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Impact of inorganic fertilizer and microbial inoculation on nutrient content and uptake by soybean (*Glycine max* L. Merrill) in typic haplustepts

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***Abstract*— A field experiment was conducted during the kharif season of 2025 at the Instructional Farm, Rajasthan College of Agriculture, Udaipur to evaluate the impact of inorganic fertilizer and microbial inoculation on nutrient content and uptake by soybean (Glycine max L. Merrill) grown on Typic Haplustepts. The study employed a two-factor factorial randomized complete block design with four levels in each factor and three replications. Factor A comprised inorganic fertilizer rates expressed as proportions of the recommended dose of fertilizer (RDF): F_0 (control), F_1 (50% RDF), F_2 (75% RDF) and F_3 (100% RDF). Factor B comprised microbial inoculation treatments: M_0 (no inoculation), M_1 (Rhizobium), M_2 (Phosphate-solubilizing bacteria, PSB) and M_3 (Rhizobium + PSB). The results indicated that the highest nutrient content and uptake by soybean were recorded under 100% RDF (F_3), which was statistically at par with 75% RDF (F_2). Under F_3, the maximum nutrient content was 6.968 and 0.605% N, 0.605 and 0.220% P, and 1.353 and 2.63% K in seed and stover, respectively. Similarly, the highest total nutrient uptake was 113.72 kg N ha^{-1}, 17.00 kg P ha^{-1}, and 67.69 kg K ha^{-1}. Among microbial inoculation treatments, Rhizobium + PSB (M_3) recorded the highest nutrient content (6.934 and 0.594% N, 0.594 and 0.209% P, and 1.351 and 2.62% K in seed and stover, respectively) and total nutrient uptake (113.15 kg N ha^{-1}, 16.61 kg P ha^{-1}, and 67.76 kg K ha^{-1}), while Rhizobium and PSB alone were comparable to each other. Therefore, this study investigates the combined effects of inorganic fertilizers and microbial inoculation (Rhizobium and PSB) on the nutrient uptake and yield of soybean cultivated in the Typic Haplustepts of Rajasthan. This integrated approach offers a highly sustainable strategy to maximize soybean productivity, reduce chemical dependency and maintain soil fertility in semi-arid agricultural systems.*

Keywords*— Soybean, inorganic fertilizers, microbial inoculation, Rhizobium, PSB, nutrient content, nutrient uptake.

I. INTRODUCTION

Soybean (*Glycine max* L. Merrill) is a highly important crop worldwide. It serves as both a valuable oilseed and a nutrient-rich pulse. Often called the golden crop and the protein hope of the future, it is widely grown in India and globally for food and industrial use (Choudhary *et al.,* 2024). Its seeds are packed with nutrients, typically containing over 40% protein, 20% oil and 25–30% carbohydrates. This rich nutritional profile makes soybeans a key part of modern farming systems (Thoke *et al.,* 2022). To achieve the best possible soybean yield, farmers must maintain healthy soil. The area of soil right next to plant roots, called the rhizosphere, is full of microorganisms.

These tiny organisms shape the soil environment and help plants grow from the seedling stage all the way to harvest (Sahu *et al.,* 2023). Adding helpful microbes to the soil, such as *Rhizobium* and *Bacillus*, is a proven way to improve crop growth. When used together as a group (a microbial consortium), these microbes greatly improve root nodule formation, plant height and the amount of nitrogen, phosphorus and potassium stored in the seeds and plant parts (Yaduwanshi *et al.,* 2019).

These microbes help plants in very specific ways. *Rhizobium* sp. is a bacterium that forms a beneficial relationship with legume roots. It takes nitrogen gas from the air and turns it into a form the soybean plant can easily use to grow (Chiduwa, 2021). At the same time, Phosphate Solubilizing Bacteria (PSB), like *Bacillus* sp., help unlock phosphorus that is trapped in the soil. They change insoluble phosphorus into a soluble form that plant roots can absorb. In addition, these bacteria protect plants by fighting off soil diseases (Singh *et al.,* 2021). Using these microbes together works better than using them alone, leading to greener leaves, stronger roots and better overall nutrient uptake. While microbes provide many long-term benefits, they act slowly. High-yielding soybean plants often need nutrients faster than natural microbes can supply them. Therefore, applying inorganic fertilizers is still essential to give the crop an immediate supply of N, P and K. However, relying only on chemical fertilizers causes problems over time. Using too many synthetic chemicals harms soil health, reduces the natural microbial population and increases farming costs (Virk *et al.,* 2026).

