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Research Article

Effect of Mineral Nitrogen, Phosphorus, and Potassium Fertilizers on the Productivity of Faba Bean (*Vicia faba* L.) in Acidic Soils of Wolaita Zone, Southern Ethiopia

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Poor soil fertility is among the major factors that limit faba bean production in Wolaita Zone in southern Ethiopia. Therefore, a field experiment was conducted in the Kokate Marachare subdistrict of Sodo Zuria District of the zone during the 2019 and 2020 cropping seasons to determine the response of faba bean to different rates of nitrogen (N), phosphorus (P), and potassium (K) fertilizers under lime-treated soil conditions by using Tumsa faba bean variety. The treatments consisted of three rates of nitrogen fertilizer (0, 23, and 46 kg N ha^{-1}), three rates of phosphorus fertilizer (0, 46, and 92 kg P_2O_5 ha^{-1}), and three rates of potassium fertilizer (0, 30, and 60 kg K_2O ha^{-1}) that were laid out as RCBD and replicated three times per treatment. The results indicated that the N, P, and K fertilizer combination at 23:92:60 kg ha^{-1} increased plant height, the number of branches per plant, and stem girth by 18%, 62.6%, and 55.6%, respectively, compared with the control treatment. A significantly high aboveground dry biomass (11.8 t ha^{-1}), number of pods per plant (17 pods), number of seeds per pod (4 pods), stover yield (6.83 t ha^{-1}), and hundred seed weight (88 g) were obtained from the N, P, and K fertilizer combination at 23:92:60 kg ha^{-1}. The highest grain yield (4.97 t ha^{-1}) was obtained from the N, P, and K combination at 23:92:60 kg ha^{-1}, which was 360% higher than the yield obtained from the control treatment. Moreover, the highest mean net benefit (USD 4,109.33 ha^{-1}) with an acceptable marginal rate of return of 1,340% was obtained from the N, P, and K fertilizer combination at 23 kg N, 92 kg P_2O_5, and 60 kg K_2O ha^{-1}, respectively. Thus, these rates are suggested for faba bean production in the acidic soils of the Wolaita Zone.

1. Introduction

Faba bean (*Vicia faba* L.) is one of the major pulse crops grown in the highlands of Ethiopia [1]. Currently, it occupies 31% of the area cultivated for pulses (1,863,445 ha) in the country [2]. The crop plays a significant role in human and livestock feed and in improving soil fertility [3]. However, the productivity of the crop in the country is low (2.12 t ha^{-1}) compared with the average yield (3.7 t ha^{-1}) obtained in major faba-bean-producing countries of the world [2, 4]. Particularly, in Wolaita Zone, faba bean occupies 3.6% of the area of land cultivated for total grain production [5]. However, farmers in the study area harvest a lower average yield (1.2 t ha^{-1}) than the national average yield obtained [5].

Poor soil fertility and soil acidity are serious problems constraining faba bean productivity in Ethiopia [6]. In most cases, soils with a soil pH value of less than 5.5 are deficient in macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) [7]. In addition, the toxicity of aluminum (Al), iron (Fe), and manganese (Mn) is among the reasons for lower faba bean yield in acidic soils [8]. These reasons could affect the availability of applied fertilizer and crop nutrient uptake. Shanka et al. [9] and Mesfin et al. [10] indicated that soil acidity and related soil fertility problems are major crop yield limiting factors in the Wolaita Zone. Fanuel et al. [11] also reported that the deficiency of total N, available P, and K constrains crop production in Wolaita Zone. The deficiency of these nutrients requires immediate attention for sustaining production and improving the productivity of the smallholder faba bean farmers in the study area.

Nitrogen is the major essential nutrient applied to the crop for higher vegetative growth, productivity, and quality [12]. In addition, the application of starter N fertilization at the rate of 20 kg N ha^{-1} enhances the nodulation process in faba bean plants [13]. However, reports in Ethiopia have shown that about 50% of the applied N fertilizer remains unavailable to the crop. This is due to temporary immobilization in soil organic matter or due to losses by leaching, erosion, nitrification, or volatilization [14]. In this regard, the studied districts have been exposed to erosion, soil acidity, and a high loss of N due to leaching [10]. Confirming this problem, [8] reported that N deficiency is a major factor constraining crop production in Wolaita Zone. Shanka et al. [9] also reported that P deficiency in the soils is a constraint to common bean production in Wolaita Zone. Laekemariam et al. [8] indicated that potassium deficiency is also a constraint to crop production in Wolaita Zone. Thus, the survival, nutrient use efficiency, growth, and grain yield of faba bean are highly affected in Lolita Zone due to a lack of balanced nutrient application [15]. In general, continuous cultivation, together with inappropriate soil management, such as limited soil conservation, inadequate use of bio-fertilizers, and lack of balanced inorganic fertilizer application, has aggravated soil fertility problems in Wolaita Zone [10].

About 8.3% more yield response of faba bean was obtained from the combined application of N, P, and K at 36 kg N, 54 kg P_2O_5, and 114 K_2O kg ha^{-1} compared with P alone applied at 54 kg P_2O_5 ha^{-1} [16]. Abebe et al., 2014 [17] indicated significant contributions of N, P, and K fertilizer application to improved growth and grain yield productivity of faba bean. In many parts of Ethiopia, a significant improvement in the grain yield of faba bean was obtained in response to applying inorganic fertilizers [18]. For instance, Bezabih et al. [19] showed that the combined application of 30 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} in rhizobium-inoculated faba bean contributed to 30% more grain yield than the control treatment in Alicho Wuriro Highlands in southern Ethiopia. In agreement with this, Abebe et al. [20] reported that the combined application of 46 kg P_2O_5 ha^{-1} and 24 kg K_2O ha^{-1} contributed a 38% more grain yield improvement in faba bean than the control treatment in Sekela District in northern Ethiopia. Similarly, a 31% mean improvement in the grain yield of faba bean was reported due to the application of phosphorus fertilizer at 15, 30, 45, and 60 kg ha^{-1} compared with the control treatment in Boloso Sore District in Wolaita Zone in southern Ethiopia [15].

To improve the grain yield of faba bean, a balanced application of all major nutrients (N, P, and K) is vital [21]. However, the optimum requirements of combined N, P, and K fertilizers for faba bean production are not well known in Wolaita Zone in general and the study area in particular. Therefore, this research was conducted to determine the effect of the application of N, P, and K fertilizers on the productivity of faba bean in the Sodo Zuria District in Wolaita Zone. It was hypothesized that the application of balanced N, P, and K fertilizers improves the growth and yield of faba bean.

2. Materials and Methods

2.1. Description of the Experimental Site. The study was conducted for two consecutive years during the 2019 and 2020 main cropping seasons (June to November) on farmers' fields in the Kokate Marachere subdistrict of Sodo Zuria District in Wolaita Zone, southern Ethiopia (Figure 1).

The study site was selected purposively based on its high faba bean production potential. The experimental site is located at 7°25′21″ N latitude and 37°46′52″ E longitude and an altitude of 2,156 m above sea level [9]. In the 2019 and 2020 cropping seasons, the mean monthly temperature of Sodo Zuria District ranged from 15°C to 23.8°C and from 14.5°C to 25.8°C, respectively (Table 1; Figure 2). In addition, in the 2019 and 2020 cropping seasons, the total monthly precipitation of the study district was 1,187 mm and 1,376 mm, respectively [22]. The dominant soil type of the study area is silty clay, which is deep and clay in texture [9].

2.2. Experimental Materials

2.2.1. Planting Material. A faba bean variety "Tumsa," which was released in 2010 by the Holetta Agricultural Research Center in Ethiopia, was used. It needs 700–1,000 mm of rainfall for high yield and grows at an altitude of 900–2,800 m above sea level. The variety needs 120–130 days to reach maturity [23].

2.2.2. Fertilizer and Liming Materials. Urea ($CO(NH_2)_2$; 46% N), triple superphosphate (TSP; $Ca(H_2PO_4)_2$; 20% P), and KCl (62% K_2O) were used as a source of N, P, and K, respectively. The liming material used for this experiment was $CaCO_3$. The purity of lime ($CaCO_3$) used for the field experiment was 89%.

2.3. Treatments and Experimental Design. The treatments consisted of three rates of N (0, 23, and 46 kg N ha^{-1}), P (0, 46, and 92 kg P_2O_5 ha^{-1}), and K (0, 30, and 60 kg K_2O ha^{-1}). The middle rates of N and P were fixed based on the Ethiopian Institute of Agricultural Research's recommendation for faba bean production [22]. Although there is no recommended K rate for faba bean by the Ethiopian Institute of Agricultural Research, the rate of K was fixed based on research work in Ethiopia [13]. The experiment was laid out as a randomized complete block design in factorial arrangement and replicated three times per treatment. The randomization in the 2019 cropping was used in 2020 without any change in location in order to avoid biases. The plot size was 2.8 m × 2.1 m (5.8 m^2) with 0.5 m spacing between plots and 1 m between blocks. The inter- and intra-row spacings were 40 and 10 cm, respectively, and each row and plot consisted of 21 and 168 plants, respectively [23].

