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Growth and reproductive attributes of Mungbean (*Vigna radiata* L.) under organic and synthetic fertilization in Eastern Nepal

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Abstract: Mungbean (*Vigna radiata* L.) is a short-duration, protein-rich legume widely cultivated for its nutritional value and nitrogen-fixing ability, playing a vital role in sustainable agriculture. Despite its potential, mungbean productivity in Nepal remains limited due to suboptimal nutrient management. To evaluate the impact of various organic and inorganic nutrient sources on mungbean growth and yield, a field experiment was conducted at the Directorate of Agricultural Research, Tarahara, Sunsari, during the summer season (March-June 2023). The study employed a randomized complete block design (RCBD) with three replications and nine treatments: T1 (Control), T2 (Recommended dose of NPK: 20:40:20 kg/ha), T3 (Nano urea 2000 ml/acre per spray), T4 (Nano DAP 2000 ml/acre per spray), T5 (Farmyard manure 10 t/ha), T6 (½ Recommended NPK + ½ FYM), T7 (Seed treated with *Rhizobium* 25 ml/kg + 40:20 P_2O_5:K_2O kg/ha), T8 (Seed treated with PSB 25 ml/kg + 20 kg N/ha), and T9 (Seed treated with *Rhizobium* 25 ml/kg + PSB 25 ml/kg). Results showed significant effects on most growth and yield parameters. T4 recorded the highest grain yield (2030.02 kg/ha), pods per plant (28.83), straw yield (4026.04 kg/ha), branches per plant (5.60), and trifoliate leaves (7.17), while T3 had the highest seeds per pod (11.47). T7 excelled in nodule formation. Regression analysis indicated strong yield correlations with pods per plant (R^2= 0.70), test weight (R^2= 0.67), and straw yield (R^2 = 0.60). Treatments T4 and T6 also had the highest benefit-cost ratios (2.24 and 2.23, respectively). These findings highlight the potential of nano and integrated nutrient management in enhancing productivity while promoting sustainable and resource-efficient mungbean cultivation for future food security.

1. Introduction

Mungbean (*Vigna radiata* L.), a short-duration grain legume of the

Fabaceae family, is an important crop for food and nutritional security across South and Southeast Asia (Tiwari *et al*., 2022). It plays a crucial role in smallholder cropping systems due to its rapid growth cycle (60-75 days), capacity for biological nitrogen fixation, and adaptability to marginal soils and low-input conditions. Globally, mungbean is cultivated over an area of approximately 6 million hectares, producing about 3.5 million tonnes annually, with India alone accounting for nearly 50% of global production (Pratap *et al*., 2020; Bam *et al.*, 2022). In Nepal, mungbean cultivation covers an estimated 12,000 hectares, predominantly in the Terai region, with an average productivity of 500 kg ha^{-1} (Neupane *et al*., 2023). Its integration into rice-wheat cropping systems as a catch crop during the spring fallow window offers a promising opportunity to intensify land use, improve soil fertility, and enhance income diversification in subtropical farming systems (Khanal *et al*., 2004).

Beyond its agronomic versatility, mungbean is highly valued for its nutritional profile. The seeds are rich in digestible protein (~24%), essential amino acids such as lysine and tryptophan, vitamins including folate, vitamin A, and riboflavin, and minerals such as iron, calcium, and zinc (Muchira *et al*., 2018; Tarafder *et al*., 2020). Agronomically, mungbean improves soil health through nitrogen fixation contributing up to 42 kg N ha^{-1} and leaves behind biologically enriched biomass that enhances organic matter and microbial activity (Verma *et al*., 2017; Rijal *et al*., 2023). Through its symbiotic association with *Rhizobium* species, mungbean forms root nodules that convert atmospheric nitrogen into plant-available forms, reducing the dependence on synthetic nitrogen fertilizers. This process not only sustains soil fertility but also benefits subsequent crops in rotation by improving nutrient availability and soil biological balance. Additionally, mungbean residues enhance soil organic carbon and promote beneficial microbial interactions, strengthening the agroecosystem's overall productivity and resilience.

It performs optimally in well-drained loam to sandy loam soils with a pH range of 6.2-7.2 and moderate temperatures, making it suitable for dryland agriculture and resource-poor regions. However, despite its agronomic potential, mungbean yields in many South Asian countries, including Nepal, remain well below the genetic potential due to suboptimal nutrient management and limited input responsiveness. Conventional mungbean cultivation in South Asia has relied heavily on inorganic fertilizers such as urea and diammonium phosphate (DAP), which are often applied indiscriminately without consideration for nutrient losses, soil conditions, or long-term sustainability. In high-rainfall or poorly managed systems, nutrient use efficiency is alarmingly low-estimated losses reach 40-70% for nitrogen, 80-90% for phosphorus, and 50-90% for potassium- resulting in financial losses, eutrophication, and degradation of soil microbial communities (Mandal *et al*., 2023; Tomar and Bhatnagar, 2023).

Prolonged use of chemical fertilizers has been associated with declining soil fertility, acidification, and loss of beneficial soil organisms. To address the inefficiencies of conventional urea, the introduction of Nano Urea, a novel liquid fertilizer containing nanoscale nitrogen particles, has emerged as a promising alternative. It enables higher nutrient absorption due to its increased surface area and targeted delivery, thereby reducing nitrogen losses and environmental contamination. According to recent studies, a 500 mL bottle of Nano Urea can potentially replace a 45 kg bag of conventional urea when applied properly, significantly improving nitrogen use efficiency and lowering input costs. In contrast, organic nutrient sources such as farmyard manure, compost, and crop residues contribute to improved soil aggregation, water-holding capacity, and microbial activity while supplying nutrients in synchrony with crop demand (Subedi and Yadav, 2013). Biofertilizers, especially *Rhizobium* and phosphate-solubilizing bacteria (PSB), enhance nutrient acquisition, root architecture, and stress tolerance in legumes. These microbial inputs improve nitrogen and phosphorus availability through biological fixation and mineral solubilization and help mitigate the adverse effects of chemical inputs on soil health and the environment (Kishor *et al*., 2021; Chamuah *et al*., 2023). Although various nutrient sources have been tested individually, limited research has focused on the comparative and interactive effects of organic, inorganic, and biological inputs on mungbean performance under field conditions. Given the urgent need to transition toward more sustainable crop nutrition strategies, understanding how mungbean responds to different nutrient regimes is essential for maximizing yield while conserving soil and ecological resources.

