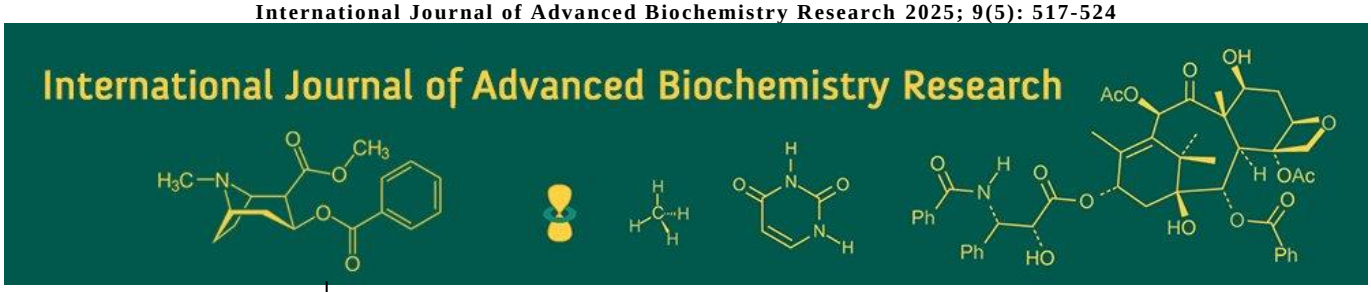

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating: 5.29
IJABR 2025; 9(5): 517-524
www.biochemjournal.com
Received: 21-02-2025
Accepted: 25-03-2025

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Soil health and nutrient dynamics in wheat under integrated nutrient management

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DOI: https://www.doi.org/10.33545/26174693.2025.v9.i5g.4381

Abstract
Wheat (*Triticum aestivum* L.) is a globally significant cereal crop whose productivity is adversely affected by late sowing, leading to reduced yield potential due to a shortened growing season. Under such conditions, integrated nutrient management (INM) strategies that combine organic and inorganic nutrient sources offer a promising solution for enhancing soil fertility and crop performance. This study investigated the impact of various INM practices on potassium content and uptake in wheat under late-sown conditions. A field experiment was conducted using a randomized block design with twelve treatments, including different combinations of farmyard manure (FYM), Vermicompost, and nitrogen levels. Soil samples collected before sowing and after harvest were analyzed for pH, electrical conductivity (EC), organic carbon (OC), and available N, P, and K. Grain and straw samples were evaluated for nutrient content and uptake. Results showed that INM treatments, particularly those involving Vermicompost with recommended or enhanced nitrogen levels, significantly improved soil fertility parameters and nutrient uptake. The treatment with 125% RDN plus 25% nitrogen from Vermicompost (T_3) consistently recorded the highest values for available soil potassium, organic carbon, and potassium uptake in both grain and straw. These findings highlight the potential of INM for improving nutrient use efficiency and sustaining wheat production under late-sown conditions.

Keywords: Integrated nutrient management, farmyard manure, vermicompost, soil fertility, sustainable agriculture

Introduction
Wheat (*Triticum aestivum* L.) is one of the most important staple food crops globally, contributing significantly to global food security. Its productivity, however, is highly influenced by climatic conditions, soil fertility, and agronomic management practices. Among these factors, the timely sowing of wheat plays a critical role in determining yield potential. Late sowing, which often results from delayed harvesting of preceding crops or climatic uncertainties, leads to a shortened growing period and suboptimal crop development, thereby limiting yield (Wu and Ma, 2015; Banjara *et al*., 2022) [30, 3]. Under such adverse conditions, effective nutrient management becomes increasingly important to maximize resource use efficiency and sustain crop productivity. Integrated Nutrient Management (INM) has emerged as a sustainable strategy that optimizes the use of both organic and inorganic nutrient sources to enhance soil fertility, nutrient availability, and crop performance (Chejara *et al*., 2021) [9]. INM practices aim to improve the synchrony between nutrient supply and crop demand while minimizing nutrient losses and environmental degradation (Sarkar *et al*., 2020) [2].