A more sustainable approach is to combine both methods. By mixing inorganic fertilizers with helpful microbes, farmers can provide instant nutrients while protecting the biology of the soil. The added microbes also help the plants absorb the chemical fertilizers more efficiently, so less fertilizer goes to waste. Testing this combined strategy is especially important for specific soil types, such as the Typic Haplustepts found in regions like Rajasthan. These soils often have low organic matter and hold onto phosphorus too tightly, making it difficult for plants to get the nutrients they need. Therefore, this study aims to evaluate how the combined application of inorganic fertilizers and microbial inoculation affects the nutrient content, nutrient uptake and total yield of soybeans grown in the Typic Haplustepts of Rajasthan.

II. MATERIALS AND METHODS

The field experiment was conducted during the 2025 *kharif* season at the Instructional Farm, Rajasthan College of Agriculture, Udaipur (24°35′ N, 74°42′ E; 579.5 m above mean sea level), located in agro-climatic zone IVa (Sub-humid Southern Plain and Aravalli Hills) of Rajasthan, to study the Impact of inorganic fertilizer and microbial inoculation on nutrient content and uptake by soybean (*Glycine max* L. Merrill) in typic haplustepts. The soil at the site is classified as a typic haplustepts. The region has a subtropical climate with mild winters and moderate summers; the southwest monsoon occurs from late June to September and the long-term mean annual rainfall is 664.33 mm.

A two-factor randomized complete block design with three replications was employed. Factor A comprised inorganic fertilizer levels: F_0:- control, F_1:- 50% of the recommended dose of fertilizer (RDF), F_2:-75% RDF and F_3:-100% RDF. Factor B comprised microbial inoculation treatments: M_0:-no inoculation, M_1:-*Rhizobium*, M_2:-Phosphate-solubilizing bacteria (PSB) and M_3:-*Rhizobium* + PSB. The RDF was 40:60:40 kg ha^{-1} (N: P_2O_5: K_2O), applied as urea and single superphosphate (SSP). *BradyRhizobium japonicum* was used for *Rhizobium* inoculation and Bacillus spp. as the PSB inoculant. Seed treatment was carried out before sowing. After treatment, the seeds were shade-dried and then sown. Control treatments received no seed inoculation and no fertilizer application. Chemical fertilizers were applied according to the treatment combinations, except in the control plots. The recommended dose of fertilizer (RDF) for soybean was 40:60:40 kg N: P_2O_5: K_2O ha^{-1}, applied at the time of sowing.

Factor A: Inorganic Sources		**Factor B: Microbial Inoculation**	
F_0	Control	M_0	No inoculation
F_1	50 % RDF	M_1	*Rhizobium*
F_2	75 % RDF	M_2	PSB
F_3	100 % RDF	M_3	*Rhizobium* + PSB

The experimental field consisted of a clay loam textured soil with alkaline reaction (pH 8.42). Electrical conductivity measured 0.77 dS m^{-1} and organic carbon was 0.60%. Soil physical characteristics comprised a bulk density of 1.36 Mg m^{-3}, particle density of 2.60 Mg m^{-3}, total porosity of 47.69% and a water-holding capacity of 45.26%. Initial fertility assessment showed available N, P and K at 243, 18 and 270 kg ha^{-1}, respectively. DTPA-extractable micronutrient concentrations were: Zn 0.47 mg kg^{-1}, Mn 2.31 mg kg^{-1}, Cu 0.56 mg kg^{-1} and Fe 3.12 mg kg^{-1}.

