RESEARCH

Effects of Integrated Nutrient Management on Growth, Nodulation, and Yield of Soybean [*Glycine max* (L.) Merr. var. Puja]

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Abstract

Inefficient fertilizer management is a major reason for the low soybean productivity in Nepal. This study conducted at an altitude of 811 meters in Baitadi, Nepal, examined the effects of integrated nutrient management on soybean growth, nodulation, and yield. Employing an RCBD experimental layout with 3 replications, the study evaluated 9 treatments, namely: Control, Rhizobium+100% PK, Rhizobium+50% RDF, Rhizobium+75% RDF, Vermicompost+50% RDF, Vermicompost+75% RDF, FYM+50% RDF, FYM+75% RDF, RDF (NPK @ 10:40:30 kg/ha). The results revealed that 'Rhizobium+100% PK' produced maximum plant height (140.8 cm), dry weight growth rate (2.89 gram/plant/day), nodule count (11.33), and nodule mass (0.55 gram). 'Rhizobium+75% RDF' produced the highest number of trifoliate leaves (62.78) and leaf area index (15.30). Furthermore, 'Vermicompost+50% RDF' resulted in a maximum fresh weight growth rate (7.86 gram/plant/day), 'RDF' resulted in the highest root diameter (12.89 mm), and 'FYM+75% NPK' produced highest 1000-grain weight (145.9 g). The treatments 'VC+75 % RDF' and 'Rhizobium+50 % RDF' stood out with a remarkable grain yield of 3.659 tons/ha and 3.642 tons/ha respectively. These two treatments were statistically indistinguishable regarding grain yield. The application of 'VC+75 % RDF' or 'Rhizobium+50 % RDF' can prove to be an effective way to enhance the productivity of soybean. However, the performance of soybean can vary depending on the variety, intercultural operations, environmental conditions, and residual nutrient status of the soil. Therefore, we recommend further research to solidify these findings.

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Statement of Sustainability: This research aims to promote the incorporation of organic, chemical, and biofertilizers in crop production. Through this measure, we can strengthen crop productivity, enhance soil microbiota, and reduce the hazardous effects of agrochemicals in our soil and the environment, which aligns with the motive of Sustainable Development Goals (SDGs) set by the United Nations (UN), particularly: Zero Hunger (SDG 2), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13). By adopting Integrated Nutrient Management (INM) strategies, we can contribute to environmental sustainability and a sound food system.

1. Introduction

The soybean (*Glycine max* (L.) Merr.) is a crop that originated in East Asia and belongs to the Fabaceae family, which comprises legumes. Soybeans are cultivated primarily for their high protein and oil content (Nout, 2015). They are one of the most concentrated plant-based sources of protein, with a protein and lipid content of 36.5% and 19.9%, respectively (USDA, 2018). A 100-gram serving of soybean provides 1870 kilojoules of energy and 9.3 grams of dietary fiber, according to data from the United States Department of Agriculture (USDA, 2018). It accounts for approximately two-thirds of the global protein concentrate for livestock (Agarwal et al., 2013). Integrated Nutrient Management (INM) is a comprehensive approach that integrates the use of organic, chemical, and biofertilizers (Selim, 2020). INM provides crops with the essential nutrients required for optimal growth and development, thereby enhancing crop productivity. As it minimizes the use of chemical fertilizers, it is an economically and environmentally sustainable approach to ensuring food security (Imran and Amanullah, 2023; Khan et al., 2022; Khalid et al., 2022; Nadia et al., 2023). The lower carbon footprint, capacity to sequester carbon in the soil, and diminished greenhouse gas emissions from synthetic fertilizers have rendered integrated nutrient management a highly desirable component of sustainable and climate-resilient agricultural systems (FAO and ITPS, 2016).

In Nepal during the 2021/22 agricultural year, soybeans were cultivated across 24,921 hectares, resulting in a production of 35,138 tons with a productivity of 1.41 tons per hectare (MoALD, 2023a). The productivity of soybeans is constrained by the limited use of fertilizers in legumes by Nepalese farmers. Furthermore, a comprehensive analysis of import and export statistics published by the Ministry of Industry, Commerce and Supply (MoICS, 2023) indicates that Nepal is a significant importer of crude soybean oil, which is then refined and subsequently exported as refined soybean oil. Notwithstanding the fact that refined soybean oil has been ranked as the first and fifth most exported commodity over the past two consecutive years, its direct contribution to the country's economy is not particularly noteworthy. This situation has arisen from the extensive import of crude soybean oil. It is therefore essential to enhance the productivity of soybeans within Nepal in order to bridge the gap between the export potential of refined soybean oil and the massive import of crude soybean oil. Furthermore, the use of fewer chemical fertilizers and the adoption of integrated nutrient management (INM) can enhance soil health and mitigate the adverse environmental impacts of agriculture (Abid et al., 2020; Antil and Raj, 2020), thereby addressing a global concern.

The objective of this research is to evaluate the efficacy of INM on a range of key agricultural parameters, including the number of trifoliate leaves per plant, plant height, Leaf Area Index (LAI), Crop Growth Rate (CGR), root diameter, nodule number, nodule mass, grain yield, and thousand-grain weight. The outcomes of this research are expected to provide valuable insights into the selection of appropriate combinations of organic and inorganic fertilizers for optimal growth and yield of soybean.

2. Material and Methods

2.1. Experimental Site

The research was conducted at the agronomy farm of Goukuleshwor Agriculture College in Dilasaini rural municipality of Baitadi, Nepal, from May 20 to October 18, 2022. The research site is located at an altitude of 811 meters above sea level. The site's geographical coordinates are 29.66 degrees north latitude and 80.54 degrees east longitude. The geographical coordinates of the research site are presented in Figure 1.

