Wiley
Advances in Agriculture
Volume 2026, Article ID 4345220, 11 pages
https://doi.org/10.1155/aia/4345220

WILEY

Research Article

Exploring the Optimal NPSB Fertilizer Application Strategies and Use Efficiency for Mung Bean (*Vigna radiata* L.) Production at Mataya, Central Ethiopia

Daniel Manore,[1] **Oumer Abdella**,[1] **Francis Abuye**,[2] **and Hiwot Kelbo**[1]

[1]*Department of Plant Science, College of Agricultural Sciences, Wachemo University, P.O. Box 667, Hossaena, Ethiopia*
[2]*Department of Natural Resource Management, College of Agricultural Sciences, Wachemo University, P.O. Box 667, Hossaena, Ethiopia*

Correspondence should be addressed to Daniel Manore; daniel.manore@wcu.edu.et

Received 26 February 2025; Revised 1 November 2025; Accepted 4 December 2025

Academic Editor: Abiram Karanam

Copyright © 2026 Daniel Manore et al. Advances in Agriculture published by John Wiley & Sons Ltd. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

This study in Mataya, Central Ethiopia, identified optimal nitrogen, phosphorus, sulfur, and boron (NPSB) fertilizer strategies for enhancing mung bean production and soil health. A 2-year field experiment evaluated three varieties (N-26, NVL-1, and Arkebe) under five NPSB rates (0, 25, 50, 75, and 100 kg ha^{-1}). Results demonstrated that NPSB application significantly improved key soil properties postharvest, including pH, organic carbon (OC), total nitrogen (TN), and available phosphorus (AP), sulfur, and boron. Agronomic performance was strongly influenced by fertilizer rate and variety. The N-26 variety achieved the highest grain yield (1.95 t ha^{-1}) at 100 kg NPSB ha^{-1}. However, nutrient use efficiency (UE) indices were generally optimized at moderate application rates of 50–75 kg ha^{-1}. Strong positive correlations were found between grain yield and efficiency parameters like physiological efficiency (PE; $r = 0.94$), underscoring the importance of efficient nutrient utilization. The study concludes that applying 75 kg NPSB ha^{-1} to the N-26 variety provides the most effective strategy for boosting mung bean productivity, improving nutrient UE, and enhancing soil fertility in the study region, offering a sustainable pathway for smallholder farmers.

Keywords: agronomic efficiency; Ethiopia; grain yield; nodulation; soil fertility; varietal response

1. Introduction

Mung bean (*Vigna radiata* L.) is gaining prominence in Ethiopia's legume-based cropping systems due to its short maturity cycle [1], nitrogen-fixing capacity, and adaptability to marginal soils [2]. As a protein-rich pulse crop, it plays a vital role in enhancing household nutrition, diversifying income sources [2], and improving soil fertility in smallholder farming systems. However, its productivity remains constrained by poor soil nutrient status, limited varietal improvement, and suboptimal fertilizer management practices [3].

Recent agronomic research has emphasized the importance of balanced nutrient application, particularly through blended fertilizers such as nitrogen, phosphorus, sulfur, and boron (NPSB) [4], which address multiple macro- and micronutrient deficiencies common in Ethiopian soils. For example, Meharie [5] demonstrated that tailored NPSB applications in Cheha District significantly improved grain yield and biomass accumulation across multiple mung bean varieties. Similarly, Choudhary et al. [6] reported that optimizing NPSB rates enhanced both agronomic efficiency (AE) and varietal responsiveness under field conditions, underscoring the need for site-specific recommendations.

Despite the growing importance of mung bean in Ethiopia's crop diversification and food security strategies, its productivity remains limited by suboptimal fertilizer management and declining soil fertility particularly in regions like Mataya, Central Ethiopia. The introduction of NPSB blended fertilizer (containing NPSB) offers promising potential to enhance both crop performance and soil health. However, there is a lack of

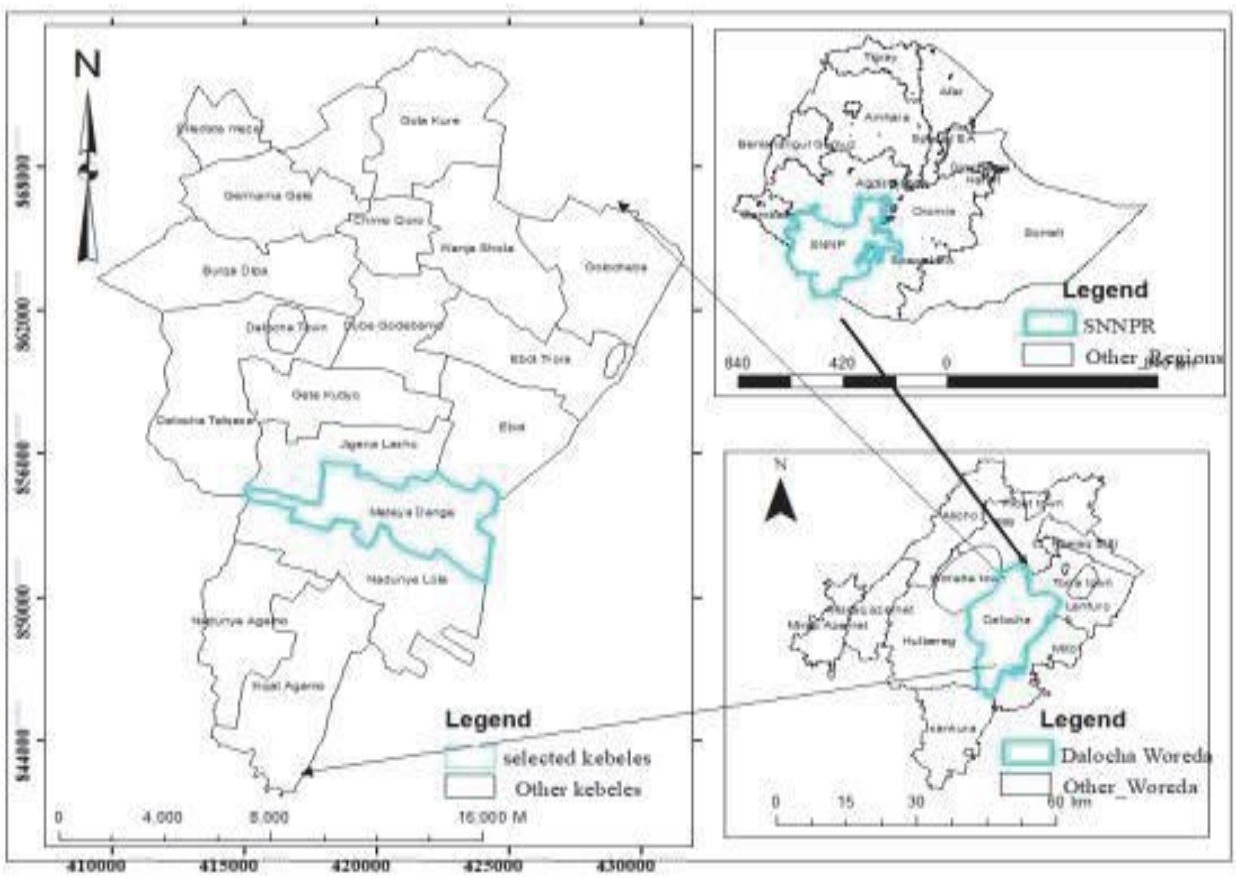


Figure 1: Geographical location of the study area.

