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Effect of Integrated Nutrient Management on Chemical properties of Soil, Nutrient Content and Uptake and Economics under Wheat Agroecosystem

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Authors' contributions

This work was carried out in collaboration among all authors. Author HK conducted the original research as part of the M.Sc. experimental trial. Author KK assisted in conducting the research and collecting the data. Author Ajaypal assisted in preparing the manuscript. Author AK assisted in tabulating and analyzing the data. Author AV reviewed the manuscript. All authors read and approved the final manuscript.

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Abstract

During the *rabi* season of 2022-23, a field experiment was conducted at the Experimental Farm of the Department of Agriculture, Mata Gujri College, Sri Fatehgarh Sahib, Punjab. The experiment aimed to study the effect of integrated nutrient management on soil chemical properties, nutrient content and uptake, and the economics of a wheat agroecosystem. The experiment was conducted using a randomised block design (RBD)

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with three replications and 11 treatments involving wheat *var.* DBW-187. The results revealed that INM significantly affected soil fertility, nutrient content and uptake, and the economics of wheat. The treatment comprising 100% RDF + vermicompost at 5 t ha^{-1} + FYM at 10 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1} recorded significantly higher organic carbon (0.91%), available N (339.33 kg ha^{-1}), available P (24.99 kg ha^{-1}), available K (209.67 kg ha^{-1}), nutrient contents in grain and straw [N (2.71% and 0.67%), P (0.74% and 0.15%), and K (0.81% and 2.13%)], nutrient uptake in grain and straw [N (143.54 and 53.52 kg ha^{-1}), P (39.19 and 11.98 kg ha^{-1}), and K (42.90 and 170.16 kg ha^{-1})], the highest net return (Rs. 114,070 ha^{-1}), and the highest B:C ratio (1.82). The treatment comprising 100% RDF combined with vermicompost at 5 t ha^{-1} and *Azotobacter* at 6 kg ha^{-1} produced lower values than the best-performing treatment. The integrated application of RDF, vermicompost, FYM, and *Azotobacter* was effective in improving nutrient use and economic returns in wheat under the experimental conditions.

Keywords: Integrated nutrient management; wheat agroecosystem; vermicompost; farmyard manure; azotobacter; soil chemical properties; nutrient content; nutrient uptake; economics.

1. Introduction

Wheat is one of the major staple crops of India and contributes around 35% of the country's food basket. Wheat belongs to the family *Poaceae.* It is used in bakery products such as bread, flour, pasta, biscuits, cakes, porridge, halwa, and sweet meals, and is most commonly used for making chapatti. Wheat contains more protein than other cereals (Maskey et al., 2024). The main protein in wheat is gluten, which is an important component for bakers. Therefore, it is called the "king of cereals". It is the second most important crop after rice. Besides being a staple food for humans, wheat straw is a major source of animal feed. A key challenge is to increase wheat grain yield while maintaining its protein content (Patel et al., 2026).

Approximately 55% of the world's population depends directly or indirectly on wheat for about 20% of its calorie intake. Owing to adverse climatic conditions in India and population demand, three basic types of wheat—bread wheat, durum, and dicoccum—are cultivated. Apart from major nutrients, micronutrients such as zinc, boron, and magnesium play major roles in yield and quality (Sharma et al., 2026). Cereals are rich sources of nutrients, and wheat is one of the major sources of protein in the human diet. A 100 g portion of wheat provides 327 calories and is an excellent source of essential nutrients, including protein, dietary fibre, manganese, phosphorus, and niacin. Wheat grain contains nearly 12% protein, 2.7% minerals, 2% fibre, 1.7% fat, and 60-70% carbohydrates (Prasad, 2015).

Farmers in India depend heavily on chemical fertilisers, mainly urea, DAP, and MOP, which have induced micronutrient deficiencies (Sharma et al., 2026) and deteriorated soil health and microbial activity. Nutrient management can have detrimental effects on soil fertility and crop yield (Mishra et al., 2023). To overcome these constraints, integrated nutrient management (INM) is a practice in which organic, inorganic (chemical fertiliser), and biofertiliser sources are combined to improve and maintain soil fertility, supply plant nutrients, support soil health, obtain good-quality yields, and maintain ecological and environmental quality (Yadav et al., 2018). Agriculture remains a soil-based industry. INM is a suitable option that helps to mitigate multiple nutrient deficiencies. The judicious use of FYM with chemical fertilisers improves the physical, chemical, and biological properties of soil and enhances crop productivity. The application of organic manure may also improve the availability of native soil nutrients and the efficiency of applied fertilisers (Tiwari et al., 2017). INM is a better approach to supplying crop nutrients by integrating organic and inorganic nutrient sources. It can also improve soil health and enhance nutrient-use efficiency. The INM strategy therefore plays a significant role in plant nutrition. Nutrient-use efficiency and water-use efficiency also increase under the INM approach (Kumar et al., 2006). Wheat grain and straw yields can also be enhanced through INM because it is an environmentally compatible approach. To increase production while conserving soil health and the environment, chemical and organic nutrient sources can be used together. Other terms, such as integrated plant nutrient supply (IPNS) and integrated nutrient supply and management (INSAM), are also used as synonyms for INM.