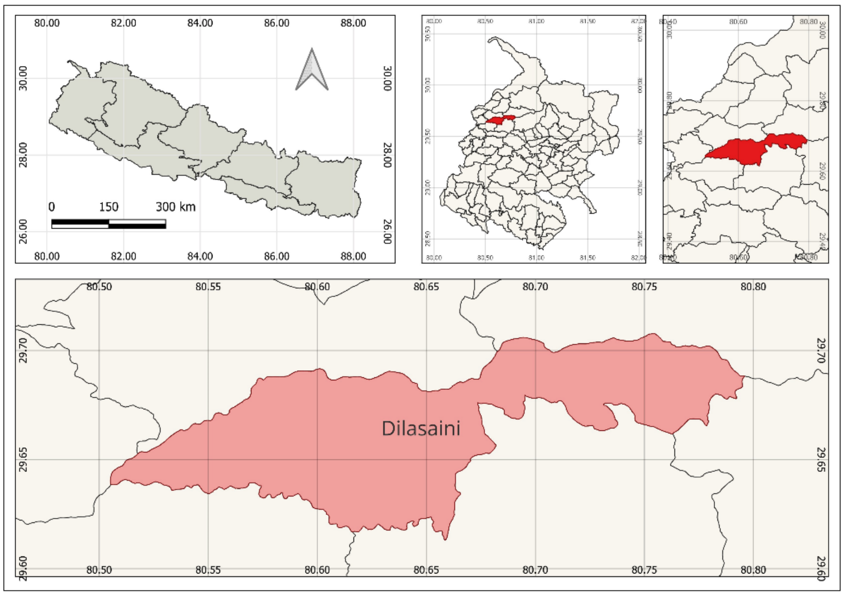

Figure 1. Location of the research site (Source: https://nationalgeoportal.gov.np).

2.2. Climate and Weather

The research was conducted in a subtropical climate, where the average rainfall and humidity were recorded at 5 mm/day and 73.3%, respectively, over the course of the research period. The mean temperature during the cropping season was 20.6°C. The climatic data for the research site throughout the research period are presented in Figure 2, which shows a bar diagram and line graph.

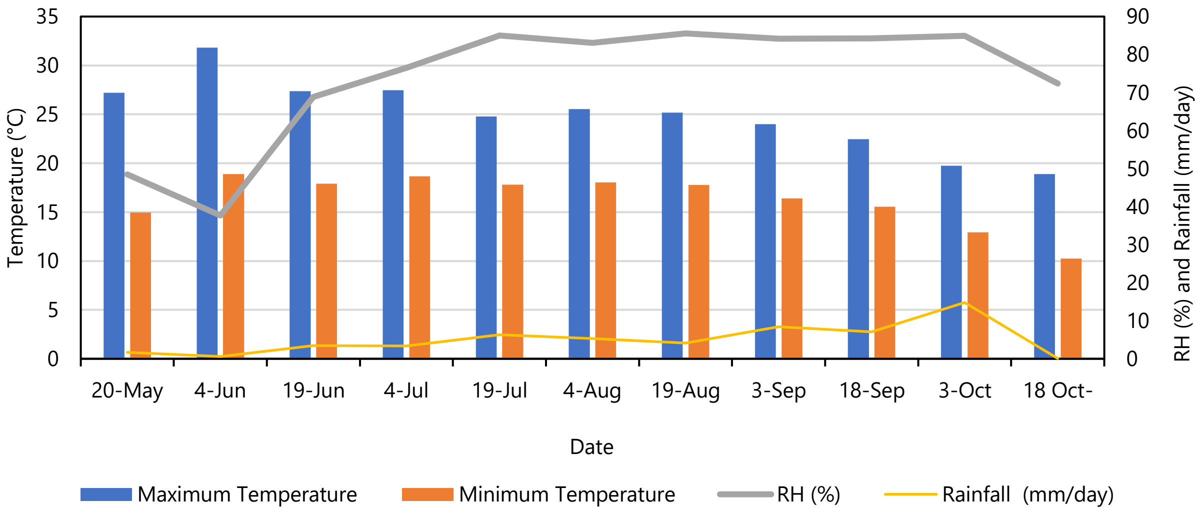

Figure 2. Climatic data of research site (Source: https://power.larc.nasa.gov).

2.3. Soil Properties at Research Site

A soil sample was collected from a depth of 0-15 cm and subsequently examined at the Soil and Fertilizer Testing Laboratory in Sundarpur, Kanchanpur, Nepal. The numerical values, remarks, and methods utilized to ascertain the physical and chemical properties of the soil are presented in Table 1.

Table 1. Physical and chemical properties of soil in the research site before the research.

Parameters	Value/ Remarks	Method of Determination
Texture	Sandy soil	Hydrometer jar method (Bouyoucos, 1962)
pH	5.38	Glass electrode digital pH meter (Mclean, 2015)
Organic Matter	1.6 %	Walkley-Black method (Walkley and Black, 1934)
Available Nitrogen	0.083%	Micro-Kjeldahl method (Jackson, 1967)
Available Phosphorous	129.66 kg/ha	Modified Olsen's bicarbonate method (Olsen et al., 1954)
Available Potassium	182.8 kg/ha	Neutral ammonium acetate flame photometer (Rajani, 2019)

2.4. Treatment Details

The study evaluated nine treatments, as detailed in Table 2. Farm Yard Manure (FYM) and Vermicompost (VC) were applied at a rate of 5,000 kg/ha and 2,000 kg/ha, respectively (MoALD, 2023b). The recommended dose of fertilizer (RDF) was 10:40:30 NPK kg/ha (MoALD, 2023b). For the treatments involving rhizobium, the seeds were treated separately with the rhizobium strain *Bradyrhizobium japonicum* (jaggery: water: rhizobium @ 5: 50: 25 g/kg seed).

Table 2. Treatments applied.