localized evidence on optimal NPSB application strategies tailored to specific mung bean varieties, as well as on the efficiency with which these nutrients are utilized under field conditions. Furthermore, the residual effects of NPSB fertilization on key soil chemical properties postharvest remain poorly understood, posing challenges for sustainable nutrient management. This study therefore aims to: (i) to determine the residual impact of NPSB fertilization on some soil chemical properties, (ii) to study the nutrient use efficiencies of mung bean varieties in the study, and (iii) evaluate the agronomic response of selected mung bean varieties to varying NPSB fertilizer rates.

2. Materials and Method

2.1. Description of the Study Area. Mataya Dange is situated in the Dalocha district of the Silte Zone, as illustrated in Figure 1. The area is characterized by a tropical savanna climate, with distinct wet and dry seasons. It lies approximately 132 km southwest of Addis Ababa, positioned between the towns of Hosanna and Butejira.

2.2. Rainfall and Temperature. The district is characterized by a mild agricultural climate, with an average annual temperature of 21.85°C. It receives approximately 161.3 mm (6.35 in.) of rainfall each year, as illustrated in Figure 2. This rainfall regime is vital for sustaining local livelihoods, as it directly affects agricultural productivity and the availability of water resources.

2.3. Experimental Materials Description. The NPSB fertilizer applied in this study contained 18.9% nitrogen, 37.75% P_2O_5, 6.95% sulfur, and 0.1% trace elements, selected based on site-specific soil fertility status and recommendations from the Ethiopian Soil Fertility Atlas [7]. Three released mung bean varieties with small seed size were evaluated: N-26 [3], Arkebe [8], and NVL-1 [3]. These varieties were chosen for their genetic diversity, agronomic relevance, and adaptability to Ethiopian conditions, providing a suitable basis for assessing varietal response to NPSB fertilization and nutrient use efficiency (UE) under the agroecological context of Mataya.

2.4. Treatments and Experimental Design. The experiment assessed three mung bean varieties in combination with five NPSB fertilizer rates (0, 25, 50, 75, and 100 kg ha^{-1}), resulting in a total of 15 treatment combinations. The study was conducted over two consecutive cropping seasons (2021/22 and 2022/23) using a factorial randomized complete block design (RCBD) with three replications. Each plot measured 4 m^2 (2 m × 2 m) and contained six rows, with 0.5 m spacing between plots and 1 m between blocks. The total experimental area was 296 m^2 (8 m × 37 m). Seeds were sown at 30 cm

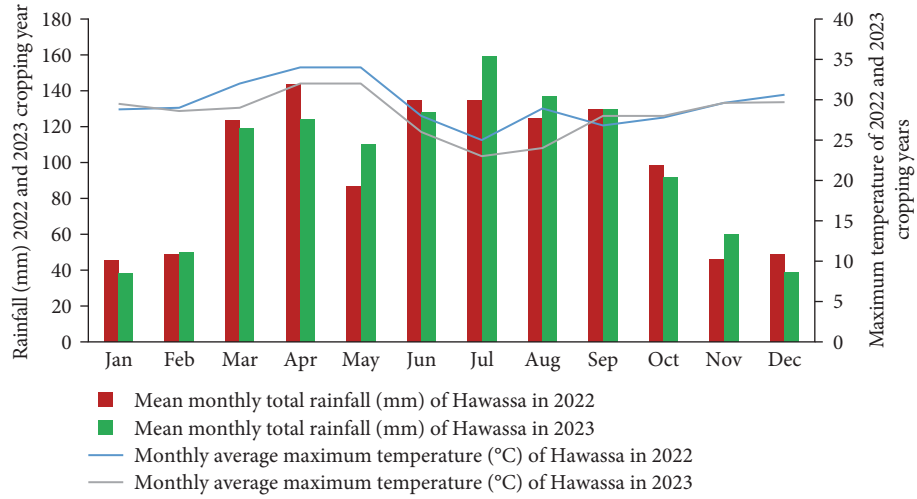


Figure 2: Weather data of cropping years at Dalocha.

interrow and 10 cm intrarow spacing, with a planting depth of 3 cm. Two seeds were placed per hole, and NPSB fertilizer was applied at sowing using the drill method, positioned 5 cm deep and covered with soil. Uniform agronomic practices including weeding, spacing, and disease management—were consistently applied across all plots to ensure experimental integrity.

2.5. Soil Chemical Properties. Prior to sowing, soil samples were collected from 45 plots at a depth of 0–30 cm. Following crop harvest in both study years, samples were again taken from each treatment plot to assess changes in soil properties. Analyses were conducted at Wachamo University's soil and plant tissue laboratory, focusing on texture, pH, organic carbon (OC), total nitrogen (TN), available phosphorus (AP), cation exchange capacity (CEC), available sulfur (AS), and available boron (AB). Soil pH was measured potentiometrically in a 1:2.5 soil–water suspension [9]; OC was determined using the Walkley–Black method [10]; TN via the Kjeldahl method [11]; AP using the Olsen method; AS turbidimetrically [12]. These comprehensive assessments, conducted both before planting and after harvest, enabled evaluation of soil property dynamics and provided valuable insights into the effects of agricultural practices on soil health.

2.6. Nodulation Data Collection Methods. Nodulation traits were evaluated at the flowering stage, when nodule development and nitrogen fixation are at their peak [13]. Five plants were randomly selected per plot, carefully uprooted, and gently washed to remove soil without disturbing the nodules. For each plant, visible nodules were counted to determine nodule number, then weighed fresh after blotting. The same nodules were oven-dried at 70°C for 48 h and reweighed to obtain dry weight. All measurements were recorded in milligrams per plant.

2.7. Grain Yield and Efficiency Indices Collection. Grain yield was determined by harvesting the central net plot area of each treatment at physiological maturity. Harvested plants were sun-dried, threshed manually, and cleaned to remove impurities. The grain weight was recorded using a digital balance and adjusted to 12% moisture content [13]. Yield was then extrapolated to kilograms per hectare (kg ha^{-1}) [14].

To evaluate the effectiveness of NPSB fertilizer application in mung bean, four key efficiency indices are commonly measured: UE [15], AE [16], recovery efficiency (RE) [17], and physiological efficiency (PE) [18]. These indices are calculated using grain yield and nutrient uptake data collected from both fertilized and control plots.