Evidence from field studies indicates that integrating mineral fertilisers with organic and microbial inputs can improve wheat productivity, soil organic matter, nutrient availability and economic performance compared with reliance on a single nutrient source (Hyder et al., 2021; Upadhyay et al., 2024).

Long-term evaluations in rice–wheat systems further indicate that balanced fertilisation combined with organic inputs can sustain soil nutrient transformations, soil carbon and wheat productivity (Ranjan et al., 2023; Walia et al., 2024).

However, the combined effects of the recommended dose of fertiliser, farmyard manure, vermicompost and Azotobacter on post-harvest soil chemical properties, nutrient content and uptake, and economic returns have not been sufficiently documented under the agro-ecological conditions represented by the present experiment. The present study examined the effect of INM on soil chemical properties, nutrient content and uptake, and the economics of a wheat agroecosystem.

2. Materials and Methods

A field experiment was conducted at the Experimental Farm, Department of Agriculture, Mata Gujri College, Sri Fatehgarh Sahib, Punjab, during the *rabi* season of 2022-23. The study aimed to evaluate the effect of INM practices on soil chemical properties, nutrient content and uptake, and the economics of a wheat agroecosystem. The experiment was conducted with three replications in a randomised block design (RBD) using wheat *var.* DBW-187. The experimental soil was moderately fertile and had a pH of 8.13, organic carbon of 0.63%, EC of 0.78 dS m^{-1}, available N of 280.85 kg ha^{-1}, available P of 20.12 kg ha^{-1}, and available K of 170.55 kg ha^{-1}. A seed rate of 90 kg ha^{-1} was used for line sowing at a depth of 4-5 cm and an inter-row spacing of 22.5 cm. The recorded data were statistically analysed using MS Excel and OPSTAT software. The treatment means were subjected to analysis of variance as described by Panse and Sukhatme (1985) for a randomised block design, and the critical difference (CD) was calculated at the 0.05 level of significance for comparison.

Table 1. Details of methods employed for different parameters

Soil Parameters	Method employed
pH	Glass electrode pH meter (Jackson, 1973)
EC (dSm^{-1})	Conductivity meter (Jackson, 1973)
Organic carbon (%)	Wet oxidation method (Walkley and Black,1934)
Available N (kg ha^{-1})	Alkaline potassium permanganate method (Subbiah and Asija,1956)
Available P (kg ha^{-1})	Olsen method (Olsen et al. 1954)
Available K (kg ha^{-1})	Ammonium acetate method (Merwin and Peech 1951)
Nutrient Uptake	$\frac{\text{Content (\%)} \times \text{Yield } kg\ ha^{-1}}{100}$

Table 2. Details of experiment

	Treatments
T_1	Control
T_2	RDF (75%)
T_3	RDF (100%)
T_4	RDF (75%) + FYM @ 10 t ha^{-1}
T_5	RDF (75%) + VC @ 5 t ha^{-1}
T_6	RDF (100%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}
T_7	RDF (75%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}
T_8	RDF (50%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}
T_9	RDF (50%) + FYM @ 10 t ha^{-1}
T_{10}	RDF (75%) + *Azotobacter* @ 6 kg ha^{-1}
T_{11}	RDF (100%) + VC @ 5 t ha^{-1} + FYM @ 10 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}

3. Results and Discussion

3.1 Chemical Properties of Soil

The data on organic carbon and available soil macronutrients (NPK) after harvest were significantly affected by the treatments. Among the treatments, the highest pH (8.09) was recorded in the T_1 control. However, T_{11} [100% RDF + VC at 5 t ha^{-1} + FYM at 10 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1}] recorded the highest electrical conductivity (0.85 dS m^{-1}) and organic carbon (0.91%) among the treatments. Similarly, the maximum available

N (339.33 kg ha^{-1}), available P (24.99 kg ha^{-1}), and available K (209.67 kg ha^{-1}) were recorded under T_{11}, which was statistically at par with T_6 [100% RDF + VC at 5 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1}]. The lowest available N (270.17 kg ha^{-1}), available P (15.17 kg ha^{-1}), and available K (161.83 kg ha^{-1}) were recorded in the T_1 control. The application of N, P, and K fertilisers, organic manures, and biofertilisers substantially affected soil N after crop harvest. All nutrient treatments significantly increased N availability. T_{11} recorded the highest available N and was statistically at par with T_6, whereas the absolute control recorded the lowest available soil N after harvest. Chemical fertilisers and vermicompost inoculated with *Azotobacter* improved soil N availability. Li et al. (2024) reported that vermicompost and *Azotobacter chroococcum* improved N retention in maize. Post-harvest available soil P was highest under T_{11} and was statistically at par with T_6. Plots treated with biofertiliser had higher available P. The release of organic acids during the microbial decomposition of organic materials and the increased solubility of native P may have contributed to P accumulation. Urkurkar et al. (2010) reported that the integrated application of inorganic and organic manures increased soil fertility and productivity in a rice–wheat system. The data showed that successive treatment combinations increased soil K. T_{11} recorded the highest K level and was statistically at par with T_6. After harvest, the combined application of chemical fertilisers, organic fertilisers, and biofertilisers increased soil K levels relative to the recommended fertiliser dose. K availability varied significantly compared with the control, possibly because the treatments increased soil NPK availability. Gawde et al. (2017) observed similar results in a rice–wheat cropping system, in which integrated nutrient management improved soil nutrient status. Similar results were reported by Singh et al. (2007), Urkurkar et al. (2010), Kumar et al. (2006), Ananthi and Shilpa Shree (2024), Lodhi et al. (2024), and Kumar et al. (2026).