Notation	Treatments
T1	Control
T2	Rhizobium+100% PK
T3	Rhizobium+50% RDF
T4	Rhizobium+75% RDF
T5	VC+50% RDF
T6	VC+75% RDF
T7	FYM+50% RDF
T8	FYM+75% RDF
T9	RDF (NPK @ 10:40:30 kg/ha) (MoALD, 2023b)

N: Nitrogen, P: Phosphorous, K: Potassium, RDF: Recommended Dose of Fertilizer), VC: Vermicompost, FYM: Farm Yard Manure

2.5. Experimental Materials, Design, and Raising of Crop

Table 3 provides a detailed account of the experimental materials, design, and processes employed in the cultivation of the experimental crop. On the day of sowing, the seeds were pre-soaked in water for approximately half an hour, which was done 3-4 hours prior to the actual sowing process. For the treatments involving rhizobium (T2, T3, T4), rhizobium inoculation was conducted subsequent to pre-soaking. The process of seed inoculation of rhizobium entailed the dissolution of jaggery in boiling water (jaggery : water : rhizobium ratio of 5:50:25 g/kg seed). Once the mixture had cooled, the rhizobium was added, and the seeds were treated with the prepared solution.

Table 3. Details of the experimental materials, design, and raising of experimental crops.

Research variables	Details
Soybean variety	Puja
Seed type	Foundation
Field Layout	Randomized Complete Block Design (RCBD)
Number of replications	3
Number of treatments	9
Total number of plots	27
Individual plot size	3×2 m
Source of fertilizer	Urea, SSP, MOP
Fertilizer application date	19^{th} May, 2022
Rhizobium seed inoculation	20^{th} May 2022 (Only for treatments with rhizobium)
Sowing date	20^{th} May 2022
Sowing method	Manual dibbling
Spacing	40×7.5 cm (Chauhan and Opeña, 2013)
Sowing depth	5 cm
Weeding method	Manual with a hand hoe
Weeding time	25 DAS and 45 DAS

SSP: Single Super Phosphate, MOP: Muriate of Potash, DAS: Days After Sowing.

The experimental layout is depicted in Figure 3. Each plot consisted of five rows. The fourth row was designated a destructive row in each plot, allowing for the collection of data pertaining to parameters such as the number and mass of nodules, root diameter, and crop growth rate (CGR). To obtain data regarding plant height, the number of leaves, and leaf area, six plants were randomly selected from the first, second, third, and fifth rows at 30 days after showing (DAS).

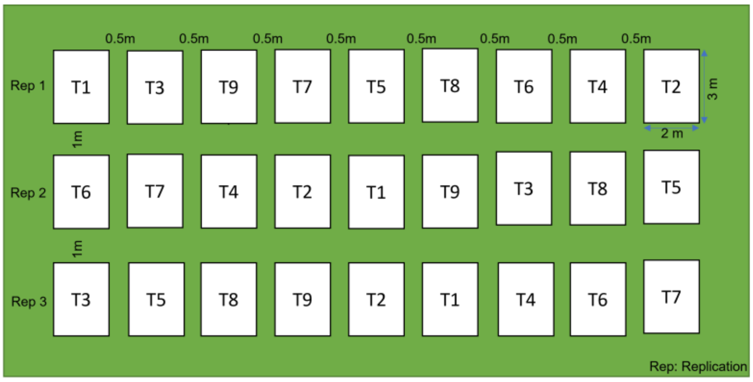

Figure 3. Experimental layout in Randomized Complete Block Design (RCBD).

2.6. Observation

2.6.1. Agro-morphological Characteristics

The morphological parameters included the number of leaves per plant, the height of the plant, and the leaf area. The aforementioned parameters were evaluated at 30, 45, 60, and 90 DAS. The measurements of plant height and leaf area were conducted using a ruler. For the measurement of leaf area, a randomly selected trifoliate leaf (a compound leaf) from each sample plant was utilized. The length of the leaflets was measured along the midrib, while the width was determined by taking measurements at the tip, middle, and base of the leaflets. The mean width of each leaflet was determined. The leaf area was subsequently determined on the basis of the aforementioned length and width measurements. Subsequently, the Leaf Area Index (LAI) was calculated using the following formula (Watson, 1947):

$$\text{LAI} = \frac{\text{Area of a trifoliate leaf} \times \text{Number of leaves in the plant}}{\text{Ground area occupied by the plant}}$$

2.6.2. Destructive Sample

The fourth row of each plot was designated as a destructive row for the assessment of various parameters, including the number of root nodules, the mass of root nodules, the root diameter, and the crop growth rate (CGR). These parameters were evaluated at 35, 70, and 105 DAS. Three plants were uprooted at each designated time interval (35, 70, and 105 DAS), resulting in a total of nine uproots throughout the research period. This was achieved by loosening the soil with water, thereby preventing any deterioration of the roots and nodules. The root mass and mass of effective root nodules were quantified using a precision balance, while the root diameter was determined with the aid of a Vernier caliper. To assess the crop growth rate (CGR; Watson, 1952), the initial step was to record the fresh weight of the plants, which was essential for calculating the fresh weight growth rate (FWGR). Subsequently, the plants were subjected to oven drying at 60°C for 24–48 hours to facilitate the calculation of the dry weight growth rate (DWGR).

$$\text{CGR (gram/plant/day)} = \frac{W_2 - W_1}{T_2 - T_1}$$

Here, for Fresh Weight Growth Rate (FWGR), W_2 = Fresh biomass of a plant (gram) at T_2, W_1 = Fresh biomass of a plant (gram) at T_1, T_2 = DAS at which the destructive sample was taken, T_1 = DAS at which the previous destructive sample was taken; for Dry Weight Growth Rate (DWGR), W_2 = Oven-dried biomass of a plant (gram) at T_2, W_1 = Oven-dried biomass of a plant (gram) at T_1, T_2 = DAS at which the destructive sample was taken, and T_1 = DAS at which the previous destructive sample was taken.