The role of organic amendments such as farmyard manure (FYM) and Vermicompost in improving soil structure, microbial activity, and nutrient mineralization is well documented (Sharma *et al*., 2021) [31]. These inputs not only supply essential macro-and micronutrients but also enhance soil water-holding capacity, aeration, and biological activity, thereby creating a conducive environment for crop growth (Yadav *et al*., 2021) [31]. When used in combination with chemical fertilizers, organic sources can enhance nutrient use efficiency, improve the soil's buffering capacity, and support long-term agricultural sustainability. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are central to wheat growth and yield formation. Nitrogen influences vegetative growth and grain filling; phosphorus is vital for energy transfer and root development; and potassium plays a key role in stomatal regulation, enzyme activation, and stress resistance.

Under late-sown conditions, efficient uptake and assimilation of these nutrients become critical for ensuring satisfactory crop performance within a limited growing window. Recent studies have emphasized the potential of INM to improve nutrient uptake, especially under suboptimal growing conditions. For example, combining FYM or Vermicompost with recommended or slightly enhanced nitrogen levels has been shown to increase nutrient availability and uptake efficiency in wheat (Reddy *et al*., 2013; Yadav *et al*., 2021; Kumar *et al*., 2022) [23, 31, 3]. However, the specific effects of these combinations on nutrient content and uptake in late-sown wheat remain underexplored. The present study was undertaken to evaluate the effects of various INM practices on potassium content and uptake in wheat under late-sown conditions. Different combinations of FYM and Vermicompost with varying nitrogen doses were examined to identify the most effective treatments that enhance nutrient use efficiency, improve soil fertility, and support sustainable wheat production.

Materials and Methods

Experimental Design

The study was conducted at the experimental farm of the School of Agricultural & Environmental Sciences, with wheat as the test crop. A randomized block design (RBD) with three replications was employed to evaluate the effect of different INM treatments. The treatments included varying nitrogen levels combined with organic inputs (FYM and Vermicompost) applied before sowing. The details of the treatments are as follows:

T_1: Control (No nutrient application)
T_2: 125% Recommended Dose of Nitrogen (RDN) + 25% Nitrogen from FYM
T_3: 125% RDN + 25% Nitrogen from Vermicompost
T_4: 100% RDN + 25% Nitrogen from FYM
T_5: 100% RDN + 25% Nitrogen from Vermicompost
T_6: 75% RDN + 25% Nitrogen from FYM
T_7: 75% RDN + 25% Nitrogen from Vermicompost
T_8: 50% RDN + 50% Nitrogen from FYM
T_9: 50% RDN + 50% Nitrogen from Vermicompost
T_{10}: 25% RDN + 75% Nitrogen from FYM
T_{11}: 25% RDN + 75% Nitrogen from Vermicompost
T_{12}: 100% RDN (without organic inputs)

Soil Fertility Parameters

Soil fertility parameters were systematically evaluated through comprehensive sampling and laboratory analysis conducted at two critical stages: before sowing (BS) and after harvest (AH). Composite soil samples were collected from the 0-15 cm depth layer of each experimental plot using a stratified random sampling approach to ensure representative coverage. Laboratory analyses were carried out to determine key soil fertility parameters, including available nitrogen (N), phosphorus (P), potassium (K), soil organic carbon (OC), pH, and electrical conductivity (EC), following standard protocols (Jackson, 1973; Subbiah and Asija, 1956; Olsen *et al*., 1954; Walkley and Black, 1934) [12, 32, 17, 29] (Table 1).

Table 1: Physico-chemical properties of the experimental soil and methods of analysis

Parameter	Method	Reference
pH	Calibrated pH meter	Jackson (1973) [12]
ECe (dSm^{-1})	Conductivity meter	Page *et al*. (1982) [18]
Organic Carbon (%)	Titration with 0.2N Ferrous Ammonium Sulphate after digesting soil with $K_2Cr_2O_7$ and H_2SO_4	Walkley and Black (1934) [29]
Available N (kg ha^{-1})	Alkaline $KMnO_4$ method	Subbaiah and Asija (1956) [32]
Available P (kg ha^{-1})	Available phosphorus was extracted using 0.5 M $NaHCO_3$ (pH 8.5)	Olsen *et al*. (1954) [17]
Available K (kg ha^{-1})	Available potassium was extracted using 1 N ammonium acetate and measured using a calibrated flame photometer	Jackson (1973) [12]

