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Soil microbial population dynamics as affected by organic residues and nitrogen gradients in wheat production

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Abstract
A two-year field experiment (*Rabi* 2023–24 and 2024–25) was undertaken at RCA, Udaipur to quantify the effects of crop residue incorporation and nitrogen levels on soil microbial populations following wheat (*Triticum aestivum* L.) harvest. The split-plot design comprised five crop residues (C_0–C_4) and four nitrogen levels (N_0–N_3), replicated thrice. Soil microbial populations-bacteria (10^6 cfu g^{-1}), fungi (10^4 cfu g^{-1}) and actinomycetes (10^5 cfu g^{-1})-responded significantly to both main factors in individual years and pooled analysis. Cluster bean stover @ 5 t ha^{-1} (C_3) recorded the highest bacterial (66.02), fungal (20.54) and actinomycetes (14.98) counts, significantly surpassing the control. Among nitrogen treatments, 100% RDN (N_3) yielded the maximum microbial populations (bacteria 65.69, fungi 20.39, actinomycetes 14.89), indicating improved substrate availability and nutrient-driven microbial proliferation. Control plots consistently exhibited the lowest values. Interaction effects (C × N) remained non-significant, suggesting independent contributions of residue quality and nitrogen supply. The results demonstrate that integrating nutrient-rich crop residues with optimal nitrogen fertilization substantially improves soil microbial communities, which are essential indicators of soil fertility, nutrient cycling and long-term sustainability of wheat-based cropping systems.

Keywords: Crop residues, nitrogen fertilization, soil microbes, wheat system, microbial biomass

Introduction
Soil microbial communities play a central role in maintaining soil fertility, nutrient cycling, organic matter turnover and overall soil health in agroecosystems. These microbial groups-particularly bacteria, fungi and actinomycetes-serve as sensitive indicators of soil biological functioning and respond rapidly to changes in management practices (Zhou *et al.*, 2020) [7]. The continuous intensification of wheat-based systems in India has increased pressure on soil resources, making the management of soil biology crucial for sustaining long-term productivity. Crop residue incorporation has emerged as an essential practice for improving soil biological activity. Residues act as a carbon and energy source for microorganisms, thereby stimulating microbial growth, enzyme activity and nutrient mineralization (García-González *et al.*, 2018) [3]. The quality and biochemical composition of residues-particularly their C:N ratio, lignin content and cellulose–hemicellulose fractions-influence the rate of decomposition and the resulting microbial dynamics (Zhang *et al.*, 2021) [6]. Legume residues such as soybean, cluster bean and groundnut generally decompose faster and support higher microbial activity compared with cereal residues due to their higher nitrogen concentration and favorable biochemical traits (Razaq *et al.*, 2019) [4]. Nitrogen fertilization is another major factor regulating microbial populations in soil. Adequate nitrogen enhances microbial metabolism, accelerates residue decomposition and promotes microbial biomass accumulation (Chen *et al.*, 2020) [1]. However, imbalanced or excessive nitrogen can alter microbial community composition, suppress fungal populations and reduce enzymatic efficiency (Ding *et al.*, 2021) [2]. Therefore, understanding the interactive influence of nitrogen levels and residue incorporation is vital for optimizing nutrient cycling and improving soil health in wheat production systems. Wheat (*Triticum aestivum* L.) is a key staple crop in India, contributing significantly to food security. With declining soil organic matter and increasing dependence on chemical fertilizers, strategies that enhance soil

microbial functioning are necessary for building resilient and sustainable wheat-based cropping systems (Singh & Prasad, 2022) [5]. Despite substantial research on residues and nitrogen applications individually, comprehensive studies evaluating their combined influence on microbial communities under semi-arid wheat systems remain limited.

Materials and Methods

The field experiment was conducted during the *Rabi* seasons of 2023–24 and 2024–25 at the Instructional Farm of Rajasthan College of Agriculture, Udaipur, an area characterized by a semi-arid climate and sandy clay loam soils typical of the region. The study aimed to investigate how crop residue incorporation and nitrogen levels influence soil microbial populations after wheat harvest. To achieve this, a split plot design with three replications was employed. The main plot treatments consisted of five types of crop residues-control (no residue), maize stover, soybean straw, cluster bean stover and groundnut straw-each applied @ rate of 5 t ha^{-1} and incorporated uniformly into the soil prior to sowing. Subplot treatments included four nitrogen levels (0%, 50%, 75% and 100% of the Recommended Dose of Nitrogen), ensuring a comprehensive evaluation of nutrient interactions. Wheat variety HD 3086 was grown under standard agronomic practices, with phosphorus and potassium applied uniformly and nitrogen supplied in splits according to treatment. Residues were incorporated 15 days before sowing to allow partial decomposition and enhance microbial activity.