2.6.3. Yield Parameters

The fully matured crops were harvested on October 18, 2022, and subsequently permitted to undergo natural drying in their respective plots. Following a period of two weeks, the harvested plants were subjected to threshing. The resulting grain yield and thousand-grain weight were subsequently quantified using a precision weighing apparatus. The moisture content of the seeds was determined using a digital moisture meter. Ultimately, the grain yield was determined through the application of the following formula (Mulvaney and Devkota, 2020):

$$\text{Grain Yield (Tons/ha)} = \frac{(100 - \text{MC}) \times \text{Plot Yield (kg)} \times 10{,}000}{(100 - \text{SMC}) \times \text{Net plot area (m}^2) \times 1{,}000}$$

Here, MC = Moisture content, SMC = Standard Moisture Content (13% for soybean) (Mulvaney and Devkota, 2020), Net plot area = 5.73 m^2 (6 m^2 minus area covered by destructive samples), and the above formula gives the yield in tons/ha. (1 ton = 1,000 Kg).

2.8. Data Analysis

The data were entered into MS Excel and subsequently analyzed using RStudio version 2023.03.0+386. The data were subjected to analysis using the F-test, least significant difference (LSD) method, coefficient of variation (CV), and standard error of the mean (SEM). The Duncan Multiple Range Test (DMRT) was employed for the purpose of separating the means between the treatments. The data were analyzed at the 5% level of significance (LOS), and the resulting values were interpreted.

3. Results and Discussion

3.1. Number of Trifoliate Leaves per Plant and Plant Height

Table 4 presents the data regarding the plant height of the soybean at 30, 45, 60, and 90 DAS. The impact of INM on plant height at 30 and 60 DAS was found to be statistically insignificant. Nevertheless, the effect was found to be statistically significant at both 30 and 90 DAS. At 90 DAS, the control treatment exhibited the lowest number of trifoliate leaves per plant (45.5), while the Rhizobium+75% RDF treatment demonstrated the highest number of trifoliate leaves (62.78). The Rhizobium+50% RDF treatment exhibited a similar number of trifoliate leaves (60.39), while the Rhizobium+100% PK treatment exhibited the lowest number of trifoliate leaves (57.06). The treatments "Rhizobium + 100% PK," "Rhizobium + 50% RDF," and "Vermicompost + 75% RDF" exhibited comparable outcomes to the treatment with the highest number of leaves, "Rhizobium + 75% RDF," at 90 DAS. The three treatments with rhizobium inoculation exhibited the greatest number of trifoliate leaves per plant, which can be attributed to the efficient absorption of phosphorus and iron facilitated by rhizobium bacteria (Wei et al., 2023). This, in turn, results in enhanced hormone production, which promotes the growth of crops (Wei et al., 2023). Furthermore, the results of the studies conducted by Koushal and Singh (2011) and Chauhan et al. (2023) indicate that the application of biofertilizers has led to an increase in the number of leaves per plant.

As evidenced by the results presented in Table 4, the F-test did not identify a statistically significant difference in plant height. Nevertheless, the Duncan Multiple Range Test (DMRT) indicated that there were statistically significant differences between the treatments at all observation periods for plant height. At 90 DAS, the treatment designated as "FYM+50% RDF" exhibited the lowest plant height, measuring 119.7 cm. The maximum plant height was observed in treatment 'Rhizobium + 50% RDF', with a height of 140.8 cm, followed by 'RDF', with a plant height of 138.3 cm, and 'RDF', with a plant height of 135.5 cm. The treatments "Rhizobium + 50% RDF" and "RDF" are comparable to the treatment with the maximum plant height, "Rhizobium + 100% PK." Similarly, Baghdadi et al. (2018) observed that the application of N-fixing bacteria led to a notable increase in plant height in soybean plants. As reported by Chauhan et al. (2023) and Jaga and Sharma (2015), the co-inoculation of biofertilizers with other organic and inorganic fertilizers has been observed to result in taller soybean plants. Furthermore, they posit that the enhanced plant height may be attributed to elevated metabolic activity and enhanced root growth, which collectively facilitate improved nutrient uptake. The capacity of microorganisms such as Rhizobia to produce and release phytohormones has the potential to alter the chemical composition of the rhizosphere, thereby promoting plant growth (Jaiswal et al., 2021). Furthermore, Devi et al. (2013) also indicated that the application of biofertilizers resulted in taller soybean plants. Similarly, Wang et al. (2021) and Ahmad et al. (2021) reported that the integrated application of chemical and biofertilizer resulted in plants with increased plant height and number of trifoliate leaves, respectively.

Table 4. Effect of integrated nutrient management on the number of trifoliate leaves per plant and plant height.

Treatments	Number of Trifoliate Leaves per Plant				Plant Height (cm)			
	30 DAS	45 DAS	60 DAS	90 DAS	30 DAS	45 DAS	60 DAS	90 DAS
Control	7.94^{ab}	17.54^{a}	29.22^{abc}	45.50^{a}	14.99^{ab}	49.78^{ab}	99.93^{abc}	124.3^{ab}
Rhizobium+100% PK	6.27^{a}	18.55^{ab}	28.28^{ab}	57.06^{bcd}	14.86^{ab}	48.39^{a}	92.17^{ab}	140.8^{b}
Rhizobium+50% RDF	8.22^{ab}	20.89^{ab}	35.50^{c}	60.39^{cd}	16.60^{ab}	54.72^{ab}	103.31^{abc}	138.3^{ab}
Rhizobium+75% RDF	7.44^{ab}	23.06^{bc}	31.72^{abc}	62.78^{d}	13.76^{a}	54.50^{ab}	89.72^{a}	127.6^{ab}
VC+50% RDF	7.33^{ab}	23.28^{bc}	32.89^{bc}	52.61^{abc}	15.88^{ab}	56.93^{ab}	98.72^{abc}	127.1^{ab}
VC+75% RDF	7.89^{ab}	27.05^{c}	30.39^{abc}	55.94^{bcd}	16.07^{ab}	53.81^{ab}	95.78^{abc}	126.1^{ab}
FYM+50% RDF	7.83^{ab}	20.50^{ab}	28.67^{abc}	51.11^{ab}	18.38^{b}	60.04^{b}	104.56^{bc}	119.7^{a}
FYM+75% RDF	7.72^{ab}	20.95^{ab}	30.04^{abc}	51.28^{ab}	14.44^{a}	58.44^{ab}	100.17^{abc}	129.8^{ab}
RDF	8.83^{b}	21.61^{ab}	25.44^{a}	50.00^{ab}	16.50^{ab}	59.47^{ab}	109.78^{c}	135.5^{ab}
F test	NS	*	NS	**	NS	NS	NS	NS
LSD	2.019	4.803	6.134	7.853	3.166	10.16	12.99	16.78
CV (%)	15.1	12.9	11.7	8.4	11.6	10.7	7.6	7.5
SEM (±)	0.673	1.602	2.046	2.619	1.056	3.39	4.33	5.60
Grand Mean	7.722	21.49	30.24	54.07	15.72	55.12	99.3	129.89