The concentration of NPSB in grain was calculated using the following formula:

$$\text{Use efficiency} = \frac{\text{Grain yield (kg/ha)}}{\text{NPSB rate(kg/ha)}}. \quad (1)$$

$$\text{Agronomic efficiency, AE} = \frac{\text{Grain yield at NPSB rate} - \text{grain yield at control}}{\text{NPSB rate(kg/ha)}}. \quad (2)$$

$$\text{Recovery efficiency, RE} = \frac{\text{Uptake at NPSB rate} - \text{uptake at control}}{\text{NPSB rate (kg/ha)}} \times 100\%. \quad (3)$$

$$\text{Physiological efficiency, PE} = \frac{\text{Grain yield at NPSB rate} - \text{grain yield at control}}{\text{Uptake at at NPSB rate} - \text{uptake at control}}. \quad (4)$$

2.8. Data Analysis. Before conducting the data analyses, we evaluated the assumptions related to data distribution and performed tests for multivariate normality, homogeneity of covariance matrices, and linearity. The multivariate analysis of variance (MANOVA) analysis was carried out using SAS version 9.34 following the procedures described by Gomez and Gomez (1984). Interpretations were then derived from

Table 1: Effects of cropping year, variety, and NPSB fertilizer rate on selected soil chemical properties.

Factor	Level	Parameters					
		pH (1:2.5 H_2O)	OC (%)	Total N (%)	P (ppm)	S (ppm)	B (ppm)
Cropping year	2022 before planting	5.63[c]	2.80[c]	0.06	27.25[c]	18.25[b]	0.57
	2022 after planting	5.80[b]	3.50[b]	0.14	29.92[b]	20.49[a]	0.66
	2023 after planting	6.00[a]	3.64[a]	0.17	30.70[a]	20.60[a]	0.8
LSD (5%)	—	0.011	0.018	ns	0.28	1.2	ns
CV (%)	—	2.9	5.3	2.9	7.5	4.2	4.4
Varieties	NVL-1	5.85[c]	3.40[c]	0.13[a]	30.10[c]	20.10[a]	0.70[a]
	N-26	5.95[b]	3.55[b]	0.14[a]	30.60[b]	21.00[a]	0.72[a]
	Arkebe	6.05[a]	3.65[a]	0.15[a]	31.20[a]	21.50[a]	0.74[a]
LSD (5%)	—	0.012	0.014	0.54	0.34	1.2	ns
CV (%)	—	2.5	3.9	2.4	5.8	3.8	6.3
NPSB rate (kg ha^{-1})	0	5.80[e]	3.20[e]	0.10[e]	28.50[e]	19.00[e]	0.60[e]
	25	5.85[d]	3.30[d]	0.12[d]	29.50[d]	20.00[d]	0.65[d]
	50	5.90[c]	3.40[c]	0.14[c]	30.50[c]	21.00[c]	0.70[c]
	75	5.95[b]	3.50[b]	0.16[b]	31.50[b]	22.00[b]	0.75[b]
	100	6.00[a]	3.60[a]	0.18[a]	32.50[a]	23.00[a]	0.80[a]
LSD (5%)	—	0.002	0.003	0.006	0.33	1	0.5
CV (%)	—	3.2	2.3	2.8	8.3	4.5	6.3
P statics							
Years	—	*	*	*	*	*	ns
Variety (V)	—	*	***	ns	*	*	—
NPSB rate	—	*	**	*	*	*	ns
CR × V	—	ns	ns	ns	ns	ns	ns
CR × Fertilizer	—	ns	ns	ns	ns	ns	ns
V × Fertilizer	—	ns	ns	ns	ns	ns	ns
CR × V × NPSB	—	ns	ns	ns	ns	ns	ns

Note: Significance levels are represented by *5%, **1%, and ***0.1%. Letters were assigned according to mean separation, with "a" indicating the highest mean value, followed by "b," "c," "d," and "e" in descending order, based on the LSD at the 5% significance level.
Abbreviation: NS, nonsignificant.

the results. To compare the means of significant treatments, we applied a 5% probability level and used Tukey's HSD.

2.8.1. Correlation and Regression. We conducted analyses to assess relationships between yield and its components in mung bean varieties.

3. Results

3.1. Soil Analysis Results. The data presented in Table 1 highlight the significant influence of year, variety, and NPSB fertilizer rate on key soil chemical properties before sowing and after mung bean harvest across the 2022 and 2023 cropping seasons.

3.2. Nodulation Parameters. Table 2 illustrates the main effects of year, mung bean variety, and NPSB fertilizer rate on key nodulation parameters, including nodule number, nodule dry weight, and nodule effectiveness. Significant variation across years suggests that seasonal factors such as rainfall distribution, temperature, and soil moisture may have influenced rhizobial activity and root development. Varietal differences in nodulation likely reflect genetic variation in root architecture, symbiotic efficiency, and responsiveness to nutrient inputs. Increasing NPSB rates generally enhanced nodulation performance, particularly in terms of nodule biomass and effectiveness, indicating improved nutrient availability especially phosphorus and sulfur, which are critical for nodule formation and function.

3.3. Grain Yield and Efficiency Indices. Table 3 presents the effects of year, variety, and NPSB fertilizer rate on mung bean grain yield and associated efficiency indices, including UE, AE, PE, and nutrient uptake efficiency. Grain yield varied significantly across years, likely due to seasonal differences in rainfall, temperature, and soil nutrient dynamics. Varietal performance also differed, reflecting genetic variation in yield potential and nutrient UE.

3.3.1. Treatment Interaction Efficiency Indices. Table 4 reveals significant interaction effects among year, variety, and NPSB fertilizer rate on mung bean efficiency indices, including AE and nutrient uptake efficiency. These interactions suggest that the response of efficiency metrics is not solely dependent on individual factors but rather on their combined influence. Notably, specific variety × NPSB rate combinations yielded superior AE and PFP values, indicating that certain genotypes

Table 2: Effects of cropping year, variety, and NPSB fertilizer rate on mung bean.