After the harvest of wheat, soil samples were collected from each plot at a depth of 0–15 cm using a sterilized auger, ensuring representative sampling. The samples were processed immediately and analyzed for major microbial groups-bacteria, fungi and actinomycetes-using the serial dilution and plate count technique. Nutrient Agar, Rose Bengal Agar and Kenknight's Agar were used as selective media for bacteria, fungi and actinomycetes, respectively and colonies were incubated under controlled conditions before enumeration. The microbial populations were expressed as colony-forming units (cfu g^{-1} soil). Statistical analysis of the data was conducted using ANOVA appropriate for the split plot design and treatment differences were assessed using the (CD) at the 5% probability level to determine the significance of crop residues, nitrogen levels and their interactions.

Results and Discussion

The results of the two-year investigation revealed a pronounced and consistent enhancement in soil microbial populations as a consequence of crop residue incorporation and nitrogen application. All three microbial groups-bacteria, fungi and actinomycetes-responded positively to the addition of organic residues, with the magnitude of improvement varying according to residue type. Among the treatments, cluster bean stover @ 5 t ha^{-1} (C_3) emerged as the most effective, registering the highest bacterial, fungal and actinomycete counts in both individual years and pooled data. In the pooled analysis, C_3 exhibited 66.02 $\times 10^6$ cfu g^{-1} bacteria, 20.54 $\times 10^4$ cfu g^{-1} fungi and 14.98 $\times 10^5$ cfu g^{-1} actinomycetes, values substantially higher than those observed under the residue-free control (C_0). The superior performance of cluster bean and groundnut residues can be attributed to their higher nitrogen content, favorable C:N ratios and rapid degradability, which collectively create a biologically enriched niche that supports vigorous microbial proliferation. This pattern aligns with earlier findings where leguminous biomass, owing to its enhanced biochemical quality, stimulated microbial abundance and accelerated soil biochemical transformations (Razaq *et al*., 2019; Zhang *et al*., 2021) [4, 6]. In contrast, soils lacking residue inputs presented lower microbial counts, likely due to limited carbon availability and reduced microbial substrate supply-a phenomenon also described by García-González *et al.* (2018) [3] in residue-depleted systems.Nitrogen application further reinforced microbial growth, exhibiting a clear and progressive increase from N_0 to N_3. The 100% RDN level (N_3) consistently produced the highest microbial densities, reaching 65.69 $\times 10^6$ cfu g^{-1} bacteria, 20.39 $\times 10^4$ cfu g^{-1} fungi and 14.89 $\times 10^5$ cfu g^{-1} actinomycetes in pooled data. This enhancement can be attributed to the role of nitrogen in facilitating microbial metabolism and accelerating the decomposition of added residues. Adequate nitrogen availability stimulates the synthesis of microbial enzymes and biomass, thereby intensifying decomposition processes and nutrient turnover. Chen *et al*. (2020) [1] similarly reported that balanced nitrogen inputs promote microbial growth by harmonizing nutrient supply with microbial demand, whereas deficient nitrogen limits microbial efficiency. However, the absence of an exponential increase beyond 100% RDN indicates that microbial communities favor balanced rather than excessive nutrient inputs, a trend consistent with observations from long-term fertilization studies demonstrating microbial sensitivity to nutrient stoichiometry (Ding *et al*., 2021) [2]. Interestingly, the C × N interaction remained non-significant across years and microbial groups, highlighting that crop residues and nitrogen influence microbial dynamics independently rather than synergistically. This suggests that while residues primarily act as a carbon-energy source, nitrogen functions as a metabolic enhancer, each contributing distinct yet complementary roles in shaping soil biological activity. Similar independent effects have been reported in studies where microbial responses were predominantly governed by substrate quality and nitrogen regulated the rate rather than the direction of microbial transformations (Zhou *et al*., 2020) [7].