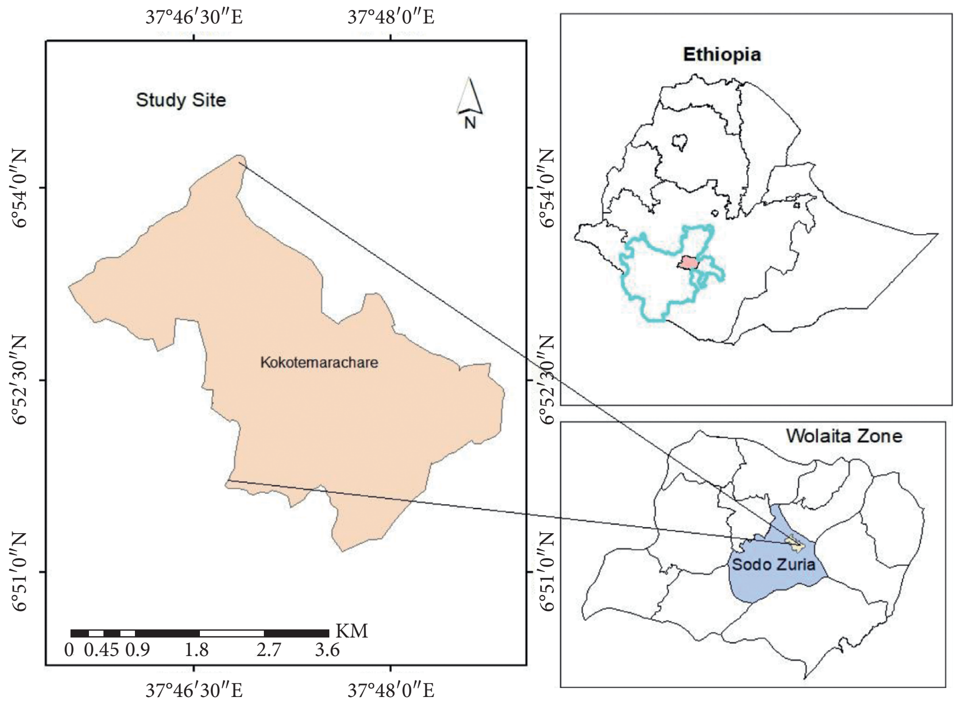

Figure 1: Map of the experimental subdistrict in Wolaita Zone, southern Ethiopia.

Table 1: Ten-year (2011–2020) monthly rainfall (mm) and monthly maximum and minimum temperature (°C) during the rainy seasons at Sodo Zuria District of Wolaita Zone, southern Ethiopia.

Month	Rainfall (mm)			Max.Temp (°C)			Min.Temp (°C)		
	2019	2020	2011–2020	2019	2020	2011–2020	2019	2020	2011–2020
January	0.0	103.8	24.31	28.7	27.1	28.09	15.5	14.2	14.59
February	20.7	82.6	31.07	29.6	27.3	28.90	17.5	16.3	16.24
March	38.8	123.4	80.24	30.3	26.90	28.8	17.2	15.7	16.7
April	212.2	154.8	178.4	27.5	25.72	26.8	16.4	15.4	15.8
May	115.2	274.6	185.3	26.3	25.20	25	16.3	16.1	15.8
June	300.6	320	177.6	22.7	23.69	23.4	15.4	15.3	15.2
July	159.78	229.3	190.7	22.4	21.05	22.3	15.0	14.4	14.6
August	269.7	304.4	202.6	22.4	22.10	22.7	14.8	14.6	14.7
September	154.8	160	127.6	23.4	21.10	23.8	15.3	14.4	14.8
October	161.7	194.0	112.05	25.6	33.2	26.38	14.6	13.9	14.99
November	140.0	168.0	97.39	26.0	33.8	26.64	15.1	14.4	15.33
December	25.6	30.7	18.984	26.3	34.2	27.18	14.5	13.8	16.10
Total	1,599.08	2,145.6	1,426.24	311.2	321.36	309.99	187.6	178.5	15.40
Mean	133.26	178.8	118.85	25.93	26.78	25.83	15.6	14.9	15.40

Note: Max.Temp (°C), maximum temperature in °C; Min.Temp (°C), minimum temperature in °C.

2.4. Soil Sampling and Analysis. Before planting, surface soil samples (0–30 cm depth) were collected in a zigzag pattern from 16 spots from the experimental field by using augur. Then the soil samples were mixed to form a 1 kg composite sample. Afterward, the soil samples were air-dried, ground, and sieved through a 2 mm sieve to determine their pH and available phosphorus. The soil samples were analyzed at the Hawassa Soil Laboratory for soil pH, CEC, soil organic carbon (OC), total N, available P, exchangeable cations, and soil texture. Soil pH (1:2.5 soil-to-water ratio) was measured using a glass electrode pH meter, as described by [24]. The CEC of the soil was determined from NH_4OAc-saturated samples, which was measured through distillation using the micro-Kjeldahl procedure. The soil OC was determined by the chromate acid oxidation method [25]. Total nitrogen was analyzed using the macro-Kjeldahl digestion method, followed by the ammonium distillation and titration method [26]. Soil available P was analyzed using the Olsen method [27]. Exchangeable K was extracted by the ammonium acetate (1 M NH_4OAc at pH 7) extraction method, as described by Rowell [28], and determined by flame photometry. The particle size distribution was determined following the Bouyoucos hydrometer method [29], and the textural class was determined based on the soil textural triangle using the International Soil Science Society (ISSS) system [28].

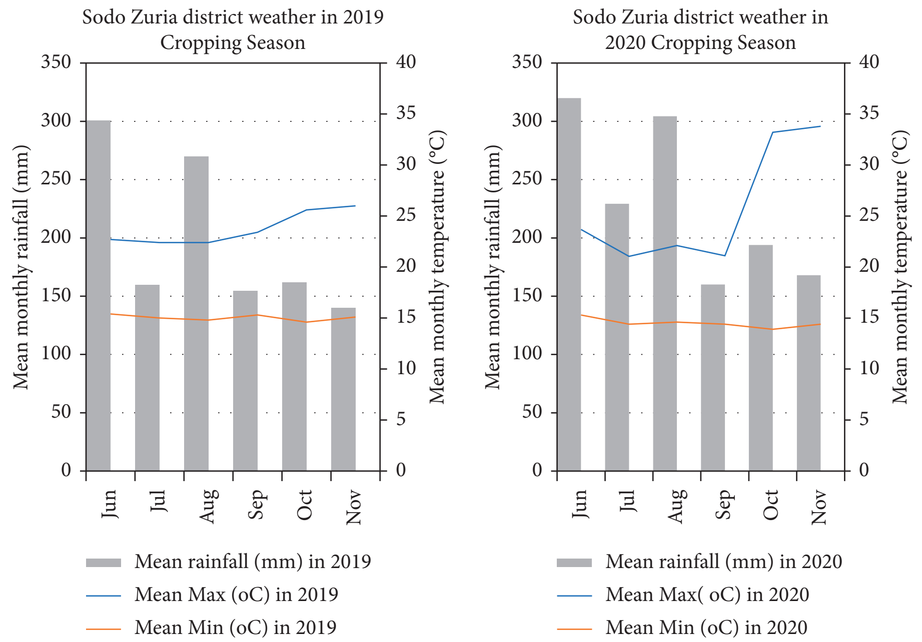

Figure 2: Monthly total rainfall and average maximum and minimum air temperatures in 2019 and 2020 growing seasons in Sodo Zuria District (National Meteorological Agency, 2020).

2.5. Experimental Procedures

2.5.1. Land Preparation and Crop Management. The experimental field was ploughed three times with local oxen-drawn *maresha*, followed by manual seed-bed preparation, and laid out according to the experimental scheme. Two seeds per hill were sown by hand at a seeding rate of 200 kg ha^{-1} with an intra- and inter-row spacing of 10 cm and 40 cm, respectively [23], on 8 June 2019 and 9 June 2020. Later, the seedlings were thinned to have one plant per hill. Weeds were removed by hand, weeding two times at 25 and 50 days after crop emergence. Harvesting was performed manually using hand sickles. The crop was harvested on 4 November 2019 and 17 November 2020 in the two cropping seasons.

2.5.2. Fertilizer Application. Phosphorus fertilizer was applied in the form of TSP (46% P_2O_5) at the time of planting at the specified rate. Nitrogen and K were applied at the specified rate in the form of urea (46% N) and KCl (62% K_2O), respectively, by splitting into 1/3 at planting and the remaining 2/3 at the active vegetative stage before flowering [30]. The liming rate was fixed based on greenhouse findings as 2 t ha^{-1} and applied in broadcast 2 months before planting [9]. The Tumsa faba bean variety best performing in a pot experiment was used for the study.

2.6. Crop Data Collection

2.6.1. Growth Data. All growth data were recorded from five randomly selected plants from the central rows at the flowering stage. Plant height was measured from the base to the tip of the plant by using a measuring tape. The stem girth was recorded by using a digital caliper that was attached to the center of a stem. Lodging was assessed based on a scale of 1–5, where 1 (0–15°) indicates no lodging, 2 (15–30°) indicates 25% lodging, 3 (30–45°) indicates 50% lodging, 4 (45–60°) indicates 75% lodging, and 5 (60–100°) indicates 100% lodging [31]. The scale was determined by the angle of inclination of the main stem from the vertical line to the base of the stem by visual observation [32]. The score was then calculated as described by [33]. The number of branches was determined by counting all branches originating from the main stem, and secondary growth branches were excluded.

2.6.2. Yield and Yield Component Data. The total above-ground sundry biomass was determined by weighing the shoots along with the seeds using a sensitive balance. The number of pods per plant and the number of seeds per pod were determined from five randomly selected plants in the net plot area at harvest. The grain yield (kg ha^{-1}) was determined after threshing the sun-dried plants harvested from each net plot area, and the yield was adjusted at 10% moisture content [34] by using Dicky Johns' hand moisture tester (M20P, V-Tech, Tokyo, Japan). The moisture correction factor was obtained by the following formula:

$$\text{moisture correction factor} = \frac{100 - y}{100 - x}, \quad (1)$$

where Y is the actual moisture content measured and is the standard moisture content for pulse crops, that is, 10%. Therefore, according to Birru [34], the 10% adjusted grain yield was calculated as follows:

$$\text{adjusted grain yield} = \text{moisture correction factor grain yield}, \quad (2)$$

obtained from each plot. The hundred seed weight was determined by counting the number of seeds randomly taken from each plot, and the weight was adjusted to 10% moisture content. The harvest index (HI) was calculated as the ratio of grain yield to the aboveground dry biomass yield. The stover yield was calculated as the difference between the total aboveground biomass and grain yield.