Nutrient Estimation in Grain and Straw

At harvest, wheat grain and straw samples were collected and analyzed for their nitrogen, phosphorus, and potassium content. The nutrient uptake was calculated by multiplying the nutrient concentration by the respective dry matter yield of the grain and straw. At physiological maturity, wheat grain and straw samples were collected from each treatment plot. Samples were oven-dried at 65 °C to constant weight to determine dry matter yield. Estimated using the micro-Kjeldahl digestion method (AOAC, 2000) [1]. Determined by vanadomolybdate yellow color method after triacid digestion (Jackson, 1973) [12]. Measured using a flame photometer after diacid digestion (Page *et al*., 1982) [18].
Nutrient uptake (kg ha^{-1}) was computed as:

Nutrient Uptake = (Nutrient concentration (%) 100) × Dry matter yield (kg ha^{-1})

Separate calculations were performed for grain and straw, and total uptake was derived by summing both values.

Statistical Analysis

The data obtained were analyzed using analysis of variance (ANOVA) to determine the significance of treatment effects and treatment means were compared at $p < 0.05$ via LSD. Statistical significance was tested at the 5% level using R software.

Results and Discussion

Effect of Integrated Nutrient Management on Soil Fertility

The results presented in Table 2 show that Integrated Nutrient Management (INM) significantly influenced various soil fertility parameters, including soil pH, electrical conductivity (EC), organic carbon (OC), and the availability of nitrogen (N), phosphorus (P), and potassium (K). Soil pH exhibited a slight decrease after harvesting across all treatments, which is consistent with the general effect of organic amendments like farmyard manure (FYM) and Vermicompost. The pH values for the control treatment (T_1) were the highest both before sowing (7.2 BS) and after harvesting (7.1 AH), while the lowest pH values were

observed in treatments with higher organic inputs, such as T_{10} and T_{11} (6.7 BS and 6.6 AH). This slight acidification is likely due to the production of organic acids during the decomposition of FYM and Vermicompost, which contribute to a marginally lower pH in the soil (Table 2).

Electrical conductivity (EC), which indicates the ionic concentration in the soil, also increased after harvesting across all treatments. The highest EC value was recorded in T_3 (0.56 dS/m AH), which involved the application of 125% RDN with 25% nitrogen from Vermicompost. This increase in EC suggests that nutrient mineralization and release from Vermicompost enhanced the ionic concentration in the soil. The trend of increasing EC with organic amendments highlights the role of organic sources in promoting soil nutrient dynamics and mineralization. Organic carbon (OC) content showed a noticeable improvement with the INM treatments, with the highest OC (0.66% AH) recorded in T_3, followed by T_5 and T_{11}. In contrast, the control treatment had the lowest OC content (0.55% BS and 0.52% AH). The increase in OC is primarily attributed to the addition of organic matter from FYM and Vermicompost, which enhances soil structure, water retention, and microbial activity. These amendments not only add carbon directly but also foster an environment that supports the growth of soil microorganisms that contribute to the stabilization of organic matter in the soil. Available nitrogen (N) exhibited significant improvements under all treatments, with T_3 (125% RDN + 25% N through Vermicompost) recording the highest available nitrogen content (245 kg/ha AH). This increase can be linked to the gradual and sustained release of nitrogen from the organic sources, which improves soil fertility by ensuring a continuous supply of this essential nutrient for plant growth. Treatments that combined Vermicompost with the recommended dose of nitrogen (RDN) resulted in the most notable increases in available nitrogen, suggesting that Vermicompost provides a slow-release form of nitrogen that benefits soil fertility over time. Similarly, available phosphorus (P) and potassium (K) levels were significantly higher under the INM treatments compared to the control. The highest available phosphorus (14.2 kg/ha AH) was recorded in T_3, which had 125% RDN with 25% nitrogen from Vermicompost, followed closely by T_2. The increased phosphorus availability can be attributed to the role of Vermicompost in producing organic acids that enhance phosphorus solubilization. Available potassium also showed a marked improvement across all treatments, with T_3 recording the highest value (192 kg/ha AH), followed by T_2 and T_5. This increase in potassium can be explained by the contribution of both FYM and Vermicompost in releasing potassium into the soil, thus improving nutrient availability (Table 2).

In conclusion, the combined application of recommended doses of nitrogen (RDN) with organic amendments, particularly Vermicompost, was found to be the most effective treatment for improving soil fertility parameters. Treatments like T_3 and T_5 consistently exhibited higher levels of soil health indicators, including pH, EC, OC, and the availability of nitrogen, phosphorus, and potassium. These findings highlight the significant role of integrated nutrient management in enhancing soil fertility, improving nutrient availability, and promoting sustainable agricultural practices.