Therefore, the present study was conducted to evaluate the effects of organic, inorganic, and biofertilizer nutrient sources on the growth, yield attributes, and productivity of mungbean (*Vigna radiata* L.).

2. Materials and Methods

Site selection

The field experiment was conducted at the Directorate of Agricultural Research (DoAR), Tarahara, Sunsari, under the Nepal Agricultural Research Council (NARC), located in the eastern Terai region of Nepal. The experimental site is situated at an altitude of 130 meters above sea level, with geographical coordinates of 26°70’45’’ North latitude and 87°28’11’’ East longitude. During the study period, the area received an average rainfall of 481.9 mm, and the maximum and minimum recorded temperatures were 38.7°C and 11°C, respectively.

Soil sample collection and analysis

Before sowing the crop, a composite soil sample was collected from the upper 0-25 cm depth of the experimental field to determine its initial physico-chemical properties. The sample was air-dried, ground, and passed through a 2-mm sieve before analysis. Standard laboratory protocols were followed to analyze various soil properties. Total nitrogen was determined using the Kjeldahl digestion method, while available phosphorus was assessed using the Olsen method. Available potassium was measured using the ammonium acetate extraction technique. Soil pH was measured using a 1:2.5 soil-to-water suspension with a potentiometer, and soil organic matter content was determined using the Walkley and Black rapid titration method. The soil texture, including the percentage of sand, silt, and clay, was analyzed using the Bouyoucos hydrometer method. The general characteristics of the soil at the experimental site are presented in Table 1.

Table 1 - Soil chemical and physical properties with parameters and methods adopted for laboratory analysis at DoAR, Tarahara, Sunsari, 2024

Parameters	Units	Method	Analysis result
Total nitrogen	%	Kjeldahl Digestion	0.14
Available P_2O_5	ppm	Olsen	13.6
Available K_2O	ppm	Ammonium acetate	38.5
pH	-	Potentiometric 1:2.5	6.37
Soil organic matter	%	Walkley and Black	2.73
Textural class	-	Bouyoucos Hydrometer	Silty clay loam

Source: DoAR, Tarahara, Sunsari, NARC.

Experimental design and layout details

The experiment was laid out using a Randomized Complete Block Design (RCBD) with three replications and nine treatments. A total of 27 experimental units were established, each measuring 3×2 m², within a total field area of 242 m². To minimize inter-plot interference, a spacing of 1 meter was maintained between replications and 50 centimetres between individual plots within each replication.

Treatment details

The experimental design consisted of nine treatments, each arranged in three replicates, as detailed in Table 2.

Table 2 - Treatments for field trial conducted at DoAR, Tarahara, Sunsari

SN	Treatments
T1	Control
T2	Recommended dose of PNs through urea, DAP and MOP (N: P_2O_5: K_2O @ 20: 40: 20 kg/ha)
T3	Foliar spray @ 2000 mL/acre per spray at 25 and 45 DAS with Nano urea
T4	Foliar spray @ 2000 mL/acre per spray at 25 and 45 DAS with Nano DAP
T5	Farmyard manure @ 10 t/ha
T6	1/2 of T2 +1/2 of T5
T7	*Rhizobium* @ 25 mL/kg seed + 100% phosphorus and potassium through SSP and MOP (N: P_2O_5: K_2O @ 0:40:20 kg/ha)
T8	PSB @ 25mL/kg seed + 100% nitrogen through urea (N@ 20 kg/ha)
T9	*Rhizobium* @ 25 mL/kg seed + Treatment with PSB @ 25 mL/kg seed

Cultural practices and treatment applications

After harvesting the previous crop, the experimental field was prepared by crushing soil clods and achieving a fine tilth using a rotavator. The land was levelled, and all weeds and stubbles were removed. The plots were laid out according to the experimental design, slightly raised to prevent waterlogging, and a surrounding furrow was dug to ensure proper drainage during rainfall.

Mungbean variety ‘Pratigya’ was used in this experiment, with breeder seeds sourced from the Grain Legume Research Program, NARC, Khajura, Banke.

Seeds were soaked in water for 12 hours, air-dried under shade for 3 hours, moistened with jaggery solution, and treated with *Rhizobium* and PSB @ 25 ml/kg seed, specifically for treatments 7, 8, and 9. Sowing was done by maintaining a spacing of 30 cm between rows and 10 cm between plants, with one plant per hill and 200 plants per plot. Replications were spaced at 1 meter and treatments at 50 cm. Irrigation was applied lightly from germination to pod development at 7-10-day intervals, totalling 3-4 irrigations depending on soil type and environmental conditions. Fertilizers were applied on a net plot basis, where different NPK doses were used in treatments 2, 6, 7, and 8 using granular Urea, MOP, and DAP. Foliar sprays of nano urea and nano DAP were applied at 25 and 45 DAS in treatments 3 and 4. FYM was applied as a basal dose in treatments 5 and 6. Details about the treatment applications are presented in Table 3.