To evaluate nutrient content and uptake, representative plant samples (both seeds and stover) were collected from each plot at the time of harvest. The plant materials were gently washed with distilled water to remove dirt and oven-dried at 65°C until they reached a constant weight and then ground into a fine powder. The nitrogen content was determined by wet digestion of the plant sample with H_2SO_4 and H_2O_2 was estimated on a colorimeter after the development of colour with Nesseler's reagent (Snell and Snell, 1949). For phosphorus and potassium analysis, the ground samples were first broken down using a di-acid digestion method (Johnson and Ulrich, 1959). Following digestion, phosphorus levels were measured using the Vandomolybdo phosphoric acid yellow colour method, while potassium levels were recorded using a flame photometer (Jackson, 1973). Once the nutrient concentration (as a percentage) in the seeds and stover was found, the total nutrient uptake was calculated by multiplying those percentages by the crop's yield. This calculation was done using the following formula:

$$Uptake\ (kg\ ha^{-1}) = \frac{Nutrient\ content\ (\%) \times Yield\ (kg\ ha^{-1})}{100}$$

III. RESULTS AND DISCUSSION

Nutrient content:

A complete analysis of the crop's nutrient profiling from Table no.1 and Fig.1 revealed that a distinct, statistically significant relationship between the applied treatments both the Recommended Dose of Fertilizer (RDF) and microbial inoculations and the plant's final nitrogen and phosphorus content, even as potassium levels remained largely unaffected (Pawar *et al*., 2018). As the fertilizer levels increased from the F_0 (control) to the highest F_3 (100% RDF) level, nitrogen concentration in the seeds experienced a strong and steady flow from F_0 (control) 6.133%, F_1 (50% RDF) 6.617%, F_2 (75% RDF) 6.884% to a peak of F_3 (100% RDF) 6.968%. The treatment F_3 (100 % RDF) is comparable to F_2 (75% RDF), whereas nitrogen concentration in the stover also showed a strong and steady flow from F_0 (control) 0.463%, F_1 (50% RDF) 0.530%, F_2 (75% RDF) 0.589% to a peak of F_3 (100% RDF) 0.605%. The treatment F_3 (100 % RDF) is comparable to F_2 (75% RDF). Concurrently, microbial inoculation demonstrated a corresponding positive influence on the nitrogen content of the soybean crop. Progression from the uninoculated control to successive inoculation levels resulted in a significant incremental increase in seed nitrogen concentration, recording at 6.308% M_0 (no inoculation), 6.689% M_1 (*Rhizobium*) and 6.671% M_2 (PSB), with the M_1 and M_2 treatment levels remaining statistically at par with one another. The maximum nitrogen content of 6.934% was ultimately achieved under the highest inoculation intensity M_3 (*Rhizobium* + PSB). Similarly, the nitrogen content in stover was recorded at M_0 (no inoculation) 0.494 %, M_1 (*Rhizobium*) 0.540 % and M_2 (PSB) 0.558, with the M_1 and M_2 treatment levels remaining statistically at par with one another. The maximum nitrogen content in stover was ultimately achieved under the highest inoculation intensity M_3 (*Rhizobium* + PSB) 0.594 %.

The accumulation of phosphorus in the seeds exhibited a discrete positive trend in response to increasing levels of RDF and microbial inoculation. Under the RDF treatments, seed P content increased from 0.463 % F_0 (control) to 0.530 % F_1 (50 % RDF) and 0.589 % F_2 (75 % RDF) with a highest value of 0.605% F_3 (100 % RDF). Remarkably, the concentrations recorded at F_3 and F_2 were statistically at par. In the same way stover P content increased from 0.145 % F_0 (control) to 0.197% F_1 (50 % RDF) and 0.214 % F_2 (75% RDF) with a highest value of 0.220% F_3 (100 % RDF). Remarkably, the concentrations recorded at F_3 and F_2 were comparable to each other. A similar effect was observed with microbial inoculation, where P concentrations in seed increased from 0.494 % M_0 (no inoculation) to 0.540 % M_1 (*Rhizobium*) and 0.558 % M_2 (PSB), ultimately reaching 0.594% M_3 (*Rhizobium* + PSB). The P concentrations at M_1 (*Rhizobium*) and M_2 (PSB) were determined to be statistically at par, whereas P concentrations in stover increased from 0.175% M_0 (no inoculation) to 0.194 % M_1 (*Rhizobium*) and 0.199 % M_2 (PSB), ultimately reaching 0.209 % M_3 (*Rhizobium* + PSB) and P concentrations in stover at M_1 (*Rhizobium*) and M_2 (PSB) were determined to be statistically at par. These data validate that both the RDF application and microbial inoculation serve as effective mechanisms to enhance the final phosphorus concentration within the plant tissue.