Here, DAS: Days After Sowing, cm: Centimeter LSD: Least Significant Difference, CV: Coefficient of Variation, SEM: Standard Error of Mean. Treatment significance is represented by * for $P < 0.05$, ** for $P < 0.01$, *** for $P < 0.001$, and NS for Non-significant.

3.2. Leaf Area Index (LAI)

As evidenced by the F-test presented in Table 5, the treatments exhibited significant differences in LAI at 45 and 90 DAS, while no significant differences were observed at 30 and 60 DAS. The control treatment exhibited the lowest LAI, with a value of 10.16. In contrast, the treatment combining rhizobium and 75% RDF demonstrated the highest LAI, with a value of 15.29. This was followed by the treatment combining rhizobium and 50% RDF, which exhibited an LAI of 14.38, and the treatment combining vermicompost and 50% RDF, which exhibited an LAI of 13.16, at 90 DAS. The treatments that included rhizobium inoculation exhibited the highest number of leaves and the greatest leaf area. As a result, the aforementioned increments resulted in a higher LAI in the treatments that had been inoculated with rhizobia. The observed increase in leaf area can be attributed to the enhanced efficiency of phosphorus absorption, which has been demonstrated to be facilitated by rhizobium bacteria (Wei et al., 2023; Faozi et al., 2019). Our findings align with those of Baghdadi et al. (2018), who observed that the treatment with N-fixing bacteria exhibited the highest LAI. Similarly, Kanase et al. (2006) observed that the application of rhizobium biofertilizer resulted in plants with the highest leaf area and leaf area index. As reported by Nagwanshi et al. (2018), the control treatment exhibited the lowest LAI among the 10 integrated fertilizer treatments. This finding aligns with the results of our research.

In this experiment, we observed an increase in the level of above-ground biomass, as indicated by the higher LAI. While the optimal LAI for soybean plants to reach their yield potential is between 6.0 and 6.5 for indeterminate cultivars, it was observed to reach 9.5 to 10 based on the date of sowing (Tagliapietra et al., 2018). Furthermore, the LAI was also observed to increase while decreasing the plant spacing (Zhou et al., 2017), which corroborates the findings of our experiment. The number of leaves per unit area of the field increases in response to reduced plant spacing, resulting in an overall increase in LAI. It is also possible, however, that the higher LAI observed in our experiment may be a characteristic of the Puja variety. Consequently, further research is required to ascertain whether the higher LAI observed in the Puja variety is a definitive characteristic.

Table 5. Effect of integrated nutrient management on Leaf Area Index (LAI) and Crop Growth Rate (CGR).

Treatments	**Leaf Area Index**				**Crop Growth Rate (g/plant/day)**			
					FWGR		DWGR	
	30 DAS	45 DAS	60 DAS	90 DAS	(35-70 DAS)	(70-105 DAS)	(35-70 DAS)	(70-105 DAS)
Control	0.7749[abc]	4.784[ab]	7.867[a]	10.16[a]	4.227[a]	3.897[b]	1.184[ab]	1.785[bc]
Rhizobium+100% PK	0.5444[a]	4.366[a]	7.217[a]	12.60[abc]	4.065[a]	6.046[bc]	1.118[a]	2.886[d]
Rhizobium+50% RDF	0.8296[abc]	6.657[bc]	11.025[b]	14.35[bc]	4.366[a]	3.967[b]	1.764[bcd]	0.969[b]
Rhizobium+75% RDF	0.6321[ab]	6.389[abc]	8.459[ab]	15.30[c]	7.048[b]	-1.304[a]	1.831[cd]	-0.364[a]
VC+50% RDF	0.7401[abc]	6.487[bc]	8.651[ab]	13.18[abc]	5.358[ab]	7.860[c]	1.917[d]	1.947[c]
VC+75% RDF	0.7727[abc]	7.958[c]	9.466[ab]	12.75[abc]	4.538[a]	5.779[bc]	1.263[abc]	1.677[bc]
FYM+50% RDF	0.9776[c]	5.852[ab]	7.733[a]	10.73[a]	4.991[ab]	-0.240[a]	1.474[abcd]	-0.272[a]
FYM+75% RDF	0.8028[abc]	5.737[ab]	9.052[ab]	11.12[ab]	5.321[ab]	4.871[b]	1.374[abcd]	0.948[b]
RDF	0.8494[bc]	6.326[abc]	7.290[a]	11.47[ab]	6.012[ab]	6.010[bc]	1.708[bcd]	1.806[bc]
F test	NS	*	NS	*	NS	***	*	***
LSD	0.2550	1.870	2.707	2.969	2.095	2.605	0.5215	0.8189
CV (%)	19.2	17.8	18.3	13.8	23.7	36.7	19.9	37.4
SEM (±)	0.0851	0.624	0.903	0.990	0.699	0.869	0.1739	0.2732
Grand Mean	0.769	6.06	8.53	12.41	5.10	4.10	1.515	1.265

Here, FWGR: Fresh Weight Growth Rate, DWGR: Dry Weight Growth Rate, DAS: Days After Sowing, LSD: Least Significant Difference, CV: Coefficient of Variation, SEM: Standard Error of Mean. Treatment significance is represented by * for P < 0.05, ** for P < 0.01, *** for P < 0.001, and NS for Non-significant.