Data observation and collections

For data collection, five plants were randomly selected from each treatment plot, and observations were recorded on both vegetative and reproductive parameters. Vegetative parameters included plant height, number of branches, number of trifoliate leaves, total number of nodules, and number of effective nodules. Reproductive parameters included days to first flowering, days to 50% flowering, average number of pods per plant, average pod length, grain yield, straw yield, and biological yield. All data were recorded from field observations, and averages were calculated accordingly.

Statistical analysis

Data entry and preliminary processing were conducted using Microsoft Office Excel 2019 (Professional Plus). Statistical analyses were performed using RStudio (version 4.1.1), where Analysis of Variance (ANOVA) was employed to evaluate the significance of treatment effects, and mean separation was carried out using the Least Significant Difference (LSD) test at a 5% probability level. Additionally, correlation and regression analyses were conducted in RStudio to examine the strength and nature of relationships between dependent and independent variables, thereby providing deeper insights into treatment responses and underlying patterns in the data.

Table 3 - Description of treatments applied during field trial at DoAR, Tarahara, Sunsari

SN	Basal (Before sowing)	25 DAS	45 DAS
T1	-	-	-
T2	4.8 g Urea, 44.6 g DAP and 17.1 g MOP was applied in the soil before sowing.	-	-
T3	-	Nano urea was sprayed @ 2.53 ml/L water.	Nano urea was sprayed @ 2.53 ml/2L water.
T4	-	Nano DAP was sprayed @ 2.53 ml/L water.	Nano DAP was sprayed @ 2.53 ml/L × 2 water.
T5	17.1 kg FYM was applied in the soil before sowing.	-	-
T6	2.4 g Urea, 22.3 g DAP and 8.55 g MOP + 8.55 kg FYM was applied in the soil before sowing.	-	-
T7	Treatment with *Rhizobium* @ 0.35 ml/14 g seed + 128 g SSP and 17.1 g MOP was applied in the soil before sowing.	-	-
T8	Treatment with PSB @ 0.35 ml/14 g seed + 4.8 g Urea was applied in the soil before sowing.	-	-
T9	Treatment with PSB @ 0.35 ml per 14 g seed + Treatment with *Rhizobium* @ 0.35 ml per 14 g seed.	-	-

3. Results

Effect of different fertilizer combinations on vegetative and reproductive traits of mungbean

Plant height. The application of different nutrient management practices induced significant variation in plant height, reflecting the role of nutrient availability in driving vertical vegetative growth, as presented in Table 4. The tallest plants were recorded in the N:P:K treatment (64.87 cm), closely followed by ½ N:P:K + ½ FYM (64.77 cm) and FYM (63.87 cm). These treatments outperformed all others, indicating that both chemical fertilizers and integrated nutrient management approaches significantly enhanced vertical growth. Other treatments such as Nano DAP (61.33 cm), *Rhizobium* + PSB (61.10 cm), Nano urea (60.63 cm), and *Rhizobium* + P:K (60.63 cm) showed intermediate results. PSB + N produced slightly shorter plants (58.90 cm), while the Control exhibited the lowest height (55.37 cm), suggesting that lack of supplementation substantially limits vegetative development.

Number of branches per plant. Nutrient treatments exhibited a moderate but significant effect on the development of lateral branches, indicating that specific nutrient regimes can influence plant architecture through enhanced axillary bud initiation. The highest branching was observed under Nano DAP (5.60), followed by Nano urea (5.53), *Rhizobium* + P:K (5.47), and ½ N:P:K + ½ FYM (5.33). These treatments encouraged vigorous branching, supporting the role of nano and integrated nutrient inputs in promoting lateral shoot development. Other effective treatments included FYM and N:P: K (both 5.27), *Rhizobium* + PSB (5.23), and PSB + N (5.13). The Control treatment had the lowest branch count (4.77), emphasizing the limited growth potential in the absence of supplemental nutrients.

Number of Trifoliate leaves per plant. Although statistically non-significant, differences in trifoliate leaf count across treatments reflect trends in canopy expansion and photosynthetic surface area in response to varying nutrient inputs. The highest values were recorded in Nano DAP (7.17), FYM (7.07), and PSB + N (6.87), suggesting a potential positive effect on leaf development. Other treatments with substantial leaf counts included *Rhizobium* + P:K (6.80), N:P:K (6.70), and *Rhizobium* + PSB (6.53). The Control had the lowest number of trifoliate leaves (6.03), reflecting minimal canopy expansion without nutrient input. While these differences were not statistically significant, the trend suggests that enhanced nutrient availability, especially through biofertilizers and nano sources, may support greater foliar development.

Total number of nodules per plant. Nutrient management practices had a profound impact on total nodulation, with biological and integrated treatments demonstrating significantly enhanced symbiotic activity ($P<0.001$). The highest nodule count was recorded under *Rhizobium* + P:K (52.67),

Table 4 - Effect of different fertilizers on growth parameters of mungbean

Treatments	Plant height	No. of branches	No. of trifoliate leaves	Total no. of nodules	No. of effective nodules
Control	55.37 d	4.77 c	6.03 b	21.33 e	16.73 c
N: P: K	64.87 a	5.27 ab	6.70 ab	23.20 de	22.70 bc
Nano urea	60.63 bc	5.53 ab	6.37 ab	29.53 cd	25.27 b
Nano DAP	61.33 b	5.60 a	7.17 a	32.93 bc	27.13 b
FYM	63.87 a	5.27 ab	7.07 a	26.00 cde	22.23 bc
½ N: P: K + ½ FYM	64.77 a	5.33 ab	6.57 ab	31.93 bc	26.33 b
Rhizobium + P: K	60.63 bc	5.47 ab	6.80 ab	52.67 a	45.73 a
PSB + N	58.90 c	5.13 bc	6.87 a	32.00 bc	27.40 b
Rhizobium + PSB	61.10 bc	5.23 ab	6.53 ab	38.87 b	28.93 b
P value	<0.001	0.03	0.18	<0.001	<0.001
LSD (0.05)	2.37	0.45	0.81	7.48	7.81
SE_m (±)	0.26	0.05	0.09	0.83	0.87
CV (%)	2.24	4.86	7.03	13.49	16.75
Grand Mean	61.27	5.29	6.68	32.05	26.94