Table 2: Effect of Integrated Nutrient Management on Soil Fertility

Symbol	Treatments	Soil pH		EC (ds/m)		OC (%)		Available N (Kg/ ha)		Available P (kg/ha)		Available K (kg/ha)	
		BS	AH	BS	AH	BS	AH	BS	AH	BS	AH	BS	AH
T_1	Control	7.2	7.1	0.5	0.4	0.6	0.5	220	210	13	12	180	175
T_2	125% RDN + 25% N through FYM	7.1	7.0	0.5	0.6	0.6	0.7	230	240	13	14	185	190
T_3	125% RDN + 25% N through Vermicompost	7.1	7.0	0.5	0.6	0.6	0.7	230	245	13	14	185	192
T_4	100% RDN + 25% N through FYM	7.0	6.9	0.5	0.5	0.6	0.6	225	235	13	14	182	188
T_5	100% RDN + 25% N through Vermicompost	7.0	6.9	0.5	0.5	0.6	0.6	225	238	13	14	182	190
T_6	75% RDN + 25% N through FYM	6.9	6.8	0.5	0.5	0.6	0.6	222	230	13	13	181	185
T_7	75% RDN + 25% N through Vermicompost	6.9	6.8	0.5	0.5	0.6	0.6	222	232	13	14	181	187
T_8	50% RDN + 50% N through FYM	6.8	6.7	0.5	0.5	0.6	0.6	220	225	13	13	180	183
T_9	50% RDN + 50% N through Vermicompost	6.8	6.7	0.5	0.5	0.6	0.6	220	228	13	13	180	185
T_{10}	25% RDN + 75% N through FYM	6.7	6.6	0.5	0.5	0.6	0.6	218	222	12	13	178	180
T_{11}	25% RDN + 75% N through Vermicompost	6.7	6.6	0.5	0.5	0.6	0.6	218	225	12	13	178	182
T_{12}	100% RDN	7.0	6.9	0.5	0.5	0.6	0.6	225	230	13	13	182	185

Nutrient Content and Uptake in Wheat Grain and Straw

The present study evaluated the effect of Integrated Nutrient Management (INM) on the nitrogen (N), phosphorus (P), and potassium (K) content and uptake in wheat grain and straw under late-sown conditions. The results demonstrate that different nutrient management strategies significantly influenced nutrient content and uptake, emphasizing the potential of INM practices to improve crop nutrition and productivity.

Effect of Integrated Nutrient Management on Nitrogen (N) Content and Uptake

The nitrogen content in both grain and straw was significantly higher under treatments that included Vermicompost compared to those using only FYM. For instance, the nitrogen content in wheat grain ranged from 1.8% in the control (T_1) to 2.3% in T_3 (125% RDN + 25% N through Vermicompost), and in straw, it ranged from 0.6% (T_1 and T_{10}) to 0.9% (T_3) (Table 3). The enhanced nitrogen content in the treatments with Vermicompost is attributed to the better mineralization of organic matter, which improves nitrogen availability. The highest nitrogen uptake was recorded in T_3, with 57.5 kg/ha in grain and 22.5 kg/ha in straw, indicating the effectiveness of Vermicompost in improving nitrogen uptake due to its slow-release nature and increased microbial activity. The control treatment (T_1) exhibited the lowest nitrogen uptake (45 kg/ha in grain and 15 kg/ha in straw), highlighting the importance of organic amendments in enhancing nitrogen use efficiency.

Table 3: Effect of integrated nutrient management on Nitrogen content and Nitrogen uptake in wheat

Symbol	Treatments	N content (%)		N Uptake (kg/ha)	
		Grain	Straw	Grain	Straw
T_1	Control	1.8	0.6	45	15
T_2	125% RDN+ 25% N through FYM	2.2	0.8	55	20
T_3	125% RDN+ 25% N through Vermicompost	2.3	0.9	57.5	22.5
T_4	100% RDN+ 25% N through FYM	2.1	0.7	52.5	17.5
T_5	100% RDN+ 25% N through Vermicompost	2.2	0.8	55	20
T_6	75% RDN+ 25% N through FYM	2	0.7	50	17.5
T_7	75% RDN+ 25% N through Vermicompost	2.1	0.8	52.5	20
T_8	50% RDN+ 50% N through FYM	1.9	0.6	47.5	15
T_9	50% RDN+ 50% N through Vermicompost	2	0.7	50	17.5
T_{10}	25% RDN+ 75% N through FYM	1.8	0.6	45	15
T_{11}	25% RDN+ 75% N through Vermicompost	1.9	0.7	47.5	17.5
T_{12}	100% RDN	2	0.7	50	17.5
SEm±		0.046	0.027	1.157	0.677
LSD (p=0.05)		0.144	0.084	3.600	2.106