Treatment group	Treatment level	Parameters			
		Nodule number/plant	Nodule fresh weight (mg)	Nodule dry weight (mg)	Nodule volume (mL)
Cropping year (CR)	2022	8.8	27.4[b]	10.5[b]	15.8[b]
	2023	8.4	32.0[a]	12.4[a]	18.5[a]
LSD (5%)	—	ns	4.5	0.12	1.4
CV (%)	—	2.6	13	5.2	3.1
Varieties (V)	NVL-1	8.38[b]	27.3[b]	13.3[b]	17.5[b]
	N-26	8.45[b]	29.0[a]	14.8[a]	19.2[a]
	Arkebe	9.6[a]	30.0[a]	12.5[b]	18.0[b]
LSD (5%)	—	0.9	2.1	0.97	1.1
CV (%)	—	6.3	3.8	11	2.2
NPSB rate (kg ha^{-1})	0	8.38[d]	24.5[c]	12.63[b]	14.5[c]
	25	9.6[c]	26.3[b]	12.5[b]	15.8[b]
	50	14.7[b]	29.0[a]	14.5[a]	20.1[a]
	75	21.4[a]	31.4[a]	14.5[a]	24.5[a]
	100	20.77[a]	30.0[a]	14.2[a]	23.8[a]
LSD (5%)	—	2.1	2.7	1.2	1.4
CV (%)	—	8.7	4.8	13	3.8
P statistics					
Cropping year (CR)	—	ns	*	*	*
Variety (V)	—	*	***	ns	*
NPSB rate	—	*	**	*	*
CR × V	—	ns	ns	ns	ns
CR × fertilizer	—	ns	ns	ns	ns
V × fertilizer	—	ns	ns	ns	ns
CR × V × NPSB	—	ns	ns	ns	ns

Note: Significance levels are represented by *5%, **1%, and ***0.1%. Superscript letters were assigned based on mean separation, with "a" indicating the highest mean value, followed by "b," "c," "d," and "e" in descending order, according to the LSD test at the 5% significance level.
Abbreviation: NS, nonsignificant.

are more responsive to nutrient inputs under given environmental conditions.

3.4. Pearson Correlation Matrix. Table 5 presents the correlation matrix between grain yield and key agronomic parameters, including nutrient use efficiencies (UE, AE, RE, and PE) and nodulation traits, under NPSB fertilizer application.

4. Discussions

4.1. Effects on the Soil Chemical Properties

4.1.1. Effects on the Soil pH Dynamics. Soil pH plays a vital role in nutrient availability and crop performance. In this study, pH increased steadily across cropping years (CRs), mung bean varieties, and NPSB fertilizer rates. Initial pH in 2022 before planting was 5.63, rising to 5.80 after harvest, and reaching 6.00 in 2023 (Table 1). This shift suggests that mung bean cultivation helps neutralize soil acidity, likely due to biological nitrogen fixation and organic matter contribution [19]. Among varieties, Arkebe recorded the highest pH (6.05), followed by N-26 and NVL-1. This indicates varietal influence on soil chemistry, possibly through differences in root activity and biomass return. Similarly, increasing NPSB rates from 0 to 100 kg ha^{-1} led to a consistent pH rise from 5.80 to 6.00, showing the fertilizer's buffering effect. Recent findings by Ayele [20], support this trend, noting that NPSB application in mung bean fields improved soil pH and nutrient balance in acidic soils of Central Ethiopia. The study emphasized that balanced fertilization enhances microbial activity and organic matter decomposition, contributing to better pH regulation [21].

4.1.2. Effects on the OC (%). Before planting in 2022, OC was 2.80%, rising to 3.50% after harvest, and reaching 3.64% in 2023. This upward trend reflects the contribution of mung bean biomass and root residues to soil organic matter [19]. Among the tested varieties, Arkebe showed the highest OC (3.65%), followed by N-26 (3.55%) and NVL-1 (3.40%). These differences suggest that varietal traits such as root volume and residue quality play a role in organic matter accumulation. Similarly, increasing NPSB rates from 0 to 100 kg ha^{-1} led to a steady rise in OC from 3.20% to 3.60%, indicating that nutrient enrichment supports microbial activity and organic matter stabilization. A recent study by Maruthi et al. [22], found that applying blended NPSB fertilizer in mung bean fields significantly enhanced soil OC levels in Central Ethiopia.

Table 3: Main effects of cropping year, variety, and NPSB fertilizer rate on grain yield, nutrient uptake, and use efficiencies in mung bean crop production.

	Parameters					
Factor	**Grain yield (t ha^{-1})**	**NPSB uptake (kg ha^{-1})**	**UE (kg/kg)**	**AE (kg/kg)**	**RE (%)**	**PE (kg/kg)**
Cropping year (CR)						
2022	1.58^{b}	11.4^{b}	35.8^{b}	7.6^{b}	31.0^{b}	24.5^{b}
2023	1.70^{a}	13.2^{a}	37.0^{a}	8.2^{a}	33.5^{a}	24.6^{a}
LSD (5%)	0.45	0.45	0.6	0.45	1.2	0.2
CV (%)	0.8	4.2	12	3.2	2.1	3.1
Varieties (V)						
NVL-1	1.76^{b}	13.8^{b}	47.6^{b}	8.9^{b}	34.5^{b}	25.8^{b}
N-26	1.95^{a}	14.9^{a}	49.5^{b}	10.2^{a}	36.8^{a}	27.7^{a}
Arkebe	1.74^{b}	13.5^{b}	57.4^{a}	8.7^{b}	33.2^{b}	26.2^{b}
LSD (5%)	0.48	2.3	1.6	0.23	0.8	1.2
CV (%)	0.83	5.3	7.3	2.3	2.3	5.1
NPSB rate (kg ha^{-1})						
0	1.20^{d}	6.2^{e}	—	—	—	—
25	1.28^{d}	8.4^{d}	51.2^{a}	8.2^{a}	8.8^{e}	36.4^{a}
50	1.48^{c}	10.6^{c}	39.6^{b}	7.6^{b}	29.0^{b}	25.5^{c}
75	1.62^{b}	12.8^{b}	21.6^{c}	7.0^{b}	28.0^{b}	25.0^{c}
100	1.94^{a}	14.9^{a}	19.4^{c}	4.4^{c}	24.5^{c}	27.7^{b}
LSD (5%)	0.51	1.6	2.7	2.6	3.2	2.4
CV (%)	0.78	2.9	12	5.3	21	11.3
P statistics						
CR × V	ns	ns	ns	ns	ns	ns
CR × fertilizer	ns	ns	ns	ns	ns	ns
V × fertilizer	ns	ns	*	*	*	*
CR × V × NPSB	ns	ns	ns	ns	ns	ns

Note: Significance levels are represented by *5%, **1%, and ***0.1%. Superscript letters were assigned based on mean separation, with "a" indicating the highest mean value, followed by "b," "c," "d," and "e" in descending order, according to the LSD test at the 5% significance level.
Abbreviation: NS, nonsignificant.

Table 4: Interactions effect of variety and NPSB fertilizer rate on nutrient use efficiencies on mung bean.