Overall, the results demonstrate that integrating nutrient-rich crop residues, particularly legume-based biomass, with optimal nitrogen inputs substantially elevates soil microbial populations-an indicator of improved soil biological health. Enhanced microbial abundance under such integrated nutrient management practices promotes faster decomposition, improved nutrient mineralization and the development of a more resilient soil ecosystem. These findings reinforce the contemporary view that sustainable wheat production systems must emphasize the dual management of organic residues and balanced fertilizer inputs to maintain soil fertility and ecological stability (Singh & Prasad, 2022) [5].

Table 1: Effect of crop residues and nitrogen levels on bacteria, fungi and actinomycetes population in soil after harvest of wheat

Treatments	Soi microbial population								
	Bacteria (10^6 cfu g^{-1} soil)			Fungi (10^4 cfu g^{-1} soil)			Actinomycetes (10^5 cfu g^{-1} soil)		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
Crop Residues (C)									
C_0: Control	57.96	59.16	58.56	17.82	17.95	17.88	12.95	13.39	13.17
C_1: Maize stover 5 t ha^{-1}	61.02	62.35	61.68	18.92	19.20	19.06	13.65	14.21	13.93
C_2: Soybean stover 5 t ha^{-1}	62.20	63.61	62.91	19.23	19.54	19.38	13.97	14.45	14.21
C_3: Cluster bean stover 5 t ha^{-1}	65.26	66.79	66.02	20.35	20.84	20.59	14.67	15.29	14.98
C_4: Groundnut stover 5 t ha^{-1}	63.17	64.68	63.92	19.62	20.08	19.85	14.20	14.77	14.48
S.E. m (±)	0.74	0.78	0.54	0.27	0.27	0.19	0.19	0.20	0.14
CD at 5 %	2.42	2.55	1.62	0.88	0.87	0.57	0.60	0.66	0.41
Nitrogen level (N)									
N_0: Control	57.47	58.68	58.07	17.57	17.80	17.68	12.87	13.23	13.05
N_1: 50% RDN	62.17	63.59	62.88	19.26	19.70	19.48	13.94	14.50	14.22
N_2: 75% RDN	63.10	64.56	63.83	19.61	20.12	19.87	14.15	14.76	14.46
N_3: 100% RDN	64.95	66.44	65.69	20.31	20.47	20.39	14.59	15.19	14.89
S.E. m (±)	0.73	0.77	0.53	0.25	0.28	0.19	0.18	0.19	0.13
CD at 5 %	2.10	2.22	1.50	0.74	0.80	0.53	0.52	0.55	0.37
Interaction Effect ($C \times N$)	NS	NS	NS	NS	NS	NS	NS	NS	NS

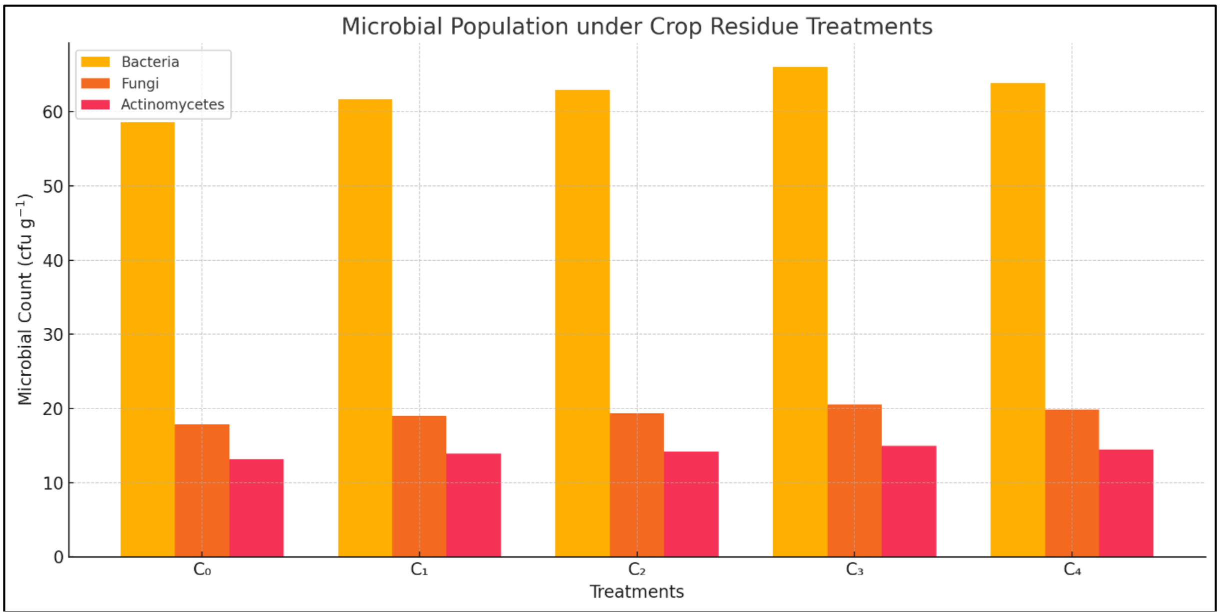

Fig 1: Effect of crop residues on bacteria, fungi and actinomycetes population in soil after harvest of wheat