followed by *Rhizobium* + PSB (38.87). These results highlight the superior nodulation induced by microbial inoculants. Moderate nodulation was observed in treatments such as Nano DAP (32.93), PSB + N (32.00), and ½ N:P:K + ½ FYM (31.93), while Nano urea (29.53), FYM (26.00), and N:P:K (23.20) showed slightly lower counts. The Control treatment resulted in the fewest nodules (21.33), reinforcing the importance of both chemical and biological nutrient inputs in promoting effective rhizobial symbiosis.

Number of effective nodules per plant. The number of effective nodules, a critical parameter for evaluating biological nitrogen fixation, was markedly influenced by the applied nutrient regimes (P < 0.001). *Rhizobium* + P:K recorded the maximum number of effective nodules (45.73), clearly outperforming all other treatments. Other nutrient regimes with strong performance included *Rhizobium* + PSB (28.93), PSB + N (27.40), Nano DAP (27.13), and ½ N:P:K + ½ FYM (26.33). Slightly lower but still improved values were seen in Nano urea (25.27), N:P:K (22.70), and FYM (22.23). The Control again showed the lowest performance (16.73), indicating minimal nitrogen fixation potential without inoculation or nutrient application. These findings underscore the pivotal role of *Rhizobium* inoculation and integrated nutrient management in enhancing nodulation efficiency and biological nitrogen fixation.

Days to first flowering. Nutrient management practices significantly influenced the onset of reproductive development, as indicated by differences in the days to first flowering (P= 0.02). The earliest flowering was observed in the Control (31 days), *Rhizobium* + P:K (31 days), and Nano DAP (31 days), indicating that these treatments hastened the transition from vegetative to reproductive stages (Table 5). Slightly delayed flowering was recorded under Nano urea, PSB + N, and *Rhizobium* + PSB (all 32 days), suggesting a minimal extension of the vegetative phase. The most delayed flowering occurred with FYM (33 days) (Table 5), which differed significantly from the control, likely due to slower nutrient mineralization and availability from organic sources. These findings imply that nutrient form and bioavailability distinctly affect phenological shifts, with quicker nutrient uptake supporting earlier flowering.

Days to 50% Flowering. A highly significant treatment effect was recorded for days to 50% flowering (P<0.01), suggesting that nutrient regimes considerably impact the synchrony and uniformity of flowering. The earliest attainment of 50% flowering was noted in the Control group (35 days), while the most delayed response was observed in *Rhizobium* + PSB (38 days) (Table 5). Treatments such as FYM (37 days) and PSB + N (37 days) also exhibited delayed flowering, likely reflecting the gradual nutrient release associated with organic or biofertilizer amendments. In contrast, quicker flowering responses were seen in N:P:K, Nano DAP, Nano urea, ½ N:P:K + ½ FYM, and *Rhizobium* + P: K, all of which achieved 50% flowering in 36 days (Table 5). These results highlight the nuanced influence of nutrient form and microbial activity on flowering dynamics. While quicker responses may be favored in short-duration crops, delayed and synchronized flowering from microbial-enhanced treatments could be advantageous for yield stability.

Table 5 - Response of different fertilizers on flowering days

Treatments	Days to first flowering	Days to 50% flowering
Control	31 c	35 d
N: P: K	32 bc	36 bcd
Nano urea	32 ab	36 cd
Nano DAP	31 bc	36 bcd
FYM	33 a	37 ab
½ N: P: K + ½ FYM	32 bc	36 bcd
Rhizobium + P: K	31 bc	36 bcd
PSB + N	32 ab	37 abc
Rhizobium + PSB	32 ab	38 a
P value	0.02	<0.01
LSD (0.05)	1.07	1.42
SE_m (±)	0.12	0.16
CV (%)	1.95	2.25
Grand Mean	31.74	36.48

Pod length. Pod length was not significantly affected by the different nutrient management practices (P= 0.62), suggesting that this parameter may be genetically regulated and less responsive to nutrient variation under the given conditions. Despite the lack of statistical significance, numerical differences were evident. The longest pods were recorded under ½ N:P:K + ½ FYM (8.52 cm), *Rhizobium* + PSB (8.44 cm), and Nano DAP (8.40 cm), which exceeded the grand mean of 8.11 cm. Treatments such as FYM (8.11 cm), *Rhizobium* + P:K (8.22 cm), and N:P:K (8.01 cm) also yielded relatively long pods. The shortest pod length was observed in the Control (7.62 cm), underscoring a trend toward enhancement with nutrient supplementation, though not statistically confirmed (Table 6).

Number of pods per plant. Nutrient application significantly influenced the number of pods per plant (P<0.001), indicating a strong response of reproductive capacity to improved nutrition. The highest pod count was observed under Nano DAP (28.83), followed by ½ N:P:K + ½ FYM (27.87), both of which were statistically superior to the Control (20.40), which had the lowest pod number. Treatments such as N:P:K (26.93), *Rhizobium* + P:K (26.37), and *Rhizobium* + PSB (25.87) also performed well, with values above the grand mean (25.80) (Table 6). This suggests that integrated and nano-based nutrient sources play a pivotal role in enhancing reproductive output, likely due to better nutrient availability and physiological stimulation during flowering and pod development.