In contrast to nitrogen and phosphorus, potassium content remained statistically stable across all treatments, showing no significant variance. Under the RDF regime, seed K concentrations were 1.338 % (F_0), 1.343 % (F_1), 1.349 % (F_2) and 1.353 % (F_3), with corresponding stover values of 2.56 %, 2.59 %, 2.60 % and 2.63 %, respectively. Microbial inoculation yielded similar consistency, with seed K levels of 1.336 % (M_0), 1.348 % (M_1), 1.347 % (M_2) and 1.351 % (M_3) and stover values of 2.5 7%, 2.60 %, 2.58 % and 2.62 %, respectively. As all variations were non-significant, every treatment level was statistically at par, confirming that neither RDF application nor microbial inoculation significantly influenced the crop's baseline potassium content.

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Table 1. Impact of Inorganic Fertilizer and Microbial Inoculation on nutrient content in soybean

Treatment	**Nutrient content (%)**					
	Nitrogen		Phosphorus		Potassium	
	Seed	Stover	Seed	Stover	Seed	Stover
RDF						
F_0	6.133	0.463	0.463	0.145	1.338	2.56
F_1	6.617	0.530	0.530	0.197	1.343	2.59
F_2	6.884	0.589	0.589	0.214	1.349	2.60
F_3	6.968	0.605	0.605	0.220	1.353	2.63
SE.m.±	0.068	0.007	0.007	0.003	0.011	0.018
C.D. at 0.05	0.197	0.020	0.020	0.008	NS	NS
Microbial Inoculation						
M_0	6.308	0.494	0.494	0.175	1.336	2.57
M_1	6.689	0.540	0.540	0.194	1.348	2.60
M_2	6.671	0.558	0.558	0.199	1.347	2.58
M_3	6.934	0.594	0.594	0.209	1.351	2.62
SE.m.±	0.068	0.007	0.007	0.003	0.011	0.018
C.D. at 0.05	0.197	0.020	0.020	0.008	NS	NS

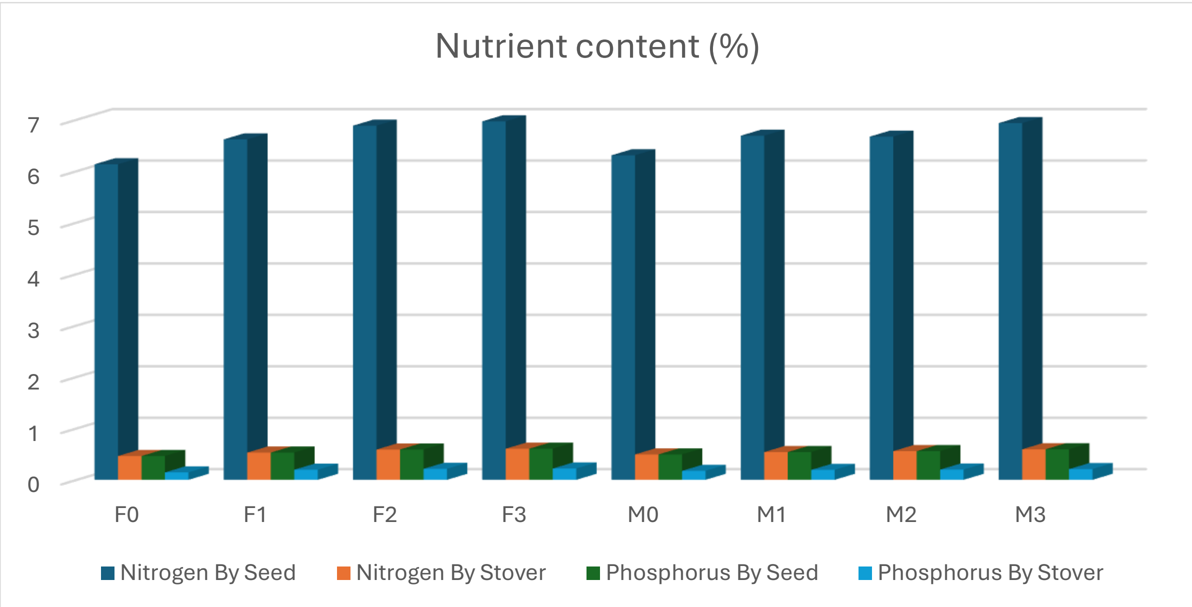

Fig. 1. Impact of Inorganic Fertilizer and Microbial Inoculation on nutrient content in soybean