3.3. Crop Growth Rate (CGR)

The data presented in Table 5 indicates that INM had no significant effect on Fresh Weight Growth Rate (FWGR) between 35 and 70 DAS, but the effect was significant between 70 and 105 DAS. Between 70 and 105 DAS, the treatment designated "Vermicompost + 50% RDF" exhibited the highest fresh weight growth rate (FWGR) of 7.860 g/plant/day, followed by the treatment designated "Rhizobium + 100% PK" and the treatment designated "RDF," which exhibited FWGRs of 6.046 g/plant/day and 6.010 g/plant/day, respectively. The treatment designated "Rhizobium + 75% RDF" exhibited the lowest FWGR, with a value of -1.304 g/plant/day. Our findings corroborate those of Baghdadi et al. (2018), who observed that the integration of 50% organic manure, 50% RDF, and N-fixing bacteria resulted in soybean plants exhibiting the highest CGR of 9.61 $g/m^2/day$. This was followed by the treatments "100% RDF" and "50% Poultry manure + 50% RDF," which demonstrated CGRs of 9.55 $g/m^2/day$ and 9.39 $g/m^2/day$, respectively.

The treatments demonstrated significant effects in dry weight growth rate (DWGR) at both the 35 to 70 DAS and 70 to 105 DAS intervals. Between 70 and 105 DAS, the treatment designated "Rhizobium+100% PK" exhibited the highest dry weight growth rate (DWGR) of 2.886 grams per plant per day. This was followed by the treatment designated "Vermicompost + 50% RDF," which exhibited a DWGR of 1.947 grams per plant per day, and the treatment designated "RDF," which exhibited a DWGR of 1.806 grams per plant per day. The lowest dry CGR was observed in the 'Rhizobium+75% RDF' treatment, with a value of -0.364 g/plant/day. The negative values observed in the growth rates can be attributed to the fact that the samples collected on the subsequent measurement day (105 DAS) differed from those obtained on the previous measurement day (70 DAS). The samples differed due to the necessity of uprooting the plants for measurement. Additionally, Raza et al. (2021) have demonstrated that the crop growth rate of soybean increases during the early reproductive stage but subsequently declines due to leaf senescence. These findings align with those of Raza et al. (2021), which indicate a reduction in CGR values from 70 to 105 DAS in Rhizobium + 75% RDF and FYM + 50% RDF.

Table 6. Effect of integrated nutrient management on root diameter.

Treatments	**Root Diameter (mm)**		
	35 DAS	70 DAS	105 DAS
Control	4.02^{ab}	8.49^{a}	11.68^{ab}
Rhizobium+100% PK	3.52^{a}	9.38^{ab}	11.80^{ab}
Rhizobium+50% RDF	4.36^{ab}	9.26^{ab}	12.16^{ab}
Rhizobium+75% RDF	4.08^{ab}	10.65$_{bc}$	10.63^{a}
VC+50% RDF	3.75^{a}	10.12^{abc}	12.54^{ab}
VC+75% RDF	4.09^{ab}	8.92^{a}	11.25^{ab}
FYM+50% RDF	4.53^{ab}	9.93^{abc}	10.74^{a}
FYM+75% RDF	4.82^{b}	10.01^{abc}	10.56^{a}
RDF	3.94^{ab}	11.37^{c}	12.89^{b}
F test	NS	*	NS
LSD	0.8990	1.498	1.906
CV (%)	12.6	8.8	9.5
SEM (±)	0.2999	0.500	0.636
Grand Mean	4.129	9.80	11.58

Here, DAS: Days After Sowing, cm: centimeter, mm: millimeter, LSD: Least Significant Difference, CV: Coefficient of Variation, SEM: Standard Error of Mean. Treatment significance is represented by * for P < 0.05, ** for P < 0.01, *** for P < 0.001, and NS for Non-significant.

3.4. Root Diameter, Root Nodule Number and Root Nodule Mass

The treatments had no significant effect on root diameter at 35 DAS and 105 DAS; however, at 70 DAS, a significant effect was observed. Although the F-test did not indicate a statistically significant difference in root diameter at 105 DAS, the DMRT results presented in Table 6 demonstrate that the minimum root diameter of 10.56 mm was observed in the 'FYM+75% RDF' treatment, while the maximum root diameter of 12.89 mm was observed in the 'RDF' treatment. The 'Vermicompost + 50% RDF' and 'Rhizobium+50% RDF' treatments exhibited root diameters of 12.54 mm and 12.16 mm, respectively. The treatments designated as "Control," "Rhizobium+100% PK," "Rhizobium+50% RDF," "Vermicompost + 50% RDF," and "Vermicompost + 75% RDF" exhibited comparable outcomes to those observed in the "RDF" treatment. In the experiments conducted by Bandyopadhyay et al. (2010) and Hati et al. (2006), the treatment comprising NPK and FYM exhibited the highest root length density (RLD) and root mass density (RMD) in soybean. The two experiments employed a total of three treatments: a control, an NPK treatment, and an NPK treatment combined with FYM. However, the authors do not present data on root diameter as a separate variable.