Number of seeds per pod. Seed number per pod exhibited significant variation among treatments (P = 0.04), reflecting a treatment effect on internal pod development and fertility. The maximum number of seeds per pod was observed in Nano urea (11.47), Nano DAP (11.40), and *Rhizobium* + P:K and PSB + N (both 10.53). These were followed by N:P:K and FYM (10.33), all of which surpassed the grand mean (10.47). Lower seed set was recorded under *Rhizobium* + PSB (9.80) and Control (9.53), the latter representing the statistically lowest value (Table 6). These results highlight the positive influence of nano-nitrogen and biofertilizer-based treatments in enhancing seed formation within pods.

Test weight. Test weight was significantly influenced by nutrient management practices (P<0.001), indicating a substantial impact on seed size and density. The highest test weight was recorded under ½ N:P:K + ½ FYM (38.90 g), followed closely by Nano DAP (38.77 g), both of which were significantly superior to other treatments. N:P:K (37.83 g), Nano urea (37.57 g), and FYM and *Rhizobium* + P:K (both 37.50 g) showed comparable values around the grand mean (37.47 g) (Table 6). The Control treatment had the lowest seed weight (35.07 g), indicating that nutrient deprivation not only reduces reproductive output but also limits seed filling and maturity. These findings emphasize that combined or nano-based nutrient sources are more effective in improving seed quality through enhanced metabolic activity during grain filling.

Grain yield. Grain yield was significantly influenced by nutrient management treatments (P< 0.001), reflecting the strong impact of nutrient availability and uptake efficiency on reproductive productivity. The highest grain yield was recorded under Nano DAP (2030.02 kg/ha), followed by ½ N:P:K + ½ FYM (1912.00 kg/ha) and *Rhizobium* + P:K (1881.60 kg/ha). These yields were significantly higher than the Control (1094.85 kg/ha), which recorded the lowest performance. Other treatments such as N:P:K (1828.31 kg/ha), PSB + N (1775.39 kg/ha), *Rhizobium* + PSB (1771.63 kg/ha), and Nano urea (1755.67 kg/ha) also performed well, exceeding the grand mean of 1755.53 kg/ha (Table 7). These

Table 6 - Effect of different fertilizers on reproductive traits of mungbean

Treatment	Pod length (cm)	No. of pods/plant	No. of seeds/pod	Test weight (g)
Control	7.62 a	20.40 d	9.53 c	35.07 d
N: P: K	8.01 a	26.93 abc	10.33 abc	37.83 bc
Nano urea	7.94 a	25.00 c	11.47 a	37.57 c
Nano DAP	8.40 a	28.83 a	11.40 ab	38.77 ab
FYM	8.11 a	25.50 bc	10.33 abc	37.50 c
½ N: P: K + ½ FYM	8.52 a	27.87 ab	10.27 bc	38.90 a
Rhizobium + P: K	8.22 a	26.37 abc	10.53 abc	37.50 c
PSB + N	7.72 a	25.40 bc	10.53 abc	37.07 c
Rhizobium + PSB	8.44 a	25.87 bc	9.80 c	37.07 c
P value	0.62	<0.001	0.04	<0.001
LSD (0.05)	1.07	2.64	1.17	1.05
SE_m (±)	0.12	0.29	0.13	0.12
CV (%)	7.68	5.92	6.44	1.62
Grand Mean	8.11	25.80	10.47	37.47

Table 7 - Effect of different fertilizers on yield traits of mungbean

Treatment	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest Index
Control	1094.85 e	1955.71 c	35.91 ab
N: P: K	1828.31 bcd	3992.74 a	31.41 c
Nano urea	1755.67 cd	3611.25 a	32.71 bc
Nano DAP	2030.02 a	4026.04 a	33.54 bc
FYM	1750.33 d	3610.46 a	32.65 bc
½ N: P: K + ½ FYM	1912.00 ab	3085.84 b	38.27 a
Rhizobium + P: K	1881.60 bc	3886.01 a	32.72 bc
PSB + N	1775.39 cd	2922.01 b	37.81 a
Rhizobium + PSB	1771.63 cd	3163.91 b	36.14 ab
P value	<0.001	<0.001	<0.01
LSD (0.05)	129.95	438.27	3.56
SEm (±)	14.45	48.73	0.40
CV (%)	4.28	7.53	5.95
Grand Mean	1755.53	3361.55	34.57

results underscore the effectiveness of combining nano-formulations, organic matter, and microbial inoculants in boosting grain yield.

Straw yield. Straw yield varied significantly across treatments (P<0.001), indicating differential impacts of nutrient regimes on vegetative biomass accumulation. The highest straw yields were observed under Nano DAP (4026.04 kg/ha), N:P:K (3992.74 kg/ha), and *Rhizobium* + P:K (3886.01 kg/ha). These treatments significantly outperformed the Control (1955.71 kg/ha), which had the lowest biomass. Nano urea (3611.25 kg/ha) and FYM (3610.46 kg/ha) also contributed to elevated straw production, further suggesting that both mineral and microbial sources enhance total plant biomass. Lower straw yields in PSB + N (2922.01 kg/ha) and ½ N:P:K + ½ FYM (3085.84 kg/ha) were still statistically superior to the control, but below the highest performers (Table 7).

Harvest Index (HI). Harvest Index, representing the proportion of economic yield (grain) to total above-ground biomass, was also significantly influenced by nutrient regimes (P<0.01). The highest HI was observed in ½ N:P:K + ½ FYM (38.27) and PSB + N (37.81), suggesting more efficient partitioning of assimilates toward grain production. These were statistically superior to N:P:K (31.41), which showed the lowest HI despite its high biological yield, indicating a vegetative bias. Other treatments showed moderate HI values: *Rhizobium* + PSB (36.14), Control (35.91), Nano DAP (33.54), *Rhizobium* + P: K (32.72), Nano urea (32.71), and FYM (32.65) (Table 7). These values imply that integrated and biologically enriched nutrient practices can improve reproductive efficiency alongside yield enhancement.