2.7. Data Analysis. The homogeneity of variances was evaluated using the F-test, as described by Gomez and Gomez [35]. Since the F-test showed homogeneity of the variances of the 2 years for most of the agronomic parameters, a combined analysis of variance (ANOVA) was performed using SAS version 9.4 [36] following the procedure described by Gomez and Gomez [35]. The treatment means were separated using the least significant difference test at a 5% level of significance.

2.8. Partial Budget Analysis. A partial budget analysis was performed, as described by [37]. Since both grain and straw are important for farmers, the partial budget analysis considered the mean grain and straw yields of each treatment in 2019 and 2020. Economic analysis was performed using the prevailing average market prices for inputs at planting and outputs at the time the crop was harvested. All costs and benefits were calculated on a hectare basis in Ethiopian Birr. Total costs that varied (TCV) included the sum of the costs incurred on the purchase of NPK fertilizer, fertilizer transport cost, and the cost of application of the fertilizers. The transport costs of NPK fertilizer were estimated from market and farm gate prices. The costs of N, P, and K fertilizers were fixed based on the market price of the agricultural input supply enterprise of Ethiopia. Actual grain and straw yields were adjusted downward by 10% to reflect the difference between the experimental yield and the yield the farmers would expect to get from the same treatment [37]. Thus, the gross field benefit, total variable costs, net benefit, and marginal rate of return were calculated.

3. Results and Discussion

3.1. Physical and Chemical Properties of the Experimental Soil. The results of the soil's physical and chemical analysis are shown in Table 2. The texture of the soil at the experimental site is silty clay. This shows that the soil has limitations in soil pH and nutrient availability for crop production. According to the soil pH rating by Murphy [38], the soil at the experimental site is strong to moderately acidic. The value is far below the range suitable for most crops and optimum for the availability of nutrients, that is, 6.5–7.5 [42]. Moreover, faba bean grows best in soils with pH values ranging from 6.5 to 9.0 [43]. Thus, the strong soil acidity could be one of the major factors responsible for reducing the grain yield of the crop, which is lower than the national average yield by about 100%. Hence, the application of lime, which increases soil pH, is necessary for improving faba bean yield in the experimental area. This is because lime application increases soil pH, in which Ca reacts with H^+ at the exchange site and neutralizes it, thereby increasing the pH of the soil [44]. The CEC value of the soil is moderate according to the rating by Hazelton and Murphy [39], which indicates its retention of adequate cations. The soil has moderate organic carbon and total N contents according to the rating by Berhanu [40]. Thus, this indicates the ability of the soil to supply organic carbon and mineralizable nitrogen for the proliferation of soil biota, which is important for soil biochemical processes that increase the mobility of nutrients, such as P and others, for plant uptake [45]. The available P content of the soil is low according to the rating by Cottenie [41]. Thus, the application of P fertilizer is required for improving faba bean yield in the study area [42]. The exchangeable K in the soil is low according to the rating by Berhanu [40], which indicates the level is not sufficient for plant growth. Since critical values for K that begin to limit plant growth are around 0.2–0.5 cmol (+) kg ha^{-1} according to Gourley [46], the content of exchangeable K is low, and the soil requires external application of the nutrient. Thus, the external application of N, P, and K fertilizers is in order.

3.2. Growth Parameters

3.2.1. Plant Height. The height of faba bean plants varied significantly ($p \leq 0.05$) in response to the main effects of the growing year and the rates of mineral N, P, and K fertilizers and their interactions. However, the interaction effect of the growing year with nitrogen, phosphorus, and potassium fertilizer rates was nonsignificant (Table 3).

The interaction of applied nitrogen, phosphorus, and potassium fertilizers significantly ($p \leq 0.05$) influenced faba bean plant height. Thus, the N, P, and K combination at 46:92:30 kg ha^{-1} produced 23.3% more height compared with the control treatment (Table 4). The highest plant height obtained by the previously mentioned treatment was statistically similar for all N, P, and K combinations, except for a single application of these nutrients (Table 4). The result signified the vital role of combinations of the three nutrients to improve the plant height of faba bean. The possible reason for the largest plant height at the N, P, and K combination of 46:92:30 kg ha^{-1} could be associated with the synergic effect of N, P, and K nutrients, which enhances plant height. Particularly, the applied P and K fertilizers might facilitate more N fixation, which provides better vegetative growth and plant height of faba bean [47]. Because of the cumulative role of the nutrients in cell division, cell expansion, and enlargement, this might have ultimately contributed to the increase in the plant height of faba bean. Consistent with this result, Abou-Amer et al. [48] reported that the application of mineral N, P, and K fertilizers at 60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 80 kg K_2O ha^{-1} leads to the growth of significantly taller faba plants than plants grown with the control treatment. Similarly, Bezabih et al. [19] reported that the combined effect of rhizobium inoculation and 60 kg ha^{-1} K fertilization results in taller plants (55.16 cm) compared to the controls (39.83 cm).

The height of faba bean also significantly ($p \leq 0.001$) varied in response to the growing year (Table 3). Thus, a greater plant height was obtained during 2019 (123.69 cm) compared with 2020 (118.34 cm; Table 4). The increased

Table 2: Soil physical and chemical properties at the study site in Sodo Zuria District, southern Ethiopia.

Parameter	Year 2019	Year 2020	Rating	Reference
Sand (%)	15	19	—	—
Silt (%)	40	43	—	—
Clay (%)	45	38	—	—
Textural class	Silty clay	Silty clay		
pH (1:2.5 H_2O)	4.9	5.6	Strong to moderately acidic	Murphy [38]
CEC (cmol + kg^{-1})	23.1	24.6	Moderate	Hazelton and Murphy [39]
OC (%)	2.7	2.9	Medium	Hazelton and Murphy [39]
Total N (%)	0.12	0.16	Moderate	Berhanu [40]
Available P (mg kg^{-1})	5.94	6.12	Low	Cottenie [41]
Exchangeable K (Cmol kg^{-1})	0.4	0.4	Medium	Berhanu [40]

Note: CEC, cation exchange capacity; OC, organic carbon; total N, total nitrogen; and available P, available phosphorus.

Table 3: Mean square values of the interaction effect of mineral N, P, and K and the effect of year on growth parameters of faba bean in Sodo Zuria District, southern Ethiopia, in 2019 and 2020 cropping seasons.

Source of variations	Degrees of freedom	Mean squares: Plant height (cm)	Mean squares: **Stem girth** (mm)	Mean squares: Logging (%)	Mean squares: NBPP
Y	1	$1{,}158.56^{***}$	1.08^{ns}	$3{,}468.89^{**}$	19.76^{*}
Y (R)	4	8.05^{ns}	0.58^{ns}	48.71^{ns}	0.61^{ns}
N rate	2	400.02^{***}	21.89^{***}	289.75^{***}	15.99^{***}
P rate	2	413.32^{***}	28.94^{***}	485.79^{***}	8.10^{***}
K rate	2	897.14^{***}	76.82^{***}	$9{,}621.04^{***}$	28.85^{***}
N rate × P rate	4	40.04^{ns}	12.11^{***}	481.91^{***}	1.67^{*}
N rate × K rate	4	38.10^{ns}	12.92^{***}	153.98^{***}	3.65^{***}
P rate × K rate	4	421.45^{***}	7.30^{***}	131.01^{**}	1.43^{*}
N rate × P rate × K rate	8	100.92^{*}	7.97^{***}	170.61^{***}	5.37^{***}
N rate × Y	2	12.85^{ns}	1.39^{ns}	59.72^{ns}	0.29^{ns}
P rate × Y	2	56.46^{ns}	1.18^{ns}	22.27^{ns}	1.62^{ns}
K rate × Y	2	60.22^{ns}	1.17^{ns}	89.98^{*}	0.59^{ns}
N rate × P rate × Y	4	10.23^{ns}	0.07^{ns}	38.27^{ns}	0.28^{ns}
N rate × K rate × Y	4	8.92^{ns}	0.045^{ns}	17.20^{ns}	0.14^{ns}
P rate × K rate × Y	4	44.99^{ns}	0.29^{ns}	15.97^{ns}	0.62^{ns}
N rate × P rate × K rate × Y	8	11.92^{ns}	0.42^{ns}	23.39^{ns}	0.59^{ns}
Error	104	38.30	0.67	21.80	0.41
CV (%)		5.11	13.91	17.58	16.35

Note: ns = not significant; *,**, and *** significant at $p \leq 0.05$, 0.01, and 0.001, respectively; Y = year, R = replication; PH, plant height; ST, stem thickness; and NBPP, number of branches per plant.

plant height in the 2019 cropping year could be attributed due to the relatively suitable precipitation (1,187 mm) availability as compared to 1,378 mm in 2020 (Table 1). Consequently, more nutrient uptake from the soil may have led to the more vigorous growth of the plants.

3.2.2. Stem Girth. The stem girth was significantly ($p \leq 0.001$) affected by the rates of mineral N, P, and K fertilizers and their interaction. However, the stem girth did not significantly respond to the effect of the growing year and its interaction with mineral N, P, and K fertilizer rates (Table 3).