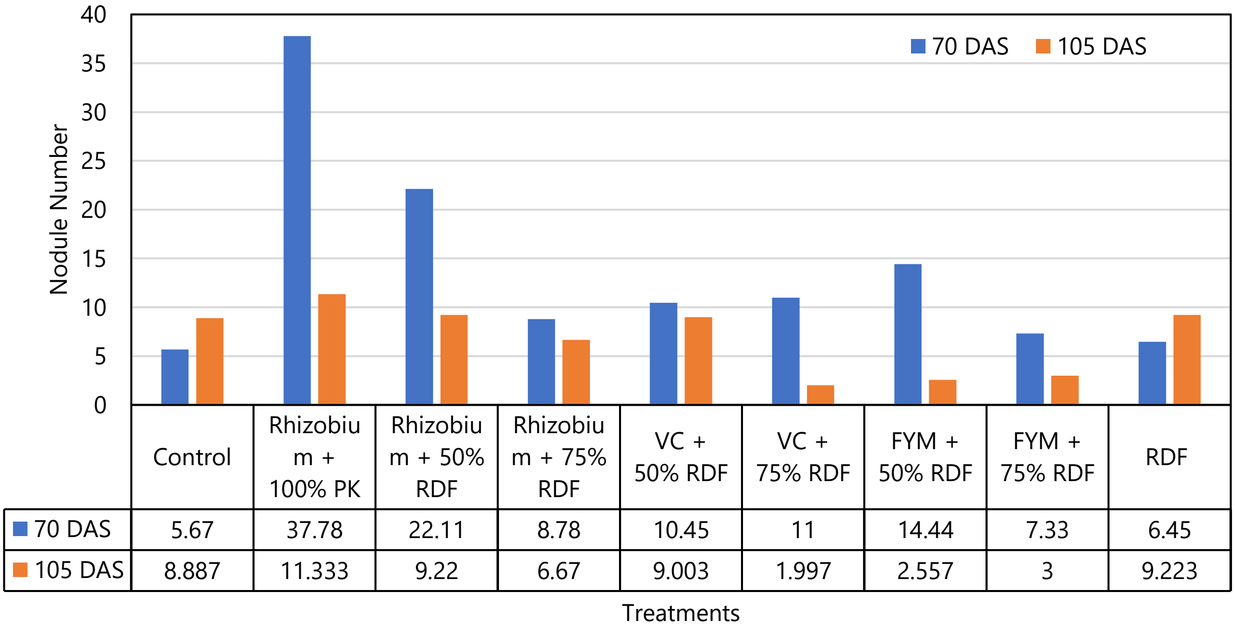

Figure 4. Bar diagram for root nodule number in response to different treatments.

At 35 DAS, no observable root nodules were detected in any of the treatments. The data regarding root nodule number at 70 and 105 DAS are presented in the bar diagram in Figure 4. The treatment designated as "Rhizobium+100%

PK" exhibited the greatest number of root nodules, with a maximum of 37.78 and 11.33 observed at 70 DAS and 105 DAS, respectively. The subsequent treatment was RDF, which exhibited 9.223 nodules, while Rhizobium + 50% RDF demonstrated 9.220 nodules at 105 DAS. Conversely, the lowest number of root nodules was observed in the Vermicompost + 75% RDF treatment, which exhibited 1.997 nodules at 105 DAS. The quantity of rhizobium applied was identical across all three treatments. However, there were notable differences in nodule formation among these treatments. The disparity in nodule formation can be attributed to the differing urea contents of the various treatments. The treatment designated "Rhizobium+100% PK" was devoid of urea, while the treatment designated "Rhizobium + 50% RDF" contained 50% urea and the treatment designated "Rhizobium + 75% RDF" contained 75% urea. It was observed that an increase in urea content had a negative impact on nodule formation (Gao et al., 2019; Shen et al., 2019). Furthermore, Devi et al. (2013) and Chauhan et al. (2023) observed that the application of biofertilizers resulted in an increase in the number of nodules per plant.

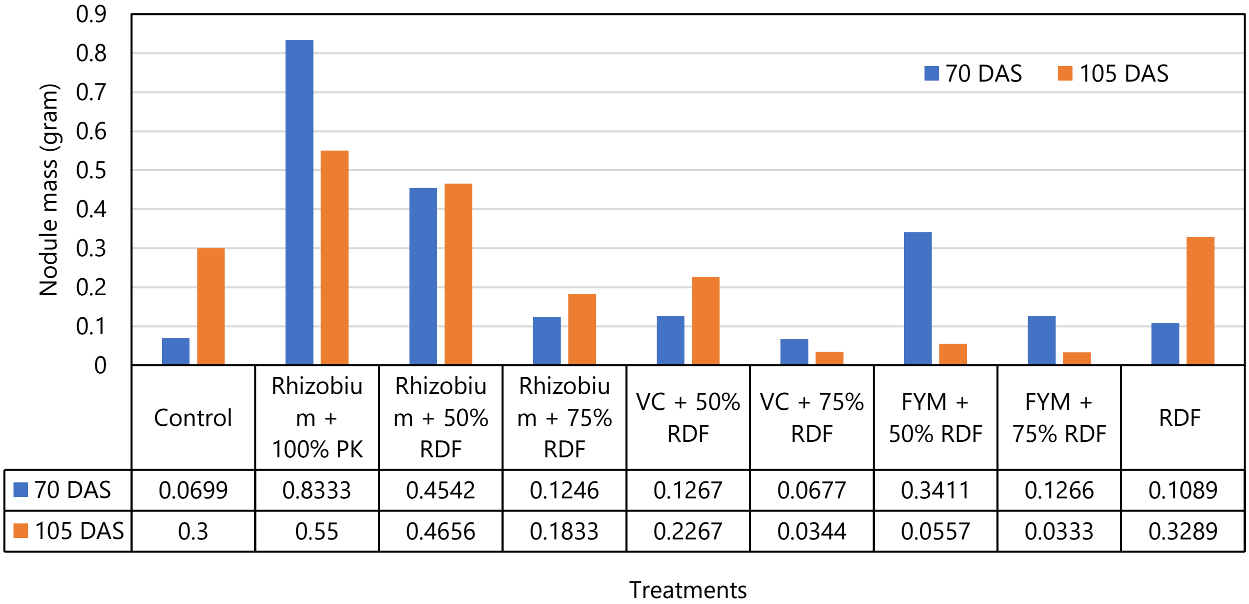

Figure 5. Bar diagram for root nodule mass in response to different treatments.