Economic analysis

The gross return and B:C ratio varied significantly among treatments, reflecting the diverse economic responses to different nutrient management strategies, as presented in Table 8. The highest gross return was recorded under Nano DAP (Rs. 446,604.4), which also produced the highest B:C ratio of 2.24, establishing it as the most economically

Table 8 - Gross returns and B:C ratio under different fertilizer regimes

Treatments	Fertilizer cost (Rs)	Total Cost (Rs)	Gross returns (Rs)	Net returns (Rs)	B:C ratio
Control	0.00 i	180000.0 i	240866.3 e	60866.27 d	1.34 c
N: P: K	6687.50 f	186687.5 f	402228.9 bcd	215541.43 bc	2.15 ab
Nano urea	7907.09 e	187907.1 e	386248.9 cd	198341.78 c	2.06 b
Nano DAP	18977.02 a	198977.0 a	446604.4 a	247627.38 a	2.24 a
FYM	10000.00 c	190000.0 c	385072.6 d	195072.60 c	2.03 b
½ N: P: K + ½ FYM	8343.75 d	188343.8 d	420640.7 ab	232296.98 ab	2.23 a
Rhizobium + P:K	14274.36 b	194274.4 b	413952.0 bc	219677.64 abc	2.13 ab
PSB + N	346.86 g	180346.9 g	390585.8 cd	210238.94 bc	2.17 ab
Rhizobium + PSB	218.72 h	180218.7 h	389759.3 cd	209540.61 bc	2.16 ab
P value	<0.001	<0.001	<0.001	<0.001	<0.001
LSD (0.05)	0	0	28588.61	28588.61	0.1532
SEm (±)	0	0	3,18E+06	3,18E+06	0.017
CV (%)	6,11E-08	6.91	4.28	8.31	4.30
Grand Mean	7.417.256	187417.3	386217.7	198800.4	2.06

rewarding treatment. This was closely followed by ½ N:P:K + ½ FYM, which yielded a gross return of Rs. 420,640.7 and a B:C ratio of 2.23, statistically comparable to Nano DAP and economically efficient due to balanced input costs and strong yield performance. Other high-performing treatments included *Rhizobium* + P:K (Rs. 413,952.0, B:C 2.13), N:P:K (Rs. 402,228.9, B:C 2.15), PSB + N (Rs. 390,585.8, B:C 2.17), and *Rhizobium* + PSB (Rs. 389,759.3, B:C 2.16). These treatments demonstrated statistically similar B:C ratios ranging from 2.13 to 2.17, indicating high profitability per rupee invested, especially when biofertilizers were involved. Notably, PSB + N and *Rhizobium* + PSB achieved excellent economic returns at minimal fertilizer costs (Rs. 346.86 and Rs. 218.72, respectively), enhancing their appeal in low-input farming systems. Nano urea (Rs. 386,248.9, B:C 2.06) and FYM (Rs. 385,072.6, B:C 2.03) delivered moderate gross returns and profitability, slightly below the grand mean of gross return (Rs. 386,217.7) and B:C ratio (2.06), suggesting reasonable efficiency but not on par with integrated or nano-enhanced combinations. In contrast, the lowest economic performance was recorded in the Control treatment, with a gross return of only Rs. 240,866.3 and a B:C ratio of 1.34. This clearly indicates that the absence of fertilizer input severely limits productivity and economic gain, making it the least viable option for sustainable cultivation.

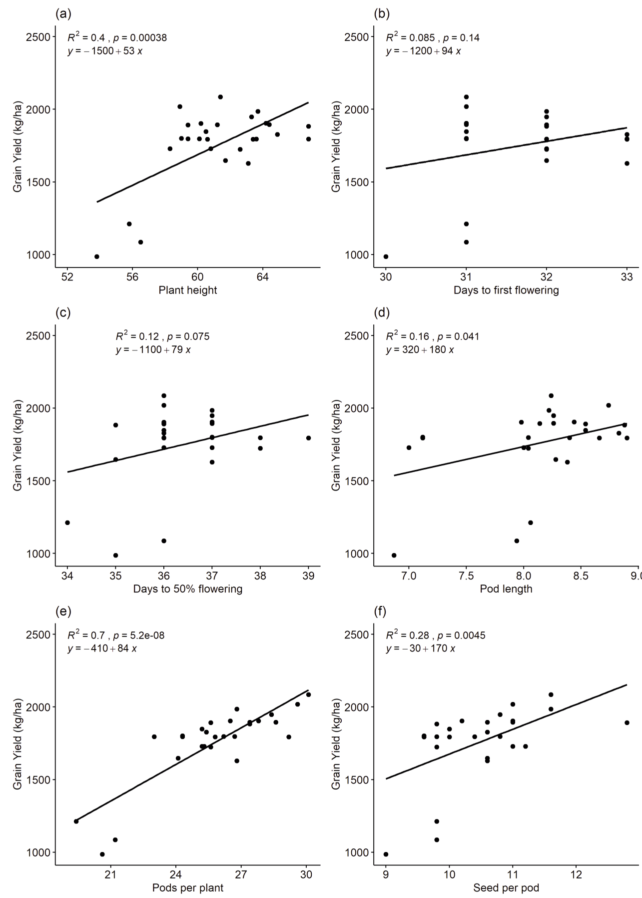

Fig. 5 - Coefficient of determination (R2), Linear regression equation, and scatter diagram showing the fitted simple regression line of Y (Yield) on X (a) Plant height, (b) Days to 1st flowering, (c) Days to 50% flowering, (d) Pod length, (e) Pods per plant, (f) Seeds per pod.