Increasing the rate of nitrogen fertilizer with the increasing rates of both phosphorus and potassium significantly increased the stem girth (Table 4). In contrast, the lowest stem girth was recorded with either nil or N, P, or K fertilizer treatment alone (Table 4). Thus, the N, P, and K combination at 46:92:30 kg ha^{-1} produced the highest stem girth (9.58 mm), and it was statistically at par with the stem girth obtained in response to the N, P, and K combinations of 46:92:60 kg ha^{-1} (Table 4). Thus, the interaction of N, P, and K at 46:92:30 kg ha^{-1} resulted in about 56.2% higher stem girth compared with the application of no fertilizer (Table 4). The result might be associated with the combined role of the three fertilizers in improving soil fertility and overall crop growth. The results are consistent with Ali et al., who reported that the combined application of N, P, and K of 36:54:114 kg ha^{-1} results in a 23% improvement in stem girth of faba bean than the controls. Bezabih et al. [19] also reported that the P and K fertilizer combination of 30: 60 kg ha^{-1} in rhizobium-inoculated faba bean produces a considerably wider stem girth (7.4 mm) than the controls (3.8 mm). The results imply that the synergistic effect of N, P, and K fertilizers improves the soil fertility status and enhances the stem girth [49].

Table 4: Interaction effect of mineral N, P, and K fertilizers and the effect of the growing year on growth parameters of faba bean.

Nitrogen (kg N ha^{-1})	Phosphorus (kg P_2O_5 ha^{-1})	Plant height (cm) Potassium (kg K_2O ha^{-1})			Stem girth (mm) Potassium (kg K_2O ha^{-1})			Lodging (%) Potassium (kg K_2O ha^{-1})			NBPP Potassium (kg K_2O ha^{-1})		
		0	30	60	0	30	60	0	30	60	0	30	60
	0	104.88 e	116.94 b–e	126.00 abc	4.20 f	4.65 ef	4.46 ef	32.25 a	0.00 c	0.00 c	2.01 d	3.41 cd	2.94 cd
0	46	117.58 b–e	120.66 abc	120.66 abc	4.36 f	7.44 bcd	7.44 bcd	31.92 a	16.14 b	15.54 b	2.94 cd	2.73 d	5.27 ab
	92	116.94 b–e	121.63 abc	121.14 abc	4.58 ef	8.24 ab	4.40 f	18.47 b	8.10 bc	7.98 bc	3.41 cd	5.27 ab	2.94 cd
	0	105.63 de	120.58 abc	126.00 abc	4.63 ef	4.92 ef	5.94 def	39.09 a	15.54 b	15.14 b	3.04 cd	3.41 cd	4.34 bc
23	46	126.00 abc	119.60 a–d	118.23 a–e	4.65 ef	5.08 ef	5.38 ef	32.25 a	16.64 b	16.64 b	3.41 cd	3.41 cd	3.41 cd
	92	117.58 b–e	126.00 abc	119.51 a–d	4.85 ef	6.27 cde	7.93 abc	30.59 a	3.10 c	3.10 c	3.41 cd	3.41 cd	5.27 ab
	0	113.86 cde	126.00 abc	121.14 abc	4.11 f	6.27 cde	8.15 ab	39.09 a	15.14 b	7.98 bc	3.04 cd	4.34 bc	5.27 ab
46	46	126.00 abc	121.14 abc	127.95 abc	4.26 f	7.39 bcd	5.38 ef	36.25 a	3.10 c	3.10 c	2.94 cd	5.89 a	4.91 ab
	92	119.28 a–d	129.35 a	127.95 abc	4.92 ef	9.58 a	9.47 a	30.59 a	16.44 b	3.10 c	3.41 cd	5.37 ab	5.37 ab
LSD (5%)		7.03			0.93			7.44			0.73		
Year													
2019		123.69 a			5.96			12.30 b			4.25 a		
2020		118.34 b			5.80			21.56 a			3.55 b		
LSD (5%)		1.93			0.25			1.46			0.19		
CV (%)		5.11			13.91			17.58			16.35		

Note: means in columns and rows followed by the same letter are not significantly different at $p = 0.05$ according to Fisher's protected LSD test. NBPP, number of branches per plant.

3.2.3. Lodging Percentage. The lodging percentage of faba bean varied significantly ($p \leq 0.001$) in response to the effect of the growing year and rates of mineral N, P, and K fertilizers and their interactions, whereas the interaction effect of the growing year with N, P, and K fertilizer rates was nonsignificant (Table 3).

The minimum (0%) and maximum (39.1%) faba bean lodging percentages were recorded for potassium applied at 30 and 60 kg ha^{-1} and nitrogen applied at 23 kg ha^{-1}, respectively (Table 4). Application of N and P without K resulted in the highest lodging percentage, whereas the increasing rate of K with N and P significantly reduced faba bean lodging. This might be due to the role of the applied K fertilizer in increasing the root growth, which improves water and nutrient uptake [50]. Thus, more uptakes of applied nutrients from the soil resulted in vigorous faba bean plants, which might have reduced the lodging percentage. In addition, potassium has an essential function in reducing the disease incidence of stem rot [51], which minimizes the lodging of the crop.

The lodging percentage of faba bean also significantly ($p \leq 0.01$) varied in response to growing seasons. Higher lodging (21.6%) was observed during 2020 compared with 2019 (12.3%; Table 4). The higher lodging in the 2020 cropping season might be linked to relatively higher precipitation (1,378 mm) than in the 2019 cropping season (1,187 mm; Table 1), which might have exposed the soil to more erosion, which might have exposed the soil to more erosion, which further affected the soil density, aggravating lodging. In addition, a higher lodging percentage in the 2020 cropping season might be associated with rainstorm damage at the vegetative stage, given the high flooding in planting in most farmers at experimental subdistricts.

3.2.4. Number of Branches per Plant. The number of branches per plant responded significantly to the main effects of year of planting, mineral N, P, and K fertilizers, and interaction of N, P, and K fertilizers, while year interaction with N, P, and K fertilizers were not significant (Table 3).

The number of branches per plant significantly ($p \leq 0.001$) responded to the combined application of N, P, and K fertilizers. In this regard, the increasing rate of N application consistently increased the number of branches per plant with the increasing rates of both P and K applications (Table 4). The result means that the highest number of branches per plant was obtained at either medium or high rates of nitrogen (23 or 46 kg N ha^{-1}) and potassium (30 or 60 kg K_2O ha^{-1}) fertilizers combined with medium phosphorus (46 kg P_2O_5 ha^{-1}) fertilizer (Table 4). However, increasing the rate of P further than 23 kg N ha^{-1} was no longer required for enhancing the number of branches per plant. Thus, the highest number of branches per plant (six) was recorded in response to the N, P, and K combination of 46:46:30 kg ha^{-1} (Table 4). This treatment gave a statistically similar number of branches per plant with N, P, and K combinations of 46:46:60 kg ha^{-1}, 46:92:30 kg ha^{-1}, 46:92:60 kg ha^{-1}, 23:92:60 kg ha^{-1}, and 23:46:60 kg ha^{-1} (Table 4).

In contrast, the lowest number of branches per plant (two) was recorded from the nonfertilized treatment, which was statistically similar to plants that received nil K with N and P combinations (Table 4). The results of this study indicated that application of N, P, or K fertilizer alone or planting with nil fertilizer application would not lead to the maximum number of branches per plant. However, the interaction of N, P, and K fertilizers led to a significantly higher number of branches per plant. Phosphorus stimulates root development that is necessary for the plant to get nutrients from the soil, which facilitates legumes in fixing nitrogen in the soil through their roots [52]. Potassium is associated with the movement of water, nutrients, and carbohydrates in plant tissue, which affects ATP production, which in turn regulates the rate of photosynthesis [53]. Overall, plants that receive sufficient nitrogen have high rates of photosynthesis and typically exhibit vigorous growth that is attributed to the number of branches [54]. This implies that balanced nutrition facilitates the healthy growth and good photosynthesis and, consequently, an increased number of branches per plant [48]. In line with this result, Walled et al. [55] indicated that the combined application of N, P, and K fertilizers leads to the highest number of branches per plant of faba bean (4.61) than the controls (4.22).

The results of this study also revealed that the 2019 growing season produced more branches per plant (4.25) than the 2020 growing season (3.55; Table 4). The fewer number of branches per plant in the 2020 cropping season might be attributed to higher rainfall (1,378 mm; Table 1), which increased the losses of applied nutrients through runoff and leaching [47]. Consequently, the growth and the number of branches might have been negatively affected.

3.3. Yield and Yield Components

3.3.1. Number of Pods per Plant. The main and interaction effects of N, P, and K rates significantly ($p \leq 0.01$) influenced the number of pods per plant. However, the main effect of the year, three fertilizers rate interaction with year, did not significantly influence the numbers of pods per plant (Table 5).

Increasing the rate of N application significantly and consistently increased the number of pods per plant with increasing rates of both P and K applications (Table 6). Consequently, the highest number of pods per plant (17) was produced in response to the N, P, and K combination of 46:92:60 kg ha^{-1}, which was statistically at par with the number of pods per plant obtained with the N, P, and K combination of 46:92:30 kg ha^{-1} (Table 6). However, the lowest average number of pods per plant (4) was produced by plants that grew with nil fertilizer (Table 6). For example, the number of pods per plant obtained in response to the N, P, and K combination of 46:92:60 kg ha^{-1} exceeded the numbers of pods per plant produced in response to nil application of the

Table 5: Mean square values of the combined analysis of variance for the effects of year, mineral N, P, and K fertilizers application and their interactions on yield components and yield parameters of faba bean in Sodo Zuria District, southern Ethiopia.