Treatment combination		**Parameters**			
Variety	**NPSB rate (kg ha^{-1})**	**UE (kg/kg)**	**AE (kg/kg)**	**RE (%)**	**PE (kg/kg)**
NVL-1	0	35.8^{d}	—	—	—
	25	37.0^{d}	8.2^{a}	33.5^{a}	24.6^{b}
	50	48.6^{b}	9.9^{a}	33.5^{a}	25.8^{b}
	75	49.8^{b}	13.2^{a}	36.8^{a}	23.7^{bcd}
	100	57.4^{a}	8.7^{a}	34.2^{a}	25.2^{b}
N-26	0	47.6^{bcd}	—	—	—
	25	49.5^{b}	10.2^{a}	36.8^{a}	27.7^{a}
	50	57.4^{a}	8.7^{a}	33.2^{a}	26.2^{a}
	75	37.0^{d}	8.2^{a}	33.5^{a}	24.6^{b}
	100	37.0^{d}	8.2^{a}	33.5^{a}	24.6^{b}
Arkebe	0	35.8^{d}	—	—	—
	25	47.6^{bcd}	8.9^{a}	34.5^{a}	25.8^{b}
	50	51.2^{b}	8.2^{a}	8.8^{d}	36.4^{a}
	75	39.6^{cd}	7.6^{a}	29.0^{b}	25.5^{b}
	100	21.6^{e}	7.0^{a}	28.0^{b}	25.0^{bcd}
LSD (5%)	—	1.7	2.6	3.2	2.4
CV (%)	—	9.4	5.8	12	8.4

Note: Significance levels are represented by *5%. Superscript letters were assigned based on mean separation, with "a" indicating the highest mean value, followed by "b," "c," "d," and "e" in descending order, according to the LSD test at the 5% significance level.
Abbreviation: NS, nonsignificant.

Table 5: Correlation matrix of grain yield with nutrient use efficiencies and nodulation parameters under NPSB fertilization.

Parameters	Grain yield	UE	AE	RE	PE	Nodule number /plant	Nodule fresh wt	Nodule dry wt	Nodule volume
Grain yield (t ha^{-1})	1	—	—	—	—	—	—	—	—
UE (kg/kg)	0.86***	1	—	—	—	—	—	—	—
AE (kg/kg)	0.91**	0.83**	1	—	—	—	—	—	—
RE (%)	0.88**	0.70*	0.69**	1	—	—	—	—	—
PE (kg/kg)	0.94***	0.78**	0.72**	0.70**	1	—	—	—	—
Nodule number/plant	0.59*	0.58*	0.55*	0.53*	0.57*	1	—	—	—
Nodule fresh weight	0.55**	0.63**	0.60*	0.59*	0.62**	0.70**	1	—	—
Nodule dry weight	0.67**	0.85**	0.62**	0.60*	0.64**	0.72**	0.74***	1	—
Nodule volume (mL)	0.81**	0.70*	0.58*	0.56*	0.59*	0.68**	0.71**	0.73**	1

Note: Significance levels are represented by *5%, **1%, and ***0.1%.

4.1.3. Effects on the TN (%). In this study, soil total N increased markedly across CRs, mung bean varieties, and NPSB fertilizer rates. Before planting in 2022, TN was 0.06%, rising to 0.14% after harvest, and reaching 0.17% in 2023 (Table 1). This steady increase reflects the nitrogen-fixing ability of mung bean and the contribution of organic residues to soil nitrogen pools. Among the varieties, Arkebe recorded the highest total N (0.15%), followed closely by N-26 (0.14%) and NVL-1 (0.13%). These differences suggest varietal influence on nitrogen fixation efficiency and biomass return [22]. Similarly, increasing NPSB rates from 0 to 100 kg ha^{-1} led to a consistent rise in total N from 0.10% to 0.18%, indicating that nutrient supplementation enhances nitrogen accumulation in the soil. A recent study by Tirfessa et al. [23], supports these findings, showing that blended NPSB fertilizer significantly improved TN levels in mung bean fields in Ethiopia.

4.1.4. Effects on the Available Phosphorous (ppm). In this study, soil phosphorus levels increased significantly across CRs, mung bean varieties, and NPSB fertilizer rates. Before planting in 2022, P was 27.25 ppm, rising to 29.92 ppm after harvest, and reaching 30.70 ppm in 2023. This upward trend reflects the combined effect of mung bean cultivation and nutrient enrichment [24]. Among the varieties, Arkebe recorded the highest P level (31.20 ppm), followed by N-26 (30.60 ppm) and NVL-1 (30.10 ppm). These differences suggest varietal influence on phosphorus uptake and root exudation. Similarly, increasing NPSB rates from 0 to 100 kg ha^{-1} led to a steady rise in P from 28.50 to 32.50 ppm, confirming the fertilizer's role in boosting phosphorus availability [25].

4.1.5. Effects on the Sulfur (ppm). Sulfur is vital for plant metabolism and soil health. In this study, soil S levels rose from 18.25 ppm before planting in 2022 to 20.60 ppm in 2023, showing a steady increase across years, varieties, and fertilizer rates. Arkebe variety led with 21.50 ppm, and higher NPSB rates (up to 100 kg ha^{-1}) boosted S from 19.00 to 23.00 ppm. Supporting this, Gebeyehu [26] reported that NPSB fertilization in common bean fields improved sulfur availability and enhanced microbial activity, contributing to better nutrient cycling and soil fertility.

4.1.6. Effects on the Boron (ppm). In this study, soil B increased from 0.57 ppm before planting in 2022 to 0.80 ppm in 2023, showing steady improvement across years, varieties, and fertilizer rates. Arkebe had the highest B level (0.74 ppm), and NPSB application from 0 to 100 kg ha^{-1} raised B from 0.60 to 0.80 ppm. According to Sahilemariam [16], blended NPSB fertilizer enhances boron availability and root function in mung bean systems, contributing to better soil micronutrient balance and crop performance.

4.2. Effects on the Nodulation Parameters

4.2.1. Effects on the Nodule Numbers. Mung bean nodulation responded positively to increasing NPSB fertilizer rates, with nodule counts rising from 8.38 at 0 kg ha^{-1} to over 21 at 75 kg ha^{-1} (Table 2). This trend highlights the role of phosphorus, sulfur, and boron in enhancing root development and rhizobial activity [27]. Arkebe consistently showed higher nodule numbers than NVL-1 and N-26, suggesting varietal differences in nodulation potential. These findings align with Tirfessa et al. [23], who reported optimal nodulation at 75–100 kg ha^{-1} NPSB, and Yoseph Ganta et al. [28], who identified Arkebe as a responsive genotype under East Shawa conditions. The results underscore the importance of integrated nutrient and varietal management in boosting biological nitrogen fixation.

4.2.2. Effects on the Nodule Fresh Weight. Nodule fresh weight in mung bean was influenced by cropping season, genotype, and NPSB fertilizer application. Higher values were recorded in 2023 compared to 2022, suggesting that favorable seasonal conditions may have enhanced rhizobial activity and root vigor [29]. Among the varieties, N-26 and Arkebe consistently produced greater nodule biomass than NVL-1, reflecting genotypic differences in nutrient responsiveness and symbiotic efficiency. Notably, nodule fresh weight increased steadily with rising NPSB rates, peaking at 31.4 mg at 75 kg ha^{-1}. This trend highlights the synergistic role of phosphorus, sulfur, and boron in promoting active nodule development. These findings are consistent with Bonilla and Bolanos [30], who reported enhanced nodulation and biomass accumulation under 50–100 kg ha^{-1} NPSB, and with Kumar et al. [31], who identified N-26 as a high-performing genotype under nutrient-enriched conditions. The results underscore the importance of integrating seasonally adaptive varieties with balanced nutrient strategies to optimize biological nitrogen fixation in mung bean.