Applying the full 100 % Recommended Dose of Fertilizer (RDF), specifically 40 kg N and 60 kg P/ha, drives higher macronutrient (N, P and K) accumulation in soybean seeds and stover by increasing soil solution concentrations for efficient root absorption and by stimulating overall biomass production (Pierozan Junior *et al*., 2020; Ciampitti *et al.,* 2021; Wysokiński *et al.,* 2024). This enhanced nutrition is particularly critical during the high-demand reproductive stages of pod formation and seed filling, when biological nitrogen fixation and early-season soil nitrogen alone are insufficient (Rahangdale *et al*., 2022). By maintaining photosynthetic capacity and protein synthesis, the added fertilizer boosts the metabolic sink strength of developing pods, enabling the plant to efficiently remobilize and translocate nutrient reserves from vegetative tissues directly into the harvested seeds. This may be attributed to the rapid multiplication of microbial populations following the application of the microbial consortium. The enhanced microbial activity stimulates vigorous soybean growth during active developmental stages, which subsequently leads to a nutrient dilution effect within the plant tissues as biomass increases. These results are in accordance with the findings of Kumar and Ismail (2017). Because total nutrient accumulation is a product of tissue concentration multiplied by plant biomass, the larger plants generated by this optimal fertility naturally uptake significantly more total nutrients (Akhila *et al*., 2025).

Table 2. Impact of Inorganic Fertilizer and Microbial Inoculation on nutrient uptake by soybean

Treatment	Nutrient uptake (kg ha^{-1})								
	N Uptake			P Uptake			K Uptake		
	Seed	Stover	Total	Seed	Stover	Total	Seed	Stover	Total
RDF									
F_0	46.53	23.72	70.25	3.53	5.47	9.00	10.19	35.72	45.91
F_1	59.05	30.93	89.99	4.71	8.10	12.80	11.89	44.24	56.13
F_2	73.21	35.99	109.55	6.11	10.20	16.42	14.21	49.73	63.94
F_3	75.84	37.88	113.72	6.37	10.64	17.00	14.41	53.27	67.69
SE.m.±	1.060	0.709	1.470	0.079	0.162	0.214	0.219	1.090	1.177
C.D. at 0.05	3.061	2.048	4.245	0.227	0.468	0.618	0.633	3.148	3.399
Microbial Inoculation									
M_0	51.06	25.29	76.35	3.96	6.42	10.40	10.83	37.68	48.52
M_1	64.57	33.95	98.62	5.22	8.57	13.82	12.99	47.47	60.45
M_2	63.03	31.91	95.02	5.40	8.97	14.40	12.72	44.22	56.94
M_3	75.98	37.05	113.15	6.13	10.44	16.61	14.17	53.59	67.76
SE.m.±	1.060	0.709	1.470	0.079	0.162	0.214	0.219	1.090	1.177
C.D. at 0.05	3.061	2.048	4.245	0.227	0.468	0.618	0.633	3.148	3.399