Source of variations	Mean squares for yield components and yield variables							
	Degrees of freedom	AGB (t ha^{-1})	NPP	NSPP	GY (t ha^{-1})	SY (t ha^{-1})	HSW (g)	HI
Y	1	10.71^{***}	0.31^{ns}	2.67^{**}	0.28^{*}	7.55^{**}	$1,517.52^{**}$	0.03^{ns}
Y (R)	4	0.03^{ns}	2.44^{ns}	0.06^{ns}	0.02^{ns}	0.10^{ns}	14.57^{ns}	0.01^{ns}
N rate	2	156.51^{***}	91.06^{***}	1.67^{***}	25.33^{***}	56.20^{***}	808.83^{***}	0.01^{*}
P rate	2	135.39^{***}	166.00^{***}	2.93^{***}	24.41^{***}	44.85^{***}	414.04^{***}	0.01^{ns}
K rate	2	128.69^{***}	443.89^{***}	4.03^{***}	20.98^{***}	45.79^{***}	568.57^{***}	0.01^{*}
N rate × P rate	4	8.35^{***}	38.13^{***}	0.33^{ns}	1.23^{***}	3.33^{***}	31.74^{*}	0.01^{ns}
N rate × K rate	4	1.21^{***}	32.39^{***}	1.17^{***}	0.08^{ns}	0.82^{**}	45.83^{**}	0.01^{ns}
P rate × K rate	4	0.30^{ns}	11.57^{***}	0.45^{*}	0.04^{ns}	0.14^{ns}	5.00^{ns}	0.03^{ns}
N rate × P rate × K rate	8	1.40^{***}	24.54^{***}	0.39^{**}	0.32^{***}	0.58^{**}	24.97^{*}	0.02^{ns}
N rate × Y	2	0.02^{ns}	10.89^{ns}	0.57^{*}	0.06^{ns}	0.01^{ns}	3.11^{ns}	0.01^{ns}
P rate × Y	2	0.02^{ns}	1.44^{ns}	0.02^{ns}	0.02^{ns}	0.01^{ns}	16.09^{ns}	0.01^{ns}
K rate × Y	2	0.01^{ns}	2.04^{ns}	0.06^{ns}	0.05^{ns}	0.02^{ns}	24.38^{ns}	0.02^{ns}
N rate × P rate × Y	4	0.05^{ns}	3.18^{*}	0.64^{**}	0.01^{ns}	0.09^{ns}	11.22^{ns}	0.01^{ns}
N rate × K rate × Y	4	0.04^{ns}	2.26^{ns}	0.12^{ns}	0.01^{ns}	0.05^{ns}	1.83^{ns}	0.02^{ns}
P rate × K rate × Y	4	0.05^{ns}	2.77^{ns}	0.44^{*}	0.05^{ns}	0.06^{ns}	5.70^{ns}	0.01^{ns}
Error	104	0.18	1.16	0.14	0.06	0.14	9.97	0.01
CV (%)		5.56	9.72	11.13	7.09	8.90	3.16	9.01

Note: ns = not significant; *, **, and *** significant at $p \leq 0.05$, 0.01, and 0.001, respectively; AGB, aboveground biomass; NPP, number of pods per plant; NSPP, number of seeds per pod; GY, grain yield; SY, stover yield; HSW, hundred seed weight; and HI, harvest index.

Table 6: Interaction of mineral nitrogen, phosphorus, and potassium fertilizers and the main effects of the growing year on the yield components and yield of faba bean.

Nitrogen (kg N ha^{-1})	Phosphorus (kg P_2O_5 ha^{-1})	NPP			NSPP			AGB (t ha^{-1})		
		Potassium (kg K_2O ha^{-1})			Potassium (kg K_2O ha^{-1})			Potassium (kg K_2O ha^{-1})		
		0	30	60	0	30	60	0	30	60
0	0	3.85 i	8.80 gh	6.55 h	2.73 ef	3.07 c–f	2.80 def	2.38 k	5.37 hi	5.63 ghi
	46	7.00 gh	14.49 a–d	14.26 a–d	3.58 a–d	2.83 def	3.58 a–d	5.08 i	7.48 cde	7.58 cd
	92	8.39 gh	15.78 ab	6.88 gh	3.07 c–f	3.58 a–d	3.00 def	5.08 i	6.06 fgh	6.56 efg
23	0	6.80 h	12.79 cde	12.29 de	2.63 f	3.31 b–f	3.48 a–e	5.75 ghi	7.91 cd	8.42 c
	46	8.80 gh	12.35 de	13.94 bcd	3.01 c–f	3.17 b–f	3.62 a–d	7.73 cd	10.29 b	10.94 ab
	92	9.30 fg	13.26 cde	15.09 abc	3.07 c–f	3.62 a–d	3.87 abc	7.79 cd	10.63 b	11.80 a
46	0	7.22 gh	12.29 de	11.29 ef	2.63 f	3.31 b–f	3.58 a–d	3.86 j	6.00 ghi	6.19 fgh
	46	6.55 h	14.49 a–d	12.35 de	2.92 def	3.90 abc	3.62 a–d	7.00 def	10.14 b	10.28 b
	92	12.29 de	14.67 a–d	16.71 a	3.31 b–f	4.17 a	3.98 ab	7.39 de	10.25 b	10.28 b
LSD (5%)		0.42				0.14			0.48	
Year										
2019		11.01 a				3.44 a			7.81 a	
2020		11.09 a				3.19 b			7.29 b	
LSD (5%)		NS				0.12			0.13	
CV		9.72				11.13			5.56	

Note: means in columns and rows followed by the same letter are not significantly different at $p = 0.05$ according to Fisher's protected LSD test. NPP, number of pods per plant; NSPP, number of seeds per plant; and AGB, aboveground biomass.

three fertilizers (control treatment) by 467%. This signifies that the soil of the study area is, in fact, deficient in the availability of these three major nutrients, and an adequate supply of balanced N, P, and K nutrients is required to enhance the number of pods per plant. Similar results were obtained by Ali et al. [56], who reported higher number of pods (32) in response to the combined application of N, P, and K at 36:54:114 kg ha^{-1} compared with the controls (5). Furthermore, Bezabih et al. [19] showed that the application of P fertilizer at the rate of 60 kg P_2O_5 ha^{-1} on rhizobium-

Table 7: Mean square values of the combined analysis of variance for correlation coefficients between grain yield and growth, yield components, and yield parameters of faba bean in response to mineral nitrogen, phosphorus, and potassium fertilizers in Sodo Zuria District, southern Ethiopia, in 2019 and 2020 cropping seasons.

Variable	L	PH	SG	NB	AGBM	NPP	NSPP	GY	SY	HSW	HI
L	1.00	-0.24^{**}	-0.39^{***}	-0.32^{***}	-0.37^{***}	-0.45^{***}	-0.26^{***}	-0.38^{***}	-0.35^{***}	-0.09^{ns}	0.06^{ns}
PH		1.00	0.26^{***}	0.36^{***}	0.35^{***}	0.27^{***}	0.39^{***}	0.34^{***}	0.35^{***}	0.40^{***}	-0.17^{*}
SG			1.00	0.64^{***}	0.44^{***}	0.69^{***}	0.49^{***}	0.42^{***}	0.45^{***}	0.41^{***}	-0.11^{ns}
NB				1.00	0.50^{***}	0.60^{***}	0.65^{***}	0.44^{***}	0.52^{***}	0.52^{***}	-0.28^{***}
AGBM					1.00	0.72^{***}	0.52^{***}	0.97^{***}	0.99^{***}	0.71^{***}	-0.35^{***}
NPP						1.00	0.52^{***}	68^{***}	0.72^{***}	0.55^{***}	-0.33^{***}
NSPP							1.00	0.50^{***}	0.52^{***}	0.47^{***}	-0.16^{*}
GY								1.00	-0.93^{***}	0.69^{***}	0.16^{*}
SY									1.00	0.69^{***}	-0.47^{***}
HSW										1.00	-0.25^{**}
HI											1.00

Note: ns = not significant; *, **, and *** significant at 0.05, 0.01, and 0.001, respectively. L, lodging; PH, plant height; SG, stem girth; NB, number of branches; RL, root length; NR, number of roots; Nod, number of nodules per root; AGBM, aboveground biomass; NPP, number of pods per plant; NSPP, number of seeds per pod; GY, grain yield; SY, stover yield; HSW, hundred seed weight; and HI, harvest Index.

inoculated plants significantly increased the number of pods per faba bean plant by 72% compared with the controls.

3.3.2. Number of Seeds per Pod. The number of seeds per pod of faba bean varied significantly ($p \leq 0.01$) in response to the main effect of the growing year and the rates of N, P, and K fertilizers applied and their interactions. However, the interaction effects of the growing year with N, P, and K fertilizer rates were nonsignificant (Table 5).

The number of seeds per pod increased in response to increasing rates of N, P, and K fertilizers (Table 6). Thus, the highest number of seeds per pod (4.17) was recorded with the N, P, and K combination of 46:92:30 kg ha^{-1}, which was 52.7% more than the control treatment (Table 6). The highest number of seeds per pod obtained with the aforesaid treatment was statistically at par with the number of seeds per pod obtained with 46 kg N ha^{-1} × 92 kg P_2O_5 ha^{-1} × 60 kg K_2O ha^{-1}. The results of this study indicated that the application of a balanced N, P, and K fertilizer rate leads to a higher number of seeds per pod. In agreement with this result, Abou-Amer et al. [48] reported a significantly higher number of seeds per pod (4.63) in response to the combined application of N, P, and K fertilizers at 60:60:80 kg ha^{-1} than the number of seeds per pod (2.26) in the controls.

The result also revealed that faba bean planted in the 2019 growing season produced more seeds per pod (3.44) than that planted in 2020 (3.19; Table 6). The higher number of seeds per pod in the 2019 cropping year might be linked to less lodging in that cropping season (Table 6), since lodging affects the number of seeds per pod by interfering with crop growth processes, such as water uptake, light interception, and healthy growth [33]. In addition, the lodging percentage was negatively associated ($r = -0.26^{***}$) with the number of seeds per pod of faba bean (Table 7).