Regression analysis

Figures 5 and 6 present twelve scatterplots (a-f in each), showing the fitted simple linear regression of grain yield (Y, in kg/ha) against various plant traits (X), each with its regression equation, R^2 value, and p-value to assess the strength and significance of the relationship. In Figure 5, plot (a) shows a moderately strong and significant positive relationship between plant height and yield (R^2= 0.4, p= 0.00038), indicating that nutrient sources, particularly those enhancing vegetative growth, may improve yield by supporting taller, more vigorous plants. Plots (b) and (c) display weak, non-significant positive correlations between days to first flowering (R^2= 0.085, p= 0.14) and days to 50% flowering (R^2= 0.12, p= 0.075) with yield, suggesting that flowering time was minimally affected by nutrient treatments. This likely reflects that nutrient inputs influenced biomass and yield more than flowering behaviour, and that environmental conditions during flowering remained relatively stable. Plot (d) shows a weak but significant positive relationship between pod length and yield (R^2= 0.16, p = 0.041), implying a modest contribution of pod development to yield, possibly supported by improved nutrient uptake. Plot (e) reveals the strongest relationship, where pods per plant are highly correlated with yield (R^2= 0.7, p= 5.2e−08), suggesting nutrient-driven enhancement of reproductive capacity. Plot (f) shows a moderate, significant positive relationship between seeds per pod and yield (R^2= 0.28, p= 0.0045), indicating improved seed setting under nutrient-rich conditions. In figure 6, plot (a) indicates a moderately strong, significant positive correlation between branches per plant and yield (R^2= 0.46, p= 9.7e−05), showing that nutrient sources promoting branching can boost photosynthetic area and yield potential. Plot (b) shows a strong, highly significant association between test weight and yield (R^2= 0.67, p= 1.8e−07),

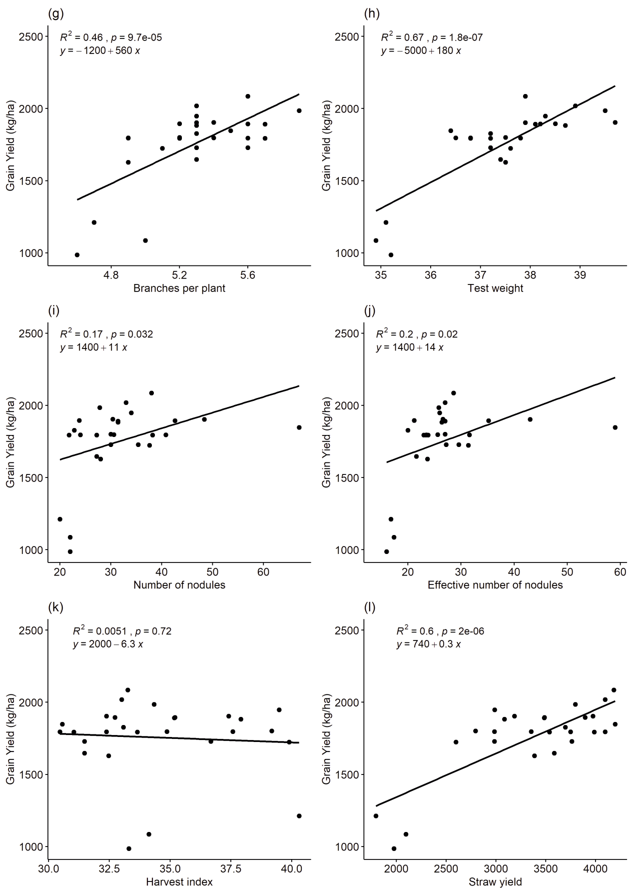

Fig. 6 - Coefficient of determination (R2), Linear regression equation, and scatter diagram showing the fitted simple regression line of Y (Yield) on X (a) Branches per plant, (b) Test weight, (c) Number of nodules, (d) Effective number of nodules, (e) Harvest index, (f) Straw yield.

reflecting that better nutrient supply enhances seed filling and grain quality. Plots (c) and (d) show weak to moderate but significant positive correlations between number of nodules (R^2= 0.17, p= 0.032) and effective nodules (R^2= 0.20, p= 0.02) with yield, indicating that biofertilizers supporting root nodulation and nitrogen fixation contribute to productivity. Plot (e) shows a very weak, non-significant negative relationship between harvest index and yield (R^2= 0.0051, p= 0.72), suggesting that nutrient sources affected both vegetative and reproductive growth similarly, resulting in little variation in partitioning. Finally, plot (f) presents a strong, significant positive correlation between straw yield and grain yield (R^2= 0.60, p= 2e−06), highlighting that higher total biomass, driven by improved nutrient availability, supports better grain output. Overall, the results indicate that nutrient sources, particularly those improving biomass, branching, pod formation, and seed filling, play a critical role in enhancing mungbean yield, while traits such as flowering time and harvest index show limited responsiveness to nutrient-based interventions.