4.2.3. Effects on the Nodule Dry Weight. Nodule dry weight was significantly affected by CR, variety, and NPSB fertilizer rate (Table 2). In 2023, plants produced higher nodule dry weight (12.4 mg) than in 2022 (10.5 mg), likely due to more favorable growing conditions. This seasonal improvement aligns with Tadewos et al. [32], who reported enhanced nodulation under optimal field environments. Among varieties, N-26 showed superior performance (14.8 mg), significantly exceeding NVL-1 (13.3 mg) and Arkebe (12.5 mg). This supports findings by Nahusenay et al. [33], highlighting genotype influence on nodulation efficiency. Nodule dry weight increased with NPSB application, peaking at 14.5 mg under 50–75 kg ha^{-1}.

4.2.4. Effects on the Nodule Volume. Plants grown in 2023 produced larger nodules (18.5 mL) than those in 2022 (15.8 mL), suggesting improved environmental conditions for root development. This seasonal effect is consistent with Tadewos et al. [32], who reported enhanced nodule volume and biomass in mung bean under favorable field conditions in Southern Ethiopia. Among varieties, N-26 recorded the highest nodule volume (19.2 mL), followed by Arkebe (18.0 mL) and NVL-1 (17.5 mL), indicating superior symbiotic efficiency in N-26. This aligns with findings by Manore and Wolde-Meskel [34], who observed varietal differences in nodulation traits and yield performance under organic and biofertilizer treatments. Nodule volume also increased with NPSB application, peaking at 24.5 mL under 75 kg ha^{-1}, with no significant gain beyond this rate.

4.3. Effects on the Grain Yield and Efficiency Indices

4.3.1. Effects on the Grain Yield. Grain yield of mung bean was significantly influenced by CR, variety, and NPSB fertilizer rate. The 2023 season recorded a higher mean yield (1.70 t ha^{-1}) compared to 2022 (1.58 t ha^{-1}; Table 3), likely due to favorable climatic conditions enhancing nutrient uptake and PE, as similarly observed by Wang et al. [35], in drought-adaptive genotypes under variable rainfall regimes. Among varieties, N-26 outperformed NVL-1 and Arkebe, achieving the highest grain yield (1.95 t ha^{-1}). Fertilizer rate had a pronounced effect, with grain yield increasing progressively from 1.20 t ha^{-1} (control) to 1.94 t ha^{-1} at 100 kg NPSB ha^{-1}. This suggests that moderate NPSB application optimizes nutrient use without compromising efficiency, echoing the nutrient optimization strategies proposed by Meena et al. [36] in blended fertilizer trials.

4.3.2. Effects on the Nutrient Uptake. Nutrient uptake of blended NPSB, was significantly influenced by CR, variety, and fertilizer rate. The 2023 season recorded a higher mean NPSB uptake (13.2 kg ha^{-1}) than 2022 (11.4 kg ha^{-1}), likely due to improved soil moisture and favorable weather conditions enhancing nutrient solubility and root absorption [37]. Among the tested varieties, N-26 exhibited the highest uptake (14.9 kg ha^{-1}), followed by NVL-1 (13.8 kg ha^{-1}) and Arkebe (13.5 kg ha^{-1}), indicating genotypic differences in nutrient acquisition efficiency. These findings align with Decouard et al. [38], who reported significant varietal variation in nutrient uptake and translocation efficiency under similar agroecological conditions.

The application of NPSB fertilizer markedly increased nutrient uptake, with values rising from 6.2 kg ha^{-1} in the control to 14.9 kg ha^{-1} at 100 kg NPSB ha^{-1}. This linear response suggests that nutrient availability was a limiting factor in the unfertilized plots. However, the marginal gain in uptake between 75 and 100 kg ha^{-1} was relatively small (12.8–14.9 kg ha^{-1}), indicating a potential plateauing effect at higher rates. This trend is consistent with the findings of Baijukya et al. [39], who observed diminishing nutrient uptake efficiency beyond optimal application thresholds in legume systems.

4.3.3. Effects on the Utilization Efficiency. UE varied widely across treatment combinations, with N-26 and NVL-1 showing superior performance at moderate to high fertilizer rates. The highest UE (57.4 kg/kg) was recorded for N-26 at 50 kg NPSB ha^{-1} and NVL-1 at 100 kg ha^{-1} (Table 4), indicating strong internal nutrient conversion capacity. In contrast, Arkebe showed a sharp decline in UE at 100 kg ha^{-1} (21.6 kg/kg), suggesting possible nutrient saturation or physiological limitations [40]. These findings align with Demie et al. [41], who reported genotype-specific nutrient uptake thresholds in legumes.

4.3.4. Effects on the AE. AE values were consistently high across varieties and rates, with no significant differences among treatments. NVL-1 at 75 kg ha^{-1} recorded the highest AE (13.2 kg/kg), followed closely by N-26 at 25 kg ha^{-1} (10.2 kg/kg). This suggests that moderate NPSB rates enhance yield per unit nutrient applied, especially in responsive genotypes. Similar trends were observed by Singh et al. [42], who emphasized the role of balanced fertilization in maximizing AE under rain fed conditions.

4.3.5. Effects on the RE. RE was highest for NVL-1 at 75 kg ha^{-1} (36.8%) and N-26 at 25 kg ha^{-1} (36.8%), indicating efficient nutrient uptake from the applied fertilizer. Arkebe showed poor RE at 50–100 kg ha^{-1}, with a notable drop to 8.8% at 50 kg ha^{-1}, suggesting limited root uptake or leaching losses. These results support the genotype × fertilizer interaction findings of Vemulakonda et al. [43], who highlighted varietal differences in root architecture and nutrient acquisition.

4.3.6. Effects on the PE. PE peaked at 36.4 kg/kg for Arkebe at 50 kg ha^{-1}, despite its low RE, indicating strong internal nutrient utilization once absorbed. N-26 also showed high PE (27.7 kg/kg) at 25 kg ha^{-1}, reinforcing the efficiency of low-to-moderate NPSB rates. The decline in PE at higher rates across all varieties suggests diminishing returns and possible nutrient dilution effects, as noted by Relyea [44], in blended fertilizer trials.

4.4. Effects on the Correlations. Grain yield showed strong positive correlations with PE ($r = 0.94^{***}$), AE ($r = 0.91^{**}$), and RE ($r = 0.88^{**}$), indicating that efficient nutrient uptake and conversion are key drivers of productivity. Utilization efficiency ($r = 0.86^{***}$) also contributed significantly, reflecting internal nutrient use capacity. Nodulation traits especially nodule volume ($r = 0.81^{**}$) and dry weight ($r = 0.67^{**}$) were moderately correlated with yield and efficiency metrics, suggesting that biological nitrogen fixation complements applied nutrient use [32, 44]. These relationships highlight the synergistic role of genotype, fertilizer, and rhizobial activity in enhancing mung bean performance.