3.3.3. Aboveground Biomass. The aboveground biomass yield of faba bean was significantly ($p \leq 0.001$) influenced by the effects of the planting year and the interaction of N, P, and K fertilizer rates. However, the interactions of the year of planting with N, P, and K fertilizer rates did not significantly influence the aboveground biomass yield (Table 5).

Increasing the rate of nitrogen application significantly and consistently increased the aboveground biomass yield of the crop plant with increasing rates of both P and K application (Table 6). The plants with sufficient nitrogen experience high rates of photosynthesis and typically exhibit vigorous growth that contributes to higher biomass yield in faba bean [57]. In addition, phosphorus is a vital component of ATP, which is involved in overall growth from the beginning of seedlings to seed formation and maturity [58]. Thus, phosphorus fertilizer plays a vital role in the biomass yield improvement of the faba bean. In addition, potassium plays an important role in cell growth and is used for higher and good-quality biomass yield [59]. Overall, the enhanced production of biomass in response to the increased rates of the three fertilizers could be attributed to the physiological roles that the nutrients play in plant growth. This implies that the balanced application of the three fertilizers fulfils the growth requirements of the faba bean through synergic effects [56]. Thus, the highest aboveground biomass yields of the crop were produced in response to the application of 23 kg N ha^{-1} and 46 kg N ha^{-1} each combined with 46 kg P_2O_5 ha^{-1} or 92 kg P_2O_5 ha^{-1} plus 60 kg K_2O ha^{-1}.

However, the lowest aboveground biomass yield was produced in response to the nil application of all three fertilizers. The application of N, P, and K fertilizers at the rate of 23:92:60 kg ha^{-1} resulted in about 4-fold biomass increment compared with the unfertilized plot. There is a long-held belief that K is not a limiting nutrient in Ethiopian soils, yet the finding verifies that the crops respond well to the application of K with N and P fertilizers. This shows that the biomass production of the plant is enhanced in response to increasing the rates of the three fertilizers, verifying that the soil of the study area is, in fact, deficient in the availability of these three major nutrients. Consistent with this result, Fatima et al. [49] reported that the application of N, P, and K fertilizers at 20:60:40 kg ha^{-1} increased the biomass yield of soybean by 201% compared with the control treatment. Similarly, Bezabih et al. [19] also showed a 73% improvement in the biomass yield of faba bean due to the combined application of 30 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} in rhizobium-inoculated faba bean.

The aboveground dry biomass was significantly ($p \leq 0.001$) influenced across the two cropping years. Higher biomass (7.81 t ha^{-1}) was obtained in the 2019 cropping season compared with the 2020 copping season (7.29 t ha^{-1}). In this regard, the growing year explained 7.1% of the total variability for the aboveground biomass (Table 6). The higher biomass in the 2019 cropping season might be linked with the positive association growth parameters such as plant height ($r = 0.35^{***}$), stem girth ($r = 0.44^{***}$), and the number of branches ($r = 0.50^{***}$), which were higher than those in the 2020 cropping season. Thus, the aforementioned parameters are indirectly attributed to the increase in the aboveground dry biomass in 2019 than in the 2020 cropping season. However, the aboveground dry biomass was negatively associated ($r = 0.50^{***}$) with the lodging percentage (Table 7), which was lower in the 2019 cropping season and indirectly reduced the loss in the aboveground biomass.

3.3.4. Grain Yield. The grain yield of faba bean was significantly affected by the effect of the growing year and the interaction of mineral N, P, and K fertilizers. However, the interaction effect of N, P, and K rates with the growing year did not significantly influence the grain yield (Table 5).

Similar to the aboveground biomass yield, increasing the rate of N application significantly ($p \leq 0.001$) and consistently increased the grain yield of the crop plant with increasing rates of both P and K application (Table 8). This means that the highest grain yields were obtained at either medium or high rates of phosphorus (46 or 92 kg P_2O_5 ha^{-1}) and potassium (30 or 60 kg K_2O ha^{-1}) fertilizers combined with the medium level of nitrogen (23 kg N ha^{-1}) fertilizer (Table 8). Accordingly, the highest grain yield (4.97 t ha^{-1}) was produced in response to the combined application of N, P, and K at the rate of 23:92:60 kg ha^{-1}. This result indicates

Table 8: Interaction of mineral nitrogen, phosphorus, and potassium fertilizers and the main effect of the growing year on yield components and the yield of faba bean.

Nitrogen (kg N ha^{-1})	Phosphorus (kg P_2O_5 ha^{-1})	Grain yield (t ha^{-1}) Potassium (kg K_2O ha^{-1})			Stover yield (t ha^{-1}) Potassium (kg K_2O ha^{-1})			Hundred seed weight (g) Potassium (kg K_2O ha^{-1})		
		0	30	60	0	30	60	0	30	60
0	0	1.08 j	2.45 h	2.50 h	1.29 j	2.92 hi	3.13 gh	88.04 f	92.77 def	93.81 c–f
	46	2.43 h	3.37 cd	3.37 cd	2.65 hi	4.11 c–f	4.21 cde	90.94 ef	101.79 ab	101.79 ab
	92	2.34 h	2.71 fgh	3.21 c–f	2.74 hi	3.35 fgh	3.35 fgh	90.50 ef	100.77 abc	100.32 abc
23	0	2.77 e–h	3.52 cd	3.67 c	2.98 hi	4.39 cd	4.75 c	97.30 b–e	103.15 ab	103.14 ab
	46	3.47 cd	4.54 ab	4.62 ab	4.26 cde	5.75 b	6.33 ab	102.13 ab	103.81 ab	103.74 ab
	92	3.47 cd	4.67 ab	4.97 a	4.33 cd	5.96 b	6.83 a	102.49 ab	105.57 a	106.67 a
46	0	1.63 i	2.67 gh	2.75 e–h	2.23 i	3.33 fgh	3.43 e–h	92.14 ef	99.96 a–d	101.10 ab
	46	3.11 d–g	4.34 b	4.51 ab	3.89 d–g	5.80 b	5.77 b	101.47 ab	103.81 ab	104.60 a
	92	3.29 cde	4.41 b	4.21 b	4.10 c–f	5.84 b	6.07 ab	88.04 f	104.55 a	103.74 ab
LSD (5%)			0.27			0.48			3.61	
Year										
2019			3.38 a			4.43 a			103.08 a	
2020			3.30 b			4.00 b			96.95 b	
LSD (5%)			0.07			0.12			0.98	
CV			7.09			8.90			3.16	

Note: means in columns and rows followed by the same letter are not significantly different at $p = 0.05$ according to Fisher's protected LSD test.

that increasing the rate of P and K fertilizers combined with the medium rate of nitrogen improves the grain yield. However, increasing the rate of N further than 23 kg N ha^{-1} was no longer required for enhancing the grain yield of the crop, indicating an already optimized rate at this level of N. This result also shows that nitrogen deficiency is of a medium level in the study area and is not so severe as the deficiency of phosphorus and potassium. However, the higher grain yield obtained in response to the application of 23 kg N ha^{-1} compared with 46 kg N ha^{-1} might be associated with the requirement of legumes for little nitrogen as a starter fertilizer [13]. For example, the maximum grain yield produced by faba bean in response to the interaction effect of 23 kg N ha^{-1} × 92 kg P_2O_5 ha^{-1} × 60 kg K_2O ha^{-1} exceeded the grain yield produced in response to nil application of the three fertilizers (control treatment) by 360%, that is, about a 4-fold increment (Table 8). This shows that the grain yield was enhanced in response to increasing rates of the three fertilizers, verifying that the soil of the study area is, in fact, deficient in the availability of these three major nutrients. The maximum grain yield obtained in this study was found to be about 5-fold more than the grain yield obtained, on average, by farmers in Wolaita Zone, which amounts to 1.2 t ha^{-1} [5]. In this study, the grain yield obtained at nil rates of the three fertilizers was comparable to the average grain yield of farmers in the study area obtained per hectare of land, which is about 1 ton [5]. Furthermore, the faba bean grain yield obtained in this study was about 2-fold higher than the national average grain yield of faba bean, which is about 2.12 t ha^{-1} [2]. The enhanced yield of the crop in response to the application of the three mineral fertilizers can be attributed to the supply of balanced nutrition to the crop. Thus, the physiologically synergistic roles played by nitrogen, phosphorus, and potassium may have improved the growth of the plant and the partitioning of photosynthate to seeds [49]. In this connection, the applied K fertilizer may have contributed to increased root growth, thereby improving water and nutrient uptake, as suggested by Marek et al. [50]. This situation creates an ideal condition for the uptake of applied N and P from the soil. Moreover, P has an essential function in the energy metabolism of plants, playing a key role in the energy supply in the N fixation process [12]. Phosphorus and potassium supply increases the supply of N in the plant by facilitating fixation, which maximizes the vegetative growth of the crop [54]. The combined application of P and K increases the level of N in the plants, which maximizes the vegetative growth of the crop [56]. This may enhance photosynthetic efficiency and lead to the vigorous growth of the crop, which may increase the partitioning of photosynthate to the grain [60]. In line with this result, Abou-Amer et al. [48] reported that the combined application of N, P, and K at 60 kg N, 60 kg P_2O_5, and 80 kg, K_2O ha^{-1}, respectively, produced 67.8% more grain yield than no fertilizer applied treatment. Also, N, P, and K fertilizer applied either a single or two nutrient combinations were less grain yield productivity of faba bean (Table 8). In agreement with this result, Ali et al. [56] reported that the combined application of N, P, and K at 46:92: 31 kg ha^{-1} improved the grain yield of faba bean by 4.7% and 1.1% than the combined application of P and K at 92: 30 kg ha^{-1} and P at 92 kg ha^{-1}, respectively.

