R.; Sarker, U.; Azam, M.G.; Hossain, J.; Alam, M.A.; Ullah, R.; Islam, M.S. Potassium augments growth, yield, nutrient content, and drought tolerance in mung bean (*Vigna radiata* L. Wilczek.). *Sci. Rep.* **2024**, *14*, 9378. [[CrossRef](#)] [[PubMed](#)]
90. Shankarlingappa, B.C.; Shivaraj, B.; Viswanatha, K.P. Interaction effect of phosphorus and sulphur on uptake of nitrogen, phosphorus, potassium and sulphur by cowpea. *Karnataka J. Agric. Sci.* **2000**, *13*, 295–298.
91. Kanwar, K.; Paliyal, S.S. Influence of phosphorus management and organic manuring on uptake and yield of chickpea (*Cicer arietinum*). *Ann. Agric. Res. New Ser.* **2002**, *23*, 642–645.
92. Jain, A.K.; Kumar, S.; Panwar, J.D.S. Response of mungbean (*Vigna radiata*) to phosphorus and micronutrients on N and P uptake and seed quality. *Legume Res.* **2007**, *30*, 201–204.
93. Fatima, Z.; Zia, M.; Chaudhary, M.F. Interactive effect of Rhizobium strains and P on soybean yield, nitrogen fixation and soil fertility. *Pak. J. Bot.* **2007**, *39*, 255.
94. Kumar, S.S.; Mir, S.A.; Wani, O.A.; Babu, S.; Yeasin, M.; Bhat, M.A.; Dar, S.R. Land-use systems regulate carbon geochemistry in the temperate Himalayas, India. *J. Environ. Manag.* **2022**, *320*, 115811. [[CrossRef](#)]
95. Sharma, R.; Verma, M.L. Effect of Rhizobium, farm yard manure and chemical fertilizers on sustainable production and profitability of rajmash (*Phaseolus vulgaris* L.) and soil fertility in dry temperate region of North-Western Himalayas. *Legume Res.* **2011**, *34*, 251–258.
96. Gidago, G.; Beyene, S.; Worku, W.; Sodo, E. The response of haricot bean (*Phaseolus vulgaris* L.) to phosphorus application on Ultisols at Areka, Southern Ethiopia. *J. Biol. Agric. Healthc.* **2011**, *1*, 38–49.
97. Baligar, V.C.; Fageria, N.K.; He, Z.L. Nutrient use efficiency in plants. *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 921–950. [[CrossRef](#)]
98. Akter, Z.; Lupwayi, N.Z.; Balasubramanian, P.M. Nitrogen use efficiency of irrigated dry bean (*Phaseolus vulgaris* L.) genotypes in southern Alberta. *Can. J. Plant Sci.* **2017**, *97*, 610–619. [[CrossRef](#)]
99. Ortiz-Monasterio, I.; Manske, G.G.B.; Ginkel, M.V. Nitrogen and phosphorus use efficiency. In *Application of Physiology in Wheat Breeding* (No. CIS-3162. CIMMYT.); International Maize and Wheat Improvement Center (CIMMYT): Mexico City, Mexico, 2001.

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