Nutrient uptake

From Table No.2 and Fig. 2, the experimental results demonstrate that the application of successive levels of the Recommended Dose of Fertilizer (RDF) and microbial inoculants significantly influenced the accumulation of nitrogen (N), phosphorus (P) and potassium (K) across both the seed and stover uptake. Evaluating the inorganic sources, N uptake in the seed and stover ranged from 46.53 and 23.72 kg ha^{-1} in the unfertilized F_0 (control) to 59.05 and 30.93 kg ha^{-1} in F_1 (50 % RDF), 73.21 and 35.99 kg ha^{-1} in F_2 (75 % RDF) and peaked at 75.84 and 37.88 kg ha^{-1} in F_3 (100 % RDF), resulting in corresponding total N uptakes of 70.25, 89.99, 109.55 and 113.72 kg ha^{-1} from control, 50 % RDF, 75 % RDF and 100 % RDF. Similarly, P uptake followed a significant upward trend across the F_0 (control), F_1 (50 % RDF), F_2 (75 % RDF) and F_3 (100 % RDF) treatments, recording seed values of 3.53, 4.71, 6.11 and 6.37 kg ha^{-1} and stover values of 5.47, 8.10, 10.20 and 10.64 kg ha^{-1}, which culminated in progressive total P uptakes of 9.00 (F_0), 12.80 (F_1), 16.42 (F_2) and 17.00 (F_3), kg ha^{-1}. For potassium, the seed and stover extraction rates increased from the F_0 (control) 10.19 and 35.72 kg ha^{-1} through F_1 (50 % RDF) 11.89 and 44.24 kg ha^{-1} and F_2 (75 % RDF) 14.21 and 49.73 kg ha^{-1}, reaching their maximum under the F_3 (100 % RDF), treatment at 14.41 and 53.27 kg ha^{-1}, yielding total K uptakes of 45.91 (F_0), 56.13 (F_1), 63.94 (F_2) and 67.69 (F_3), kg ha^{-1}. Corresponding to the inorganic fertilizer response, the microbial inoculation treatments (M_0 to M_3) generated significant variations in nutrient assimilation. Nitrogen accumulation in the seed and stover was lowest in the M_0 (no inoculation) 51.06 and 25.29 kg ha^{-1}, improving in M_2

(PSB) 63.03 and 31.91 kg ha^{-1} and M_1 (*Rhizobium*) 64.57 and 33.95 kg ha^{-1}, before reaching a maximum in M_3 (*Rhizobium* + PSB) 75.98 and 37.05 kg ha^{-1}; this translated to total N uptakes of 76.35 (M_0), 95.02 (M_2), 98.62 (M_1) and 113.15 (M_3) kg ha^{-1}, respectively. Phosphorus uptake exhibited a similar trend with seed and stover values recorded at 3.96 and 6.42 kg ha^{-1} for M_0 (no inoculation), 5.22 and 8.57 kg ha^{-1} for M_1 (*Rhizobium*), 5.40 and 8.97 kg ha^{-1} for M_2 (PSB) and highest at 6.13 and 10.44 kg ha^{-1} for M_3 (*Rhizobium* + PSB), thereby generating total P uptakes of 10.40 (M_0), 13.82 (M_1), 14.40 (M_2) and 16.61 (M_3) kg ha^{-1}. Finally, potassium extraction in the seed and stover escalated from the M_0 (no inoculation) 10.83 and 37.68 kg ha^{-1} to M_2 (PSB) 12.72 and 44.22 kg ha^{-1} and M_1 (*Rhizobium*) 12.99 and 47.47 kg ha^{-1}, achieving the highest biological concentration under the M_3 (*Rhizobium* + PSB) 14.17 and 53.59 kg ha^{-1}, which sequentially drove total K uptakes of 48.52 (M_0), 56.94 (M_2), 60.45 (M_1) and 67.76 (M_3) kg ha^{-1}. When the crop was given the full recommended fertilizer dose (100% RDF), it absorbed a lot more nutrients from the soil. This happened because the fertilizer helped the plants grow larger, deeper root systems to reach more food, while also improving the soil conditions right around the roots so nutrients were easier to take in (Sahu *et al.,* 2024). Because the plants grew much bigger and healthier overall, they naturally extracted more nutrients and were able to easily move them up into their stems and seeds. Interestingly, even though the plants absorbed a lot more potassium overall, the actual percentage of potassium inside their tissues didn't really change. This usually happens when a plant grows so fast that the extra potassium gets spread out across a much larger plant, or because the plant just stored the extra nutrients in parts we don't harvest (Mansare *et al.,* 2026). In short, giving the crop the perfect amount of fertilizer matched exactly what it needed to grow large and efficiently pull nutrients from the ground. These findings are strongly supported by Gajbhiye and Mane (2021), who observed a significant increase in total nutrient uptake following the application of various biofertilizer treatments, attributing this enhancement to improved root development and more efficient soil nutrient mobilization. Similarly, Auti *et al.* (2013) verified that utilizing a dual microbial inoculant specifically *Rhizobium* combined with *Gluconacetobacter* maximized nitrogen uptake in the grain and potassium uptake in the stover. The significant enhancement in N, P and K uptake can be primarily attributed to microbially induced modifications in root architecture. Specifically, the microbial synthesis of phytohormones (such as IAA) stimulates lateral root and root hair proliferation, drastically expanding the root surface area available for nutrient absorption (Singh *et al.,* 2015). Furthermore, synergistic microbial combinations such as co-inoculating *Rhizobium* with yeast or PSB directly increase the efficiency of N acquisition and P/K mobilization (Souza *et al.,* 2015). Consequently, this expanded root network and enhanced nutrient solubility work together to maximize total nutrient accumulation within the plant (Jaybhay *et al.,* 2017; Marinkovic *et al.,* 2018; Singh *et al.,* 2021). Together, these studies highlight how specific, synergistic microbial interactions can significantly boost both atmospheric nitrogen fixation and nutrient solubility, ultimately driving superior nutrient accumulation throughout the plant's vegetative and reproductive tissues.