Effect of Integrated Nutrient Management on Phosphorus (P) Content and Uptake

Phosphorus content in both grain and straw was also significantly influenced by INM practices. The maximum phosphorus content in grain (0.37%) and straw (0.16%) was observed in T_3, followed by T_2 (0.35% in grain and 0.15% in straw). These results suggest that the higher recommended dose of nitrogen combined with organic inputs like Vermicompost or FYM enhanced phosphorus availability and uptake. The highest phosphorus uptake (9.25 kg/ha in grain and 4.0 kg/ha in straw) was recorded under T_3, which involved 125% RDN with 25% N from Vermicompost (Table 4). The LSD values confirm that T_3 and T_2 are significantly superior to many other treatments and the control in improving phosphorus content and uptake. This is likely due to the improved microbial activity and mineralization processes in the rhizosphere, which enhance phosphorus solubilization and availability. In contrast, treatments with lower nitrogen levels, particularly T_{10} and T_{11}, resulted in lower phosphorus content and uptake, indicating the importance of adequate nitrogen supply in facilitating phosphorus acquisition. These findings emphasize the importance of organic-inorganic nutrient integration in improving nutrient availability and crop performance under late-sown conditions.

Table 4: Effect of integrated nutrient management on Phosphorus content and uptake in wheat

Symbol	Treatments	P content (%)		P Uptake (Kg/ha)	
		Grain	Straw	Grain	Straw
T_1	Control	0.25	0.1	6.25	2.5
T_2	125% RDN+ 25% N through FYM	0.35	0.15	8.75	3.75
T_3	125% RDN+ 25% N through Vermicompost	0.37	0.16	9.25	4
T_4	100% RDN+ 25% N through FYM	0.32	0.13	8	3.25
T_5	100% RDN+ 25% N through Vermicompost	0.34	0.14	8.5	3.5
T_6	75% RDN+ 25% N through FYM	0.3	0.12	7.5	3
T_7	75% RDN+ 25% N through Vermicompost	0.31	0.13	7.75	3.25
T_8	50% RDN+ 50% N through FYM	0.28	0.11	7	2.75
T_9	50% RDN+ 50% N through Vermicompost	0.29	0.12	7.25	3
T_{10}	25% RDN+ 75% N through FYM	0.26	0.1	6.5	2.5
T_{11}	25% RDN+ 75% N through Vermicompost	0.27	0.11	6.75	2.75
T_{12}	100% RDN	0.3	0.12	7.5	3
SEm±		0.008	0.004	0.19	0.09
LSD (p=0.05)		0.024	0.012	0.56	0.27

Effect of Integrated Nutrient Management on Potassium (K) Content and Uptake

he findings from the present study clearly demonstrate the significant impact of integrated nutrient management (INM) on potassium (K) content and uptake in both the grain and straw of wheat. Among the various treatments evaluated, T_3 (125% recommended nitrogen dose [RDN] + 25% N through Vermicompost) consistently showed the highest values for K content in grain (0.59%) and straw (1.75%) as well as for K uptake in grain (13 kg/ha) and straw (38.8 kg/ha). This was closely followed by T_2 (125% RDN + 25% N through FYM) and T_5 (100% RDN + 25% N through Vermicompost), both of which also recorded higher K content and uptake compared to the control (T_1, 0.35% K in grain, 1.20% in straw, 9.8 kg/ha grain uptake, 30 kg/ha straw uptake). The standard errors of the mean (SEm±) for grain K content, straw K content, grain K uptake, and straw K uptake were 0.022, 0.065, 0.552, and 1.635, respectively, indicating good precision in the mean estimates. The least significant difference (LSD) at the 5% probability level for these parameters were 0.135, 0.397, 3.361, and 9.949, respectively, confirming that the differences among treatments were statistically significant (Table 5).