5. Conclusions

The optimal application rate of 50–75 kg NPSB ha^{-1}, particularly for the high-performing N-26 variety, delivers a powerful triple benefit: it significantly boosts grain yields, maximizes nutrient UE, and concurrently enhances soil fertility by improving key properties like OC and pH. The strong link between yield and PE underscores that it is not just about adding more fertilizer, but about smarter nutrient management. Therefore, adopting these tailored fertilizer and variety recommendations provides a sustainable and profitable pathway for smallholder farmers, transforming mung bean into a reliable crop for both food security and soil health in the region.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure

After using QuillBot, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Daniel Manore led the writing and editing process, contributed to conceptual framework. Oumer Abdella gathered data and managed the fieldwork, ensuring solid empirical support. Hiwot Kelbo analyzed the data, drafted the original manuscript, refined the methodology, and participated in the review to improve clarity. Francis Abuye provided editing and co-supervision, offering valuable insights.

Funding

No funding was received for this manuscript.

Acknowledgments

We express our gratitude to Wachemo University and the Dalocha Woreda Silete zone for providing us with the necessary field and laboratory facilities. During the preparation of this work, the authors used QuillBot to improve the language and readability.

References

[1] A. Rajput, Q. A. Panhwar, and H. Babar, "Role of Leguminous Crops by Enhancing Soil Fertility and Plant," in *Legume Crops for Food Security-Cultivation and Benefits: Cultivation and Benefits*, 211, (2025).

[2] A. A. Diatta, W. E. Thomason, O. Abaye, et al., "Assessment of Nitrogen Fixation by Mungbean Genotypes in Different Soil Textures Using 15N Natural Abundance Method," *Journal of Soil Science and Plant Nutrition* 20, no. 4 (2020): 2230–2240.

[3] W. Dikr, "Mung Bean (*Vigna radiata* L.) Production Status and Challenges in Ethiopia," *Global Academic Journal of Agriculture and Biosciences* 5, no. 2 (2023): 13–22.

[4] S. Kumar, *Effect of Integrated Nutrient Management in Summer Mungbean* (Haryana Agricultural University, Hisar, 2021).

[5] T. F. Meharie, *Effect of Blended NPSB Fertilizer Rates on Growth and Yield of Mung Bean (Vigna Radiata L.) Varieties in Cheha District, Southern Ethiopia*, (Southern Ethiopia (Master's Thesis), Wolkite University Repository, 2024).

[6] H. Choudhary, N. D. Devi, V. Rinwa, et al., "Impact of Integrated Nutrient Management on Soil Health and Yield of Mungbean: A Review," *Indian Journal of Agricultural Research* 59, no. 4 (2025).

[7] E. Elias, P. F. Okoth, J. J. Stoorvogel, et al., "Cereal Yields in Ethiopia Relate to Soil Properties and N and P Fertilizers," *Nutrient Cycling in Agroecosystems* 126, no. 2-3 (2023): 279–292.

[8] S. M. Delie, T. A. Adamu, and A. M. Andualem, "Adaptability and Agronomic Performance Evaluation of Mungbean (*Vigna radiata* (L.) Wilczek) Varieties Under Non-Inoculated and Inoculated Rhizobium Bacteria Conditions," *PeerJ* 13 (2025): e19558.

[9] S. Vogel, K. Emmerich, I. Schröter, et al., "The Effect of Soil Moisture Content and Soil Texture on Fast in Situ pH Measurements With Two Types of Robust Ion-Selective Electrodes," *Soil* 10, no. 1 (2024): 321–333.

[10] A. A. Mustapha, N. Abdu, E. Y. Oyinlola, and A. A. Nuhu, "Evaluating Different Methods of Organic Carbon Estimation on Nigerian Savannah Soils," *Journal of Soil Science and Plant Nutrition* 23, no. 1 (2023): 790–800.

[11] T. D. Hicks, C. M. Kuns, C. Raman, Z. T. Bates, and S. Nagarajan, "Simplified Method for the Determination of Total Kjeldahl Nitrogen in Wastewater," *Environments* 9, no. 5 (2022): 55.

[12] J. Kohn, M. Iwanyshyn, and B. M. Olson, *Groundwater Nitrogen and Chloride Following Closure of an Earthen Manure Storage in Southern Alberta* (Wiley Online Library, 2021).

[13] R. A. Lumactud, D. Dollete, D. K. Liyanage, K. Szczyglowski, B. Hill, and M. S. Thilakarathna, "The Effect of Drought Stress on Nodulation, Plant Growth, and Nitrogen Fixation in Soybean During Early Plant Growth," *Journal of Agronomy and Crop Science* 209, no. 3 (2023): 345–354.

[14] X. A. Idrisov, M. A. Yusupova, M. A. Gaziyev, J. J. Qodirov, A. R. Fteacher, and S. Z. Tteacher, "Results of Analytical Study of Growth, Development, Grain Yield and Quality of Mung Bean Varieties as Main and Reproductive Crops," (2021).

[15] K. Nakachew, H. Yigermal, F. Assefa, Y. Gelaye, and S. Ali, "Review on Enhancing the Efficiency of Fertilizer Utilization: Strategies for Optimal Nutrient Management," *Open Agriculture* 9, no. 1 (2024): 20220356.

[16] B. M. Sahilemariam, *Response of Common Bean (Phaseolus vulgaris l.) Varieties to Rates of Blended Npsb Fertilizer at Haramaya Univesity, East Hararghe, Ethiopia* (Haramaya University, 2023).

[17] D. Gui, K. Zhang, and Z. Sha, "Response of Reactive Nitrogen Losses and Nitrogen Fate in the Soil-Crop System to Intercropping Regimes," *Field Crops Research* 326 (2025): 109870.

[18] G. Rădeanu, C. Precupeanu, G.-C. Teliban, et al., "Interactive Effects of Genotype, Irrigation, and Fertilization on Physiological, Biometric, and Biochemical Traits of Runner Bean (*Phaseolus coccineus* L.)," *Horticulturae* 11, no. 9 (2025): 1135.

[19] S. Khan, M. Ismail, M. Ibrar, and Z. Ali, "The Effect of Biochar on Soil Organic Matter, Total N in Soil and Plant, Nodules, Grain Yield and Biomass of Mung Bean," *Soil & Environment* 39, no. 1 (2020): 87–94.

[20] E. T. Ayele, *Effects of Nps Fertilizer and Vermicompost on Selected Soil Properties, Yield and Yield Components of Mungbean (Vigna radiata l.): at Amibara in Middle Awash, Afar Region, Ethiopia* (Haramaya University, 2023).

[21] Y. Xing, Y. Xie, and X. Wang, "Enhancing Soil Health Through Balanced Fertilization: A Pathway to Sustainable Agriculture and Food Security," *Frontiers in Microbiology* 16 (2025): 1536524.