A significantly ($p \le 0.05$) higher grain yield (3.38 t ha^{-1}) was obtained in 2019 than in the 2020 cropping season. Thus, faba bean that was planted in 2019 had a 2.4% more grain yield than that planted in the 2020 cropping season (Table 8). Similar to the biomass yield, the grain yield result might be linked to either positive or negative associations with the growth, yield, and yield component parameters. For instance, grain yield was positively associated with plant height ($r = 0.34^{***}$), thickness ($r = 0.42^{***}$), number of branches ($r = 0.44^{***}$), number of nodules per root ($r = 0.19^{*}$), aboveground biomass ($r = 0.97^{***}$), number of pods per plant ($r = 68^{***}$), number of seeds per pod ($r = 0.50^{***}$), hundred seed weight ($r = 0.69^{***}$), and harvest index ($r = 0.16^{*}$; Table 8), which were higher in the 2019 cropping season than in the 2020 cropping season. Consequently, the aforementioned parameters indirectly led to the increment in grain yield in the 2019 than in the 2020 cropping season. On the other hand, grain yield was negatively and significantly associated with logging ($r = 0.38^{***}$) and stover yield ($r = 0.93^{***}$; Table 7), which is lower in the 2019 cropping season and indirectly reduce the loss in the grain yield of faba bean in a cropping year.

3.3.5. Stover Yield. Stover yield responded significantly to the main effect of the year of planting as well as to the main effects of mineral N, P, and K fertilizers. The applied mineral N, P, and K fertilizers also interacted to influence the variables of the plant. However, the fertilizers and growing year did not interact to influence the variables (Table 5).

The increasing rate of N application significantly increased the stover yield with increasing rates of both P and K fertilizers (Table 8). Hence, a higher stover yield was obtained in response to the combination of medium or higher rates of nitrogen (23 or 46 kg N ha^{-1}) and phosphorus (46 or 92 kg P_2O_5 ha^{-1}) and a higher rate of potassium (60 kg K_2O ha^{-1}). Thus, the application of 23 kg N × 92 kg P_2O_5 × 60 kg K_2O ha^{-1} led to the production of 430% the highest stover yields (6.83 t ha^{-1}) than the unfertilized plot (Table 8). This shows that nitrogen and phosphorus play a significant role, whereas potassium plays a more prominent role in enhancing the stover production of faba bean, since 60–70% of potassium taken up by legume plants is found in the stover [61]. However, about 30% of nitrogen and phosphorus taken up by legume crops are found in the stover, and the remaining 70% are found in the seed [62]. The results also confirm the low availability of the three nutrients in the soil of the experimental site, as indicated by the results of the chemical analysis. The result is consistent with the finding of Ali et al. [56], who reported the highest stover yield of faba bean (7.16 t ha^{-1}) with the combined application of N, P, and K fertilizers at 15:22.5: 48 kg ha^{-1}.

The stover yield was also significantly ($p \le 0.01$) different in the experimental years in which a higher stover yield was recorded during 2019, that is, 10.8% higher than the 2020 cropping season. The higher stover yield in the 2019 cropping season might be due to the negative association with the lodging percentage ($r = -0.35^{***}$), which was higher in the 2020 cropping season, indirectly attributed to the stover yield (Table 7), since lodging affects healthy growth [63], which results in a reduction in stover yield.

3.3.6. Hundred Seed Weight. The hundred seed weight of faba bean was significantly affected by the growing year and the interaction of mineral N, P, and K fertilizers. However, the interaction effect of N, P, and K rates with the growing year did not significantly influence the grain yield (Table 5).

The increasing rate of N fertilizers significantly ($p \leq 0.05$) and consistently increased hundred seed weight across the increasing rates of P. However, increasing N fertilizers across the increasing rate of K was not markedly high (Table 8). Consequently, the highest hundred seed weight (106.67 g) was obtained with the combination of N, P, and K fertilizers at the rate of 23:92:60 kg ha^{-1}, which was statistically at par with the hundred seed weight obtained with the combinations of N, P, and K fertilizers at the rate of 23:92:30 and 46:92:30 kg ha^{-1} (Table 8). However, the lowest hundred seed weight was obtained with no fertilizer application. Thus, for example, the hundred seed weight obtained with N, P, and K fertilizers applied at 23:92:60 kg ha^{-1} was 21.2% more compared with the nontreated plot. The results indicate that phosphorus plays a critical role in increasing the hundred seed weight, followed by nitrogen. However, with the increased rate of potassium from 30 to 60 kg K_2O ha^{-1}, the role appeared to have lowered in enhancing the hundred seed weight. This is consistent with the postulation that most of the P and N taken up by plants (about 70%) is found in the seeds, whereas most of the potassium is found in the stover [64]. The enhancement of the hundred seed weight in response to the interaction effect of the three fertilizers can be attributed to a balanced supply of the nutrients for uptake by the plants, as suggested by Havlin et al. [52]. The enhancement of the hundred seed weight could be linked to the synergistic roles the nutrients may have played in plant growth, which led to increased hundred seed weight [21]. For instance, K fertilizer is crucial for root growth [50], which may have created an ideal condition for the uptake of the applied N and P nutrients. In addition, phosphorus plays an important role in energy supply in the N fixation process [12] and increases seed weight [21]. Abou-Amer et al. [48] indicated that combined application of mineral fertilizers at 60 kg Nha^{-1} × 60 kg P_2O_5 × 80 kg K_2O ha^{-1} produces about 68% higher hundred seed weight than planting with no fertilizer application.

The faba bean that was planted in the 2019 cropping season had a significantly higher hundred seed weight (103 g), which was about 6.0% more than the hundred seed weight in the 2020 cropping season (Table 8). The higher hundred seed weight in the 2019 cropping season might be associated with relatively lower rainfall (1,378 mm) than in the 2020 cropping season (Table 1). Thus, this may have helped the crop use nutrients efficiently for better growth, in which the seed weight increased. However, the relatively higher rainfall (1,378 mm) in the 2020 cropping season might have negatively affected the applied nutrients by erosion and waterlogging, and consequently, the assimilated translocation to the grain reduced. Hegab et al. [65] and Ahmed et al. [66] reported significant grain weight variability due to the cropping season of the faba bean. Furthermore, Stelling et al. [67] reported a difference in the hundred seed weight of the large size faba bean genotype from 112 to 178 g due to the prevailing moisture during the growing season.

Table 9: Effect of N and P fertilizers on the harvest index of faba bean.

Factor	Harvest index
N rate (kg ha^{-1})	
0	0.44 b
23	0.46 a
46	0.44 b
LSD (5%)	0.02
K_2O rate (kg ha^{-1})	
0	0.44 b
30	0.46 a
60	0.46 a
LSD (5%)	0.02
CV (%)	9.01

Note: means in the column followed by the same letter are not significantly different at $p = 0.05$ according to Fisher's protected LSD test.

3.3.7. Harvest Index. The harvest index of faba bean significantly ($p \leq 0.05$) varied in response to the main effects of N and K fertilizers, whereas the main effect of year and P fertilizer, the interaction of year with N, P, and K fertilizers, did not significantly influence the harvest index (Table 5).

Nitrogen applied at the rates of 23–46 kg N ha^{-1} resulted in a significantly low harvest index, which indicates the negative effect of N on biomass partitioning to the grains under increased N rates. The result is consistent with Khamooshi et al. [57], who reported that increased application of nitrogen from 0 kg N ha^{-1} to 60 kg N ha^{-1} significantly reduced the harvest index in faba bean (Table 9). In contrast, Ghafoor [66] reported that the mean harvest index of the faba bean increases with increasing application of combined N and P fertilizers from 0 kg N and P_2O_5 ha^{-1} (40.5%) to 98 kg N and 250 kg P_2O_5 ha^{-1} (43.9%). However, the increased rate of potassium from 30 to 60 K kg ha^{-1} was statistically at par, which indicates less photoassimilate production and ultimate partitioning into the stover compared with partitioning into the grain (Table 9). In contrast, Khalil et al. [69] reported that applying 96 kg K_2O ha^{-1} caused a higher significant increase in the harvest index compared with 48 kg K_2O ha^{-1} in the 2007 and 2008 cropping seasons.

3.4. Partial Budget Analysis. The adjusted grain and straw yield of faba bean were used to calculate the gross field benefits for the partial budget analysis. All N, P, and K fertilizer rate interactions were considered to analyze the partial budget of the faba bean. Furthermore, treatments

Table 10: Partial budget analysis of faba bean influenced by mineral nitrogen, phosphorus, and potassium fertilizers.