These results suggest that the integration of organic sources such as Vermicompost or FYM with chemical fertilizers enhances the availability and uptake of potassium in wheat. The superior performance of Vermicompost-amended treatments, particularly in terms of K content and uptake, can be attributed to the improved soil biological activity, better nutrient release, and enhanced root growth facilitated by Vermicompost.

Table 5: Effect of Integrated Nutrient Management on Potassium Content and Potassium Uptake in Wheat

Symbol	Treatments	K content (%)		K Uptake (Kg/ha)	
		Grain	Straw	Grain	Straw
T_1	Control	0.35	1.2	9.8	30
T_2	125% RDN+ 25% N through FYM	0.5	1.5	11.5	37.5
T_3	125% RDN+ 25% N through Vermicompost	0.59	1.75	13	38.8
T_4	100% RDN+ 25% N through FYM	0.48	1.4	12	35
T_5	100% RDN+ 25% N through Vermicompost	0.49	1.45	12.3	36.3
T_6	75% RDN+ 25% N through FYM	0.45	1.3	11.3	32.5
T_7	75% RDN+ 25% N through Vermicompost	0.46	1.35	11.5	33.8
T_8	50% RDN+ 50% N through FYM	0.42	1.25	10.5	31.3
T_9	50% RDN+ 50% N through Vermicompost	0.43	1.3	10.8	32.5
T_{10}	25% RDN+ 75% N through FYM	0.41	1.22	10.3	30.5
T_{11}	25% RDN+ 75% N through Vermicompost	0.42	1.25	10.5	31.3
T_{12}	100% RDN	0.45	1.3	11.3	32.5
SEm±		0.022	0.065	0.552	1.635
LSD (p=0.05)		0.135	0.397	3.361	9.949

Economic Analyses of Different Nutrient Management Treatments in Wheat Cultivation

The economic analysis of wheat cultivation was conducted to evaluate the financial viability of various nutrient management practices. The analysis considered the cost of cultivation, gross returns, net returns, and the Benefit-Cost (B:C) ratio for each treatment. The treatments involved different combinations of recommended dose of nitrogen (RDN) and organic or inorganic inputs, including FYM (Farm Yard Manure), Vermicompost, and biofertilizers. The statistical analysis of treatment effects on net returns and benefit-cost (B:C) ratios revealed significant differences among nutrient management strategies. T_2 (125% RDN + 25% N through FYM) emerged as the top performer in terms of net returns (₹42,000 ha^{-1}), significantly outperforming the control (₹20,000 ha^{-1}) and most other treatments. However, while T_2 delivered the highest absolute returns, its B:C ratio (1.65) was slightly lower than that of T_4 and T_5 (100% RDN + 25% organic N through FYM/Vermicompost), which achieved the highest B:C ratio of 1.67 with net returns of ₹36,000-37,000 ha^{-1}. This suggests that while increasing RDN to 125% boosts yields, the 100% RDN + organic N approach offers a better balance between profitability and input efficiency (Table 6). Treatments incorporating organic amendments (FYM or Vermicompost) consistently outperformed the control, with even 75% RDN + 25% organic N (T_6-T_7) maintaining competitive net returns (₹31,000-32,000 ha^{-1}) and favorable B:C ratios (>1.60). However, further reduction of RDN to 50% or 25% (T_8-T_{11}) led to a significant decline in profitability, though these treatments still surpassed the control. Notably, FYM and Vermicompost performed similarly at equivalent substitution levels, indicating that both are viable options for partial nitrogen replacement (Figure 1; Table 6).

The control treatment (T_1) confirmed the necessity of nutrient supplementation, as it resulted in the lowest net returns (₹20,000 ha^{-1}) and B:C ratio (1.44). Overall, the findings highlight that integrated nutrient management—combining chemical and organic sources—optimizes both economic returns and resource use efficiency. For farmers seeking maximum profitability, T_2 (125% RDN + FYM) is recommended, while those prioritizing sustainability and cost-effectiveness should consider T_4/T_5 (100% RDN + 25% organic N). Additionally, T_6/T_7 (75% RDN + 25% organic N) presents a viable middle ground for reducing chemical inputs without substantial yield penalties.