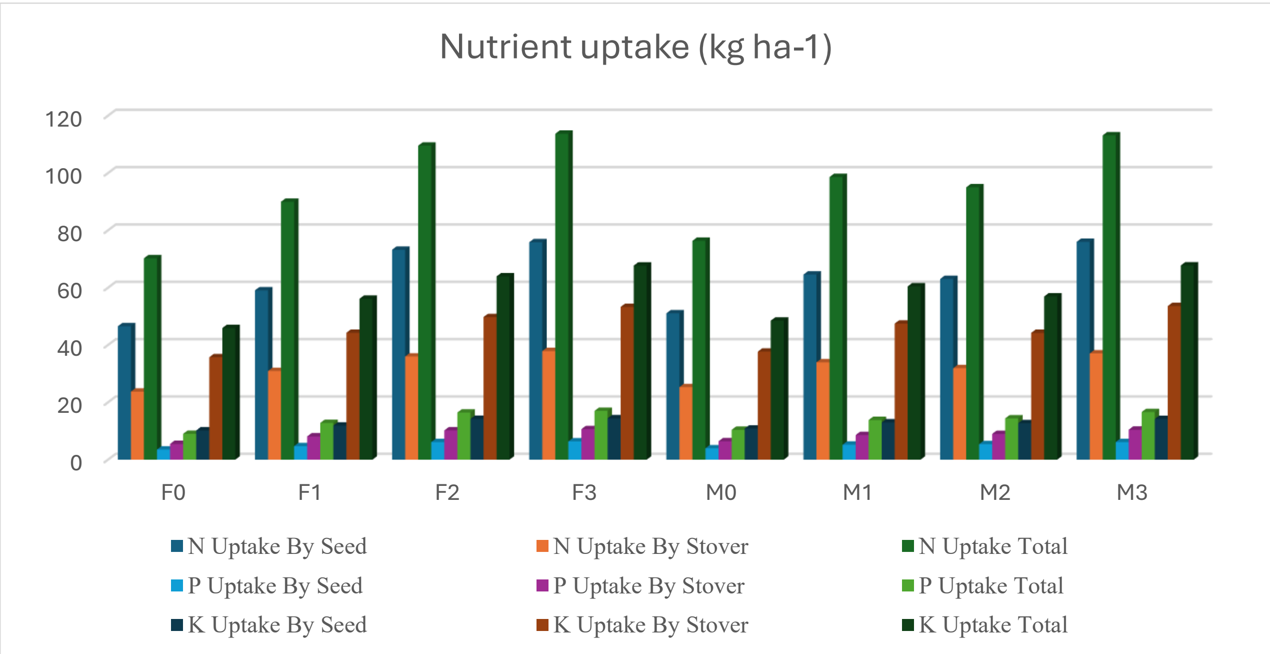

Fig. 2. Impact of Inorganic Fertilizer and Microbial Inoculation on nutrient uptake by soybean

IV. CONCLUSIONS

From the experiment result, it was concluded that the highest nutrient content and uptake was found under the 100 % RDF, which is at par with 75% RDF, along with the highest nutrient content and uptake was found under the combination of *Rhizobium* and PSB as compared to no inoculation and individually *Rhizobium* or PSB. The treatments *Rhizobium* and PSB were comparable to each other. The superior efficacy of dual microbial inoculation is driven by the metabolic synergy between biological nitrogen fixation and enhanced phosphorus solubilization. This combined action simultaneously satisfies the crop's interdependent macronutrient demands, justifying the use of microbial consortia over single inoculants to overcome physiological nutrient limitations and maximize overall plant uptake.

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