NPK treatments	UGY (t ha^{-1})	AGY (t ha^{-1})	USY (t ha^{-1})	ASY (t ha^{-1})	GFB (USD ha^{-1})	TVC (USD ha^{-1}) FC	TC	LC	TVC	NB (USD ha^{-1})
Control	1.08	0.97	1.29	1.16	917.69	0	0	0	0	917.69
23 kg N ha^{-1}	2.77	2.49	2.98	2.68	2,350.26	13.95	0.17	0.47	14.59	2,335.66
46 kg N ha^{-1}	1.63	1.47	2.23	2.01	1,387.99	27.91	0.35	0.93	29.19	1,358.80
46 kg P_2O_5 ha^{-1}	2.43	2.19	2.65	2.39	2,062.15	34.88	0.35	0.93	36.16	2,025.99
92 kg P_2O_5 ha^{-1}	2.34	2.11	2.74	2.47	1,987.74	69.77	0.70	1.86	72.33	1,915.42
30 kg K_2O ha^{-1}	2.45	2.21	2.92	2.63	2,081.72	17.44	0.17	0.47	18.08	2,063.64
60 kg K_2O ha^{-1}	2.5	2.25	3.13	2.82	2,125.78	34.88	0.35	0.93	36.16	2,089.62
23 kg N × 46 kg P_2O_5 ha^{-1}	3.47	3.12	4.26	3.83	2,949.70	48.84	0.52	1.40	50.76	2,898.94
23 kg N × 92 kg P_2O_5 ha^{-1}	3.47	3.12	4.33	3.90	2,950.43	83.72	0.87	2.33	86.92	2,863.51
46 kg N × 46 kg P_2O_5 ha^{-1}	3.11	2.80	3.89	3.50	2,644.43	62.79	0.70	1.86	65.35	2,579.08
46 kg N × 92 kg P_2O_5 ha^{-1}	3.29	2.96	4.1	3.69	2,797.33	97.67	1.05	2.79	101.5	2,695.81
23 kg N × 30 kg K_2O ha^{-1}	3.52	3.17	4.39	3.95	2,992.92	31.40	0.35	0.93	32.67	2,960.24
23 kg N × 60 kg K_2O ha^{-1}	3.67	3.30	4.75	4.28	3,122.27	48.84	0.52	1.40	50.76	3,071.51
46 kg N × 30 kg K_2O ha^{-1}	2.67	2.40	3.33	3.00	2,270.20	45.35	0.52	1.40	47.27	2,222.93
46 kg N × 60 kg K_2O ha^{-11}	2.75	2.48	3.43	3.09	2,338.22	62.79	0.70	1.86	65.35	2,272.87
46 kg P_2O_5 × 30 kg K_2O ha^{-1}	3.37	3.03	4.11	3.70	2,864.41	45.35	0.52	1.40	47.27	2,817.14
46 kg P_2O_5 60 kg × 60 kg K_2O ha^{-1}	3.37	3.03	4.21	3.79	2,865.45	69.77	0.70	1.86	72.33	2,793.13
92 kg P_2O_5 × 30 kg K_2O ha^{-1}	2.71	2.44	3.35	3.02	2,303.90	87.21	0.87	2.33	90.41	2,213.49
92 kg P_2O_5 60 × 62 kg K_2O ha^{-1}	3.21	2.89	3.35	3.02	2,722.50	104.7	1.05	2.79	108.5	2,614.01
23 kg N × 46 kg P_2O_5 × 30 kg K_2O ha^{-1}	4.54	4.09	5.75	5.18	3,861.10	66.28	0.70	1.86	68.84	3,792.27
23 kg N × 46 kg P_2O_5 × 60 kg K_2O ha^{-1}	4.62	4.16	6.33	5.70	3,934.15	76.74	0.87	2.33	79.94	3,854.21
23 kg N × 92 kg P_2O30 kg × 30 kg K_2O ha^{-1}	4.67	4.20	5.96	5.36	3,972.14	101.2	1.05	2.79	105.0	3,867.14
23 kg N × 92 kg P_2O_5 × 60 kg K_2O ha^{-1}	4.97	4.47	6.83	6.15	4,232.41	118.6	1.22	3.26	123.1	4,109.33
46 kg N × 46 kg P_2O_5 × 30 kg K_2O ha^{-1}	4.34	3.91	5.8	5.22	3,694.19	66.28	0.87	2.33	69.48	3,624.71
46 kg N × 46 kg P_2O_5 × 60 kg K_2O ha^{-1}	4.51	4.06	5.77	5.19	3,836.20	97.67	1.05	2.79	101.5	3,734.69
46 kg N × 92 kg P_2O_5 × 30 kg K_2O ha^{-1}	4.41	3.97	5.84	5.26	3,753.21	115.1	1.22	3.26	119.6	3,633.62
46 kg N × 92 kg P_2O_5 × 60 kg K_2O ha^{-1}	4.21	3.79	6.07	5.46	3,588.17	132.6	1.40	3.72	137.7	3,450.50

Note: UGY, unadjusted grain yield; AGY, adjusted grain yield; USY, unadjusted straw yield; ASY, adjusted straw yield; GFB, gross field benefit; TVC, total variable cost; FC, fertilizer cost; TC, transportation cost; LC, labor cost to fertilizer transportation and application; NB, net benefit; and USD ha^{-1} = United States dollar per hectare.

Table 11: Mean marginal rate of return of faba bean influenced by N, P, and K fertilizers.

NPK treatments	UGY (t ha^{-1})	AGY (t ha^{-1})	USY (t ha^{-1})	ASY (t ha^{-1})	GFB (USD ha^{-1})	TVC (USD ha^{-1})	NB (USD ha^{-1})	MRR (%)
Control	1.08	0.97	1.29	1.16	917.69	0	917.69	—
23 kg N ha^{-1}	2.77	2.49	2.98	2.68	2,350.26	14.59	2,335.66	9,719
23 kg N × 30 kg K_2O ha^{-1}	3.52	3.17	4.39	3.95	2,992.92	32.67	2,960.24	3,455
23 kg N × 60 kg K_2O ha^{-1}	3.67	3.30	4.75	4.28	3,122.27	50.76	3,071.51	615
23 kg N × 46 kg P_2O_5 × 30 kg K_2O ha^{-1}	4.54	4.09	5.75	5.18	3,861.10	68.84	3,792.27	3,987
23 kg N × 46 kg P_2O_5 × 60 kg K_2O ha^{-1}	4.62	4.16	6.33	5.70	3,934.15	79.94	3,854.21	558
23 kg N × 92 kg P_2O_5 × 30 kg K_2O ha^{-1}	4.67	4.20	5.96	5.36	3,972.14	105.00	3,867.14	52
23 kg N × 92 kg P2O_5 × 60 kg K_2O ha^{-1}	4.97	4.47	6.83	6.15	4,232.41	123.08	4,109.33	1,340

Note: UGY, unadjusted grain yield; AGY, adjusted grain yield; USY, unadjusted straw yield; ASY, adjusted straw yield; GFB, gross field benefit; TVC, total variable cost; NB, net benefit; USD ha^{-1} = United States dollar per hectare; and MRR, marginal rate of return.

having marginal rates of return (MRRs) below 100% were considered low and unacceptable to farmers and were, thus, eliminated [44]. This was because such a return would not balance the cost of the investment; however, MRR must be above 100% to have an attractive profit margin.

The maximum net benefit of USD 4,109.33 ha^{-1} was recorded at the N, P, and K combination of 23:92:60 kg ha^{-1}, followed by the N, P, and K combinations of 23:92: 30 kg ha^{-1}, 23:46:60 kg ha^{-1}, and 23:46:30 kg ha^{-1} (Table 10). However, the minimum net benefit of USD 917.69 ha^{-1} was gained on faba bean planted with no fertilizer (controls). Overall, the economical net gain at the N, P, and K combination of 23:92:60 kg ha^{-1} was about 4.48-fold higher compared with the control treatment (Table 10). However, the low financial capacity of smallholder farmers and the increasing price of mineral fertilizers are a cause for no-to-low inorganic fertilizer application rates in Ethiopia [64].

Economic analysis revealed that the highest mean net benefit (USD 4,109.33 ha^{-1}) with an acceptable marginal rate of return (1,340%) was obtained with the N, P, and K combination of 23:92:60 kg ha^{-1} (Table 11). However, a better net return per unit cost of production was obtained with an N, P, and K combination of 23:46:60 kg ha^{-1} (USD 3,854.21 ha^{-1}) and 23:46:30 kg ha^{-1} (USD 3,792.27 ha^{-1}), N and K combination of 23:60 kg ha^{-1} (USD 2,960.24 ha^{-1}), N and K combination of 23:30 kg ha^{-1} (USD 2,335.66 ha^{-1}), and nitrogen at 23 kg N ha^{-1} (USD 917.69 ha^{-1}; Table 11). However, the N, P, and K combination of 23:92:30 kg ha^{-1} was not considered due to the marginal rate of return below 100%. Therefore, the N, P, and K combination of 23:92: 60 kg ha^{-1} was more economical than the rest of the treatments.

4. Conclusions

The results of this study demonstrated that the phenology, growth, yield, yield components, and nutrient use efficiency are significantly influenced by the interaction of N, P, and K fertilizer rates. A maximum faba bean grain yield of 4,970 kg ha^{-1} was recorded in response to the N, P, and K fertilizer combination of 23:92:60 kg ha^{-1}. The result was in statistical parity with the grain yield obtained in response to the N, P, and K fertilizer combinations of 23:46:30 kg ha^{-1} and 46:46:60 kg ha^{-1}. However, the lowest grain yield (1.08 t ha^{-1}) was recorded in faba bean planted with no fertilizer application. Overall, the grain yield produced in response to the N, P, and K fertilizer combination of 23:92: 60 kg ha^{-1} was about 4-fold higher than that with no fertilizer treatment and the average grain yield obtained by the farmers per hectare in the study area. In addition, the faba bean grain yield obtained in this study was about 2-fold higher than the national average grain yield of faba bean, which is about 2.12 t ha^{-1}. In general, for a better grain yield (4.97 t ha^{-1}) and the highest mean net benefit (USD 4,109.33 ha^{-1}) with an acceptable marginal rate of return (1,340%), farmers are advised to use N, P, and K fertilizers in a combination of 23:92:60 kg ha^{-1}. In Ethiopia, there is a belief that the soils contain enough or sufficient quantity of the K nutrient. Consequently, management has focused on N- and P-containing fertilizers. However, this finding suggests the need for balanced fertilization including K. Meanwhile, further research that evaluates the integration of mineral N, P, and K and organic fertilizers is suggested for soil health and higher productivity.

Data Availability

Data will be made available upon request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

B. A. T. contributed to the conceptualization, methodology, software provision, formal analysis, investigation, data curation, visualization, original draft preparation, funding, and administration, and N. D., T. T., F. L., and Y. A. contributed to validation, resource provision, review and editing, and supervision. All authors have read and agreed to the final version of the manuscript.

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