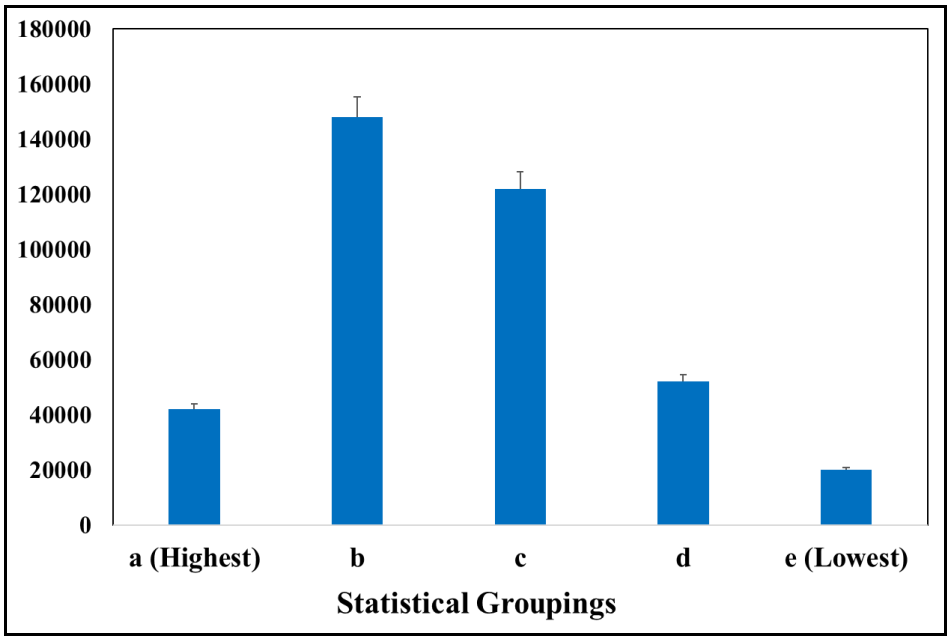

Fig 1: Sum of Net Returns (₹ ha^{-1}) across Statistical Groupings.

The bar chart illustrates the economic performance measured in Indian Rupees per hectare (₹ ha^{-1}) across five statistical groups labelled 'a' through 'e'.

The findings demonstrate that strategic integration of chemical fertilizers and organic amendments can significantly enhance wheat productivity and farm profitability. This study provides empirical evidence that balanced nutrient management-combining recommended doses of chemical fertilizers with judicious use of organic sources-offers farmers multiple pathways to optimize both crop yields and economic returns. The results particularly emphasize how organic amendments like FYM and Vermicompost can serve as effective partial substitutes for chemical nitrogen while maintaining or even improving cost-benefit ratios. These insights are especially valuable for developing sustainable wheat production systems that balance productivity goals with input-use efficiency and long-term soil health considerations. The differential performance of various treatment combinations provides farmers with flexible options to choose nutrient management strategies based on their specific resource availability and economic priorities.

Table 6: Economic Analysis of Different Nutrient Management Treatments in Wheat Cultivation

Symbol	Treatment	Net Returns (₹ ha^{-1})	Statistical Grouping	B:C Ratio	B:C Ranking
T_2	125% RDN + 25% N through FYM	42,000	a (Highest)	1.65	4
T_3	125% RDN + 25% N through VC	40,000	b	1.64	5
T_5	100% RDN + 25% N through VC	37,000	b	1.67	1
T_4	100% RDN + 25% N through FYM	36,000	b	1.67	1
T_{12}	100% RDN	35,000	b	1.66	3
T_7	75% RDN + 25% N through VC	32,000	c	1.62	6
T_6	75% RDN + 25% N through FYM	31,000	c	1.61	7
T_9	50% RDN + 50% N through VC	30,000	c	1.6	8
T_8	50% RDN + 50% N through FYM	29,000	c	1.59	9
T_{11}	25% RDN + 75% N through VC	26,000	d	1.53	11
T_{10}	25% RDN + 75% N FYM	26,000	d	1.54	10
T_1	Control	20,000	e (Lowest)	1.44	12

Discussion

This research highlights the potential of integrating organic and inorganic nutrient sources to enhance nutrient use efficiency, improve soil fertility, and ensure sustainable agricultural production (Ramesh *et al*., 2009; Sharma & Mittra, 1991) [21, 24]. It also provides evidence that vermicompost is a valuable component of INM strategies for wheat cultivation, particularly under late-sown conditions where nutrient availability is critical for crop growth and yield (Banik *et al*., 2006; Chaudhary *et al*., 2011) [2, 8]. The present study clearly establishes that Integrated Nutrient Management (INM), particularly involving combinations of inorganic fertilizers with organic amendments such as vermicompost and farmyard manure (FYM), plays a crucial role in enhancing soil fertility and nutrient uptake in wheat under late-sown conditions (Kumar *et al*., 2018; Singh *et al*., 2014) [15, 25].