4. Discussion and Conclusions

The application of diverse nutrient management practices induced notable variation in the growth, phenology, and yield attributes of mungbean, reflecting the critical influence of nutrient form and availability on plant development. Treatments involving Nano DAP and ½ N:P:K + ½ FYM produced substantial improvements in plant height, number of branches, and leaf count. The superior plant height under RDF and FYM can be attributed to the immediate nutrient availability in chemical fertilizers and the sustained release and microbial stimulation provided by organic amendments, enhancing photosynthetic activity and chlorophyll formation. Similar findings were reported by Kumar *et al*. (2015), and Rifhat *et al*. (2023), who observed that integrated nutrient management significantly enhanced vegetative growth in mungbean and other pulses. The integrated use of organic and inorganic fertilizers ensures both quick and sustained nutrient release, supporting continuous vegetative and root development. Moreover, the Nano DAP treatment recorded the highest number of lateral branches and trifoliate leaves, likely due to its nanoscale particle size and large surface area that enhance nutrient penetration, enzymatic activity, and chloroplast function (Chamuah *et al*., 2023). Although differences in leaf number were statistically non-significant, the numerical superiority of Nano DAP and FYM indicates improved canopy development and photosynthetic surface area. This observation agrees with Bam *et al.* (2022), who noted that balanced nutrient supply and nano-based interventions stimulate foliage expansion and carbohydrate accumulation in legumes. Root nodulation parameters, including total and effective nodules, were highest under biological treatments, particularly *Rhizobium* + P:K and *Rhizobium* + PSB. This outcome reflects successful symbiotic establishment and active nitrogen fixation under favorable microbial and nutrient conditions. Similar patterns were observed by Dipta *et al.* (2019), Bam *et al.* (2022), and Bhusal (2024), who demonstrated that *Rhizobium* inoculation with phosphorus and potassium supplementation enhances nodulation efficiency, nodule biomass, and root elongation. The dominance of pink nodules in inoculated plants confirms active nitrogen fixation, while the white or brown nodules in control plots suggest inactive or senescent nodules, consistent with Razzaque *et al*. (2016). Phenological traits such as days to flowering and days to 50% flowering were significantly affected by nutrient regimes. Earlier flowering observed under Nano DAP and *Rhizobium* + P:K treatments may be due to enhanced early nutrient uptake, metabolic efficiency, and hormonal stimulation, whereas delayed flowering under FYM suggests slower nutrient mineralization. These findings are in accordance with Bhardwaj *et al.* (2021) and Tomar and Bhatnagar (2023), who linked phenological advancement with improved nutrient assimilation and faster physiological maturity. Reproductive and yield attributes were also influenced by integrated and nano-fertilizer treatments. The highest pod number per plant in Nano DAP and ½ N:P:K + ½ FYM treatments may be attributed to improved nutrient partitioning, pollen viability, and pod retention. Similar yield improvements were documented by Dhakal *et al.* (2015), Verma *et al.* (2017), and Kishor *et al.* (2021), emphasizing the synergistic benefits of combined nutrient sources. Although pod length showed no significant variation, its numerical increase under Nano DAP and integrated treatments suggests partial enhancement due to nutrient-driven physiological vigor. Seed number per pod and test weight were significantly increased under Nano Urea, *Rhizobium* + P:K, and ½ N:P:K + ½ FYM treatments. These effects likely result from balanced nutrient availability promoting fertilization, pod filling, and seed development. Enhanced test weight under integrated and nano-nutrient treatments indicates better seed maturity and density, consistent with the findings of Hou *et al*. (2019) and Muchira *et al.* (2018). Grain and straw yields followed similar trends, with Nano DAP, *Rhizobium* + P:K, and ½ N:P:K + ½ FYM outperforming the control due to improved nutrient uptake, biomass accumulation, and assimilate translocation. Comparable outcomes were reported by Neupane *et al.* (2023), and Rijal *et al.* (2023), who confirmed that combined nutrient inputs significantly enhance legume productivity and resource use efficiency. The highest harvest index (HI) observed under ½ N:P: K + ½ FYM and PSB + N treatments indicate superior partitioning of assimilates toward economic yield. This validates the advantage of integrated nutrient management in optimizing both yield and nutrient use efficiency. From an economic standpoint, Nano DAP produced the highest benefit-cost ratio, followed by ½ N:P:K + ½ FYM, underscoring the profitability of integrating innovative and conventional nutrient strategies. Overall, the results highlight that while conventional fertilizers promote rapid initial growth, combining organic, biofertilizer, and nano-based sources provides a synergistic advantage by enhancing soil health, microbial activity, and nutrient use efficiency, leading to sustainable yield improvement. These findings reaffirm the conclusions of Dipta *et al*. (2019), Kishor *et al.* (2021), and Bam *et al*. (2022), emphasizing that integrated and nano-nutrient technologies can help achieve long-term soil fertility and productivity goals. Importantly, research on nano-based fertilizers in mungbean production within Nepal remains scarce. Future investigations should focus on optimizing nano-fertilizer formulations, dosages, and application timing under diverse agro-climatic conditions to validate their long-term effects on soil fertility, microbial dynamics, and crop productivity.

The field experiment demonstrated that nutrient management significantly influenced the growth, yield, and profitability of mungbean (*Vigna radiata* L.). Among the treatments, foliar application of nano Diammonium Phosphate (T4: 2000 ml/acre) produced the highest grain yield (2,030.02 kg/ha), pod number per plant (28.83), straw yield (4026.04 kg/ha), and benefit-cost ratio (2.24), highlighting its efficiency and high productivity potential. The integrated use of ½ recommended N:P:K (10:20:10 kg/ha) with ½ farmyard manure (5 t/ha) (T6) also performed well, offering a sustainable alternative that maintains high yields while improving soil fertility and microbial activity. Regression analysis confirmed that pod number per plant, test weight, and straw yield were strongly correlated with grain yield, emphasizing their importance as key determinants of productivity. These findings suggest that adopting integrated nutrient management, particularly combining nano-fertilizers or balanced chemical and organic sources, enhances crop performance and reduces environmental risks. It is recommended that farmers adopt T4 for rapid nutrient delivery and maximum yield, or T6 for sustainability and soil health benefits. Promotion through extension services, training, demonstration plots, and policy support can accelerate adoption.

Future research should validate these practices across multiple seasons and diverse agro-climatic zones to develop site-specific recommendations. Overall, integrated and eco-friendly fertilization approaches are essential for high-yielding, profitable, and sustainable mungbean production in Nepal.

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