[22] V. Maruthi, K. S. Reddy, P. K. Pankaj, et al., "Soil Resource Conservation Technologies on Rainfed Mung Bean Root Growth and Their Potential Root Carbon Additions Under Variable Rainfall Situations in Semi-Arid Agroecosystem," *Journal of Soil Science and Plant Nutrition* 24, no. 3 (2024): 5799–5814.

[23] T. Tirfessa, Z. Jalata, and K. Lamessa, "Influence of Blended NPSB Fertilizer on Nodulation and Yield Performance of *Rhizobium* Inoculated Common Bean Varieties in Acidic Soil, Western Ethiopia," *All Life* 15, no. 1 (2022): 1290–1303.

[24] A. A. Diatta, O. Abaye, M. L. Battaglia, et al., "Mungbean [*Vigna radiata* (L.) Wilczek] and Its Potential for Crop Diversification and Sustainable Food Production in Sub-Saharan Africa: A Review," *Technology in Agronomy* 4, no. 1 (2024).

[25] H. Khan, W. A. Akbar, Z. Shah, H. U. Rahim, A. Taj, and J. M. Alatalo, "Coupling Phosphate-Solubilizing Bacteria (PSB) With Inorganic Phosphorus Fertilizer Improves Mungbean (*Vigna radiata*) Phosphorus Acquisition, Nitrogen Fixation, and Yield in Alkaline-Calcareous Soil," *Heliyon* 8, no. 3 (2022): e09081.

[26] G. Gebeyehu, *Effect of Blended NPSB Fertilizer Rates on Growth, Yield Components and Yield of Common Bean (Phaseolus vulgaris l.) Varieties in Bakadawula Ari District, South Omo Zone, Southern Ethiopia*Haramaya University, 2024).

[27] Y. Hu, Y. Chen, X. Yang, L. Deng, and X. Lu, "Enhancing Soybean Yield: The Synergy of Sulfur and Rhizobia Inoculation," *Plants* 12, no. 22 (2023): 3911.

[28] T. Yoseph Ganta, D. F. Mekbib, and P. Tadele, *Genetic Diversity, Drought Tolerance, and Genotype by Environment Interaction of Mung Bean [Vigna radiata (l.) Wilczek] Genotypes in Ethiopia* (Haramaya University, 2021).

[29] V. Singh and M. Bell, "Genotypic Variability in Architectural Development of Mungbean (*Vigna radiata* L.) Root Systems and Physiological Relationships With Shoot Growth Dynamics," *Frontiers in Plant Science* 12 (2021): 725915.

[30] I. Bonilla and L. Bolanos, "Mineral Nutrition for Legume-Rhizobia Symbiosis: B, Ca, N, P, S, K, Fe, Mo, Co, and Ni: A Review," in *Organic Farming, Pest Control and Remediation of Soil Pollutants: Organic Farming, Pest Control and Remediation of Soil Pollutants*, (2009): 253–274.

[31] N. Kumar, M. Kancheti, K. K. Hazra, C. P. Nath, M. Hashim, and M. M. Deo, "Enhancing Nutrient Use Eficiency in Pulses Under Diversified Farming Through Agronomic Manipulations," in *Agricultural Diversification for Sustainable Food Production*, (Springer, 2025): 197–213.

[32] T. Tadewos, T. Ayalew, and T. Yoseph, "Growth, Nodulation and Yield of Mung Bean (*Vigna radiata* L.(Wilczek) as Affected by Bio-Chemical Fertilizers Integration at Southern Ethiopia," *Ukrainian Journal of Ecology* 12, no. 11 (2022): 39–49.

[33] G. Nahusenay, G. Wolde, W. Tena, and T. Tamiru, "Chickpea (*Cicer arietinum* L.) Growth, Nodulation, and Yield as Affected by Varieties, Mesorhizobium Strains, and NPSB Fertilizer in Southern Ethiopia," *Frontiers in Plant Science* 15 (2024): 1372082.

[34] D. Manore and E. Wolde-Meskel, "Effects of Bradyrhizobia Inoculation on Growth, Yield and Yield Components of Cowpea Varieties (*Vigna unguiculata* (L.) Walp) at Hawassa, Ethiopia," *Journal of Biology, Agriculture and Healthcare* 7, no. 17 (2017): 1–13.

[35] Z. Wang, W.-S. Yung, Y. Gao, et al., "From Phenotyping to Genetic Mapping: Identifying Water-Stress Adaptations in Legume Root Traits," *BMC Plant Biology* 24, no. 1 (2024): 749.

[36] D. K. Meena, D. Brahma, R. Dawar, A. Patidarand, and T. Singh, "Site-Specific Nutrient Management for Enhancing Nutrient Use Efficiency," in *Site-Specific Nutrient Management for Enhancing Nutrient Use Efficiency*, (2023): 1–4.

[37] M. R. Islam, U. Sarker, M. G. Azam, et al., "Potassium Augments Growth, Yield, Nutrient Content, and Drought Tolerance in Mung Bean (*Vigna radiata* L. Wilczek.)," *Scientific Reports* 14, no. 1 (2024): 9378.

[38] B. Decouard, M. Bailly, M. Rigault, et al., "Genotypic Variation of Nitrogen Use Efficiency and Amino Acid Metabolism in Barley," *Frontiers in Plant Science* 12 (2022): 807798.

[39] F. P. Baijukya, J. Van Heerwaarden, A. C. Franke, et al., "Nutrient Deficiencies are Key Constraints to Grain Legume Productivity on "Non-Responsive" Soils in Sub-Saharan Africa," *Frontiers in Sustainable Food Systems* 5 (2021): 678955.

[40] H. Zhou, Y. Liu, B. Mu, F. Wang, N. Feng, and D. Zheng, "Nitrogen Limitation Affects Carbon and Nitrogen Metabolism in Mung Bean (*Vigna radiata* L.)," *Journal of Plant Physiology* 290 (2023): 154105.

[41] D. T. Demie, T. F. Döring, M. R. Finckh, W. Van Der Werf, J. Enjalbert, and S. J. Seidel, "Mixture × Genotype Effects in Cereal/Legume Intercropping," *Frontiers in Plant Science* 13 (2022): 846720.

[42] B. Singh, J. Ryan, C. Campbell, and R. Kröbel, "Nutrient Management and Water Use Efficiency for Sustainable Production of Rain-Fed Crops in the World's Dry Areas," *Managing Water and Fertilizer for Sustainable Agricultural Intensification* 140 (2015).

[43] A. L. Vemulakonda, A. A. Saad, S. S. Kumar, et al., "Revealing the Nexus Between Fertilizer Composition and the Performance of Common Bean (*Phaseolus vulgaris* L.) Genotypes in the Himalayan Heartland of India," *Sustainability* 16, no. 14 (2024): 6234.

[44] J. Relyea, *Evaluation of Mung Bean Varieties for Adaptation to Tennessee Growing Conditions* (Tennessee State University, 2024).