Soil fertility parameters such as pH, electrical conductivity (EC), organic carbon (OC), and available macronutrients (N, P, K) showed marked improvement in treatments receiving integrated inputs compared to the control (Rautaray *et al*., 2003; Nambiar & Ghosh, 1984) [22, 16]. Slight reductions in soil pH under treatments like T_{10} and T_{11} suggest that the decomposition of organic materials leads to organic acid formation, contributing to mild soil acidification favorable for nutrient solubilization (Kale *et al*., 1982) [13]. The increase in EC after harvesting, especially in T_3 (125% RDN + 25% N through vermicompost), implies enhanced ionic concentration due to greater nutrient mineralization from organic sources (Patil & Sheelavantar, 2000) [19]. Treatments with vermicompost significantly increased soil organic carbon, with T_3 recording the highest OC content (0.66% AH), reinforcing the role of vermicompost in improving soil structure, microbial activity, and carbon dynamics (Subba Rao, 2001; Kavitha & Subramanian, 2007) [26, 14]. Available nitrogen, phosphorus, and potassium levels also increased substantially under integrated treatments, with T_3 consistently outperforming others. The slow-release nature of vermicompost and its ability to stimulate microbial-mediated nutrient transformation processes likely contributed to higher nutrient availability (Edwards *et al*., 2004; Sudhakar *et al*., 2018) [11, 27].

These improvements in soil nutrient status were directly reflected in nutrient content and uptake by wheat plants. T_3 not only had the highest grain and straw nitrogen content (2.3% and 0.9%) but also recorded the greatest nitrogen uptake (57.5 kg/ha in grain, 22.5 kg/ha in straw), confirming the superior efficiency of combining higher fertilizer doses with organic nitrogen sources (Choudhary *et al*., 2014) [10]. Similarly, phosphorus and potassium content and uptake were significantly enhanced, with T_3 again exhibiting the highest values (P uptake: 9.25 kg/ha in grain, 4.0 kg/ha in straw; K uptake: 13 kg/ha in grain, 38.8 kg/ha in straw). These findings emphasize that the synergy between inorganic and organic inputs promotes sustained nutrient supply, improved soil health, and greater nutrient use efficiency, ultimately leading to better crop productivity under challenging late-sown conditions (Reddy *et al*., 2013; Yadav *et al*., 2021) [23, 31].

Conclusion

This study conclusively demonstrates the significant benefits of Integrated Nutrient Management (INM) practices, particularly the integration of organic amendments like Vermicompost with inorganic fertilizers, in enhancing soil fertility, nutrient availability, and crop productivity in wheat under late-sown conditions. The results highlight that the inclusion of Vermicompost not only improves key soil parameters such as organic carbon, pH, EC, and nutrient availability but also promotes better nutrient uptake by wheat plants, leading to improved growth and yield. The synergy between organic and inorganic nutrients, especially the slow-release nature of Vermicompost, plays a crucial role in enhancing nutrient use efficiency, improving microbial activity, and sustaining soil health. The study also underscores the potential of

Vermicompost as a sustainable alternative to conventional fertilizers, reducing the environmental footprint of agricultural practices while maintaining or even improving crop yields. The integration of organic and inorganic inputs is shown to provide a reliable strategy for enhancing soil nutrient dynamics and ensuring the sustainability of wheat cultivation under challenging conditions, such as those found in late-sown crops. These findings provide a strong basis for promoting INM as an effective approach for sustainable agricultural production, particularly in regions facing soil fertility degradation and nutrient imbalance.

Acknowledgement
The author would like to School of Agricultural and Environmental Sciences at Shobhit Institute of Engineering and Technology Deemed-to-be University), Meerut, India, for their support.

Funding
The author(s) received no financial support for the research and publication of this article.

Conflicts of Interest
All authors declare no conflict of interest.

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