Figure 5 illustrates the data pertaining to the mass of root nodules in response to INM. The lowest mass of root nodules was observed in the treatment designated "FYM+75% RDF," which exhibited a value of 0.033 grams at 105 DAS. In contrast, the highest mass of root nodules was observed in the treatment designated "Rhizobium+100% PK," which exhibited a value of 0.833 grams at the same time point. The second-highest mass of root nodules was observed in the treatment designated "Rhizobium+50% RDF," which exhibited a value of 0.55 grams at 105 DAS. The third-highest mass of root nodules was observed in the treatment designated "RDF," which exhibited a value of 0.328 grams at the same time point. The greater mass of root nodules in RDF can be attributed to the role of phosphorus. Phosphorus plays a pivotal role in nodule formation and rhizobia growth in the host plant, as evidenced by the findings of Kucey et al. (1989) and Ponmurugan and Gopi (2006).

3.5. Grain Yield and Thousand Grain Weight

As evidenced in Table 7, the treatments demonstrated notable discrepancies in the grain yield of soybean. The treatment designated "Vermicompost + 75% RDF" exhibited the highest yield, reaching 3.659 tons per hectare. This was followed by the treatment designated "Rhizobium + 50% RDF," which yielded 3.642 tons per hectare, and the treatment designated "Rhizobium + 100% PK," which yielded 3.421 tons per hectare. The treatment comprising Rhizobium and 50% RDF yielded results comparable to those of the treatment combining vermicompost and 75% RDF, which exhibited the highest yield. The lowest yield was observed in the treatment combining vermicompost and 50% RDF, with a yield of 3.048 tons/ha. Our findings on grain yield are in alignment with the observations made by Devi et al. (2013). The researchers observed that the treatment "75% RDF + VC @ (1t/ha) + PSB" yielded the highest grain yield. However, when the 75% RDF was reduced from this treatment to 50% RDF, the treatment "50% RDF + VC @ (1 t/ha) + PSB" produced a lower grain yield by approximately 0.5 ton/ha. In this context, RDF refers to: The recommended dose of fertilizer is as follows: VC (vermicompost) and PSB (phosphorous-solubilizing bacteria). The statistical analysis of the experiment revealed that the "Vermicompost + 75% RDF" and "Rhizobium + 50% RDF" treatments were not significantly different from one another. It can thus be inferred that these two treatments exhibited the greatest grain yield of all nine treatments. As previously stated by Nakei et al. (2022), several studies (Chen et al., 2002; Halwani et al., 2021; Ohyama et al., 2017) have indicated that the yield of soybean is directly correlated to the amount of nitrogen taken by the shoot of the soybean plant. This is a crucial factor for the sustainable production of soybean. The efficient, economical, and sustainable achievement of this can be facilitated by the employment of rhizobia species biofertilizers, which are capable of fixing atmospheric nitrogen. Furthermore, Bam et al. (2022) and Tena et al. (2016) also observed an increase in nodulation and grain yield through rhizobium inoculation.

Table 7. Effect of different fertilizer combinations on grain yield and thousand grain weight.

Treatments	Grain Yield (ton/ha)	1000 Grain Weight (g)
Control	3.339[ab]	133.0[ab]
Rhizobium+100% PK	3.421[ab]	126.7[a]
Rhizobium+50% RDF	3.642[b]	142.2[ab]
Rhizobium+75% RDF	3.304[ab]	132.7[ab]
VC+50% RDF	3.048[a]	131.2[ab]
VC+75% RDF	3.659[b]	138.4[ab]
FYM+50% RDF	3.304[ab]	131.8[ab]
FYM+75% RDF	3.362[ab]	145.9[b]
RDF	3.170[a]	136.0[ab]
F test	*	NS
LSD	0.3583	14.30
CV (%)	6.2	6.1
SEM (±)	0.1195	4.77
Grand Mean	3.361	135.3

Here, ton: Metric ton (1,000 kg), ha: hectare, LSD: Least Significant Difference, CV: Coefficient of Variation, SEM: Standard Error of Mean. Treatment significance is represented by * for $P < 0.05$, ** for $P < 0.01$, *** for $P < 0.001$, and NS for Non-significant.

A probability value (P-value) greater than 0.05 indicates that the treatments did not exhibit a statistically significant difference in 1000-grain weight of soybean. Nevertheless, the DMRT results presented in Table 7 suggest that the treatment comprising FYM and 75% RDF yielded the highest thousand grain weight (145.9 g), while the treatment incorporating Rhizobium and 100% PK exhibited the lowest thousand grain weight (126.7 g). This observation is consistent with the findings of Sharma et al. (2018), who reported that the integration of FYM with chemical fertilizers resulted in a higher test weight of soybean. Moreover, the lack of a significant impact of the treatments on thousand-grain weight is consistent with the findings of Devi et al. (2013) and Sikka et al. (2018). The study also concluded that integrated nutrient management did not significantly influence seed weight in soybean.

4. Conclusion and Recommendations

The objective of this experiment was to evaluate the impact of integrated nutrient management on diverse traits of soybean. The results of this experiment revealed disparate outcomes across the various treatments. It is noteworthy that the combination of 'Rhizobium+100% PK' exhibited superior performance, as evidenced by the highest plant height, dry weight growth rate, nodule number, and nodule mass. Another noteworthy result was observed in the treatment combining Rhizobium and 75% RDF, which exhibited the highest number of leaves per plant and leaf area index. Additionally, the combination of VC and 50% RDF demonstrated the highest rate of fresh weight growth, RDF resulted in the largest root diameter, and FYM+75% RDF exhibited the highest 1000-grain weight. Notably, the treatments VC+75% RDF and Rhizobium+50% RDF exhibited particularly impressive grain yields. The two treatments were found to be statistically indistinguishable with regard to grain yield. The integrated nutrient management (INM) approach demonstrated superior performance compared to the sole application of chemical fertilizers across all parameters, with the exception of root diameter, where RDF exhibited comparable outcomes to five other treatments.

It is important to note that the performance of soybean can vary depending on a number of factors, including the variety, intercultural operation, environmental conditions, and residual nutrient status of the soil. It is therefore recommended that further research be conducted in multiple locations and over multiple years in order to establish the efficacy of INM on soybeans with greater certainty.

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