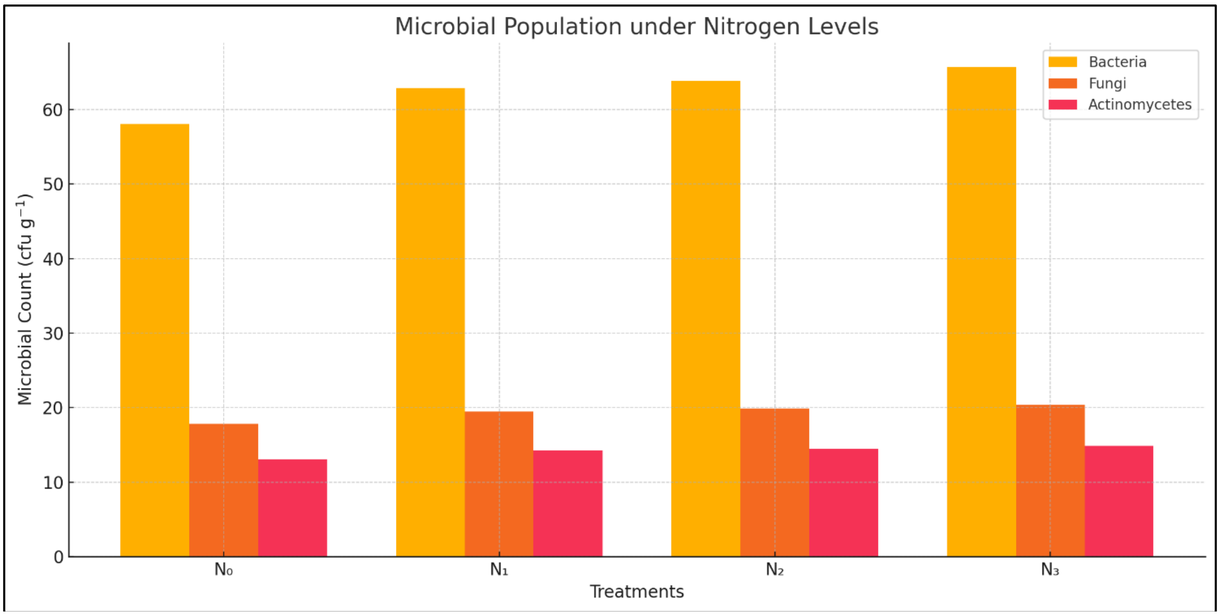

Fig 2: Effect of nitrogen levels on bacteria, fungi and actinomycetes population in soil after harvest of wheat

Conclusion

The present investigation clearly demonstrated that both crop residue incorporation and nitrogen fertilization play decisive and independent roles in shaping soil microbial dynamics after wheat harvest. The incorporation of organic residues-particularly legume-based residues such as cluster bean and groundnut straw-substantially enhanced the population of bacteria, fungi, and actinomycetes compared with the residue-free control. This improvement can be attributed to higher-quality carbon substrates, favourable C:N ratios, and greater biochemical degradability of leguminous biomasses, which collectively stimulated microbial proliferation and sustained biological activity within the soil system. Similarly, progressive increases in nitrogen application promoted microbial abundance, with 100% RDN consistently producing the highest microbial populations across both seasons. Adequate nitrogen availability supported microbial metabolism and accelerated residue decomposition, thereby strengthening soil biological functioning. The absence of a significant C × N interaction indicates that crop residues and nitrogen levels exert complementary but independent effects on microbial proliferation rather than synergistic influences. Overall, the findings underline the importance of integrating nutrient-rich organic residues with balanced nitrogen inputs to enhance soil microbial communities-an essential component of soil fertility and long-term sustainability in wheat-based cropping systems. Adoption of such integrated nutrient management practices can contribute significantly to improving soil health, nutrient cycling, and productivity in semi-arid agroecosystems.

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