Table 3. Influence of integrated nutrient management on pH, EC, OC

	Treatments	pH	EC (dSm^{-1})	OC (%)
T_1	Control	8.09	0.60	0.61
T_2	RDF (75%)	7.43	0.67	0.75
T_3	RDF (100%)	7.61	0.73	0.82
T_4	RDF (75%) + FYM @ 10 t ha^{-1}	7.50	0.68	0.76
T_5	RDF (75%) + VC @ 5 t ha^{-1}	7.56	0.72	0.80
T_6	RDF (100%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	7.68	0.79	0.88
T_7	RDF (75%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	7.63	0.75	0.85
T_8	RDF (50%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	7.40	0.65	0.74
T_9	RDF (50%) + FYM @ 10 t ha^{-1}	7.37	0.63	0.69
T_{10}	RDF (75%) + *Azotobacter* @ 6 kg ha^{-1}	7.53	0.70	0.78
T_{11}	RDF (100%) + VC @ 5 t ha^{-1} + FYM @ 10 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	7.85	0.85	0.91
SE (m)±		0.19	0.04	0.01
CD (0.05)		NS	NS	0.02

Table 4. Influence of integrated nutrient management on available NPK (kg ha^{-1}) in wheat after harvest

	Treatments	Available N	Available P	Available K
T_1	Control	270.17	15.17	161.83
T_2	RDF (75%)	292.25	18.05	177.57
T_3	RDF (100%)	312.37	20.93	193.75
T_4	RDF (75%) + FYM @ 10 t ha^{-1}	298.13	18.89	181.47
T_5	RDF (75%) + VC @ 5 t ha^{-1}	308.27	20.03	189.41
T_6	RDF (100%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	325.23	22.95	202.51
T_7	RDF (75%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	318.51	21.73	198.23
T_8	RDF (50%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	288.79	17.79	174.79
T_9	RDF (50%) + FYM @ 10 t ha^{-1}	281.85	16.69	170.97
T_{10}	RDF (75%) + *Azotobacter* @ 6 kg ha^{-1}	303.91	19.91	185.91
T_{11}	RDF (100%) + VC @ 5 t ha^{-1} + FYM @ 10 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	339.33	24.99	209.67
SE (m)±		4.91	1.03	2.52
CD (0.05)		14.47	3.04	7.42

Table 5. Influence of integrated nutrient management on NPK content in wheat

	Treatments	Grain (%)			Straw (%)		
		N	P	K	N	P	K
T_1	Control	1.57	0.44	0.47	0.38	0.03	1.40
T_2	RDF (75%)	2.03	0.50	0.63	0.47	0.08	1.73
T_3	RDF (100%)	2.17	0.58	0.68	0.55	0.12	1.83
T_4	RDF (75%) + FYM @ 10 t ha^{-1}	2.07	0.52	0.64	0.48	0.09	1.74
T_5	RDF (75%) + VC @ 5 t ha^{-1}	2.11	0.56	0.66	0.52	0.11	1.76
T_6	RDF (100%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	2.27	0.62	0.72	0.65	0.14	1.91
T_7	RDF (75%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	2.25	0.60	0.71	0.61	0.13	1.85
T_8	RDF (50%) + VC @ 5 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	1.72	0.48	0.51	0.46	0.07	1.68
T_9	RDF (50%) + FYM @ 10 t ha^{-1}	1.66	0.47	0.50	0.44	0.06	1.50
T_{10}	RDF (75%) + *Azotobacter* @ 6 kg ha^{-1}	2.09	0.54	0.65	0.50	0.10	1.75
T_{11}	RDF (100%) + VC @ 5 t ha^{-1} + FYM @ 10 t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	2.71	0.74	0.81	0.67	0.15	2.13
SE (m)±		0.21	0.06	0.07	0.07	0.02	0.13
CD (0.05)		NS	NS	NS	NS	NS	NS

Table 6. Influence of integrated nutrient management on plant nutrient uptake (kg ha^{-1}) in wheat

	Treatments	Grain (kg ha^{-1})			Straw (kg ha^{-1})		
		N	P	K	N	P	K
T_1	Control	44.21	12.39	13.23	18.02	1.4	66.40
T_2	RDF (75%)	77.76	19.15	24.13	28.20	4.80	103.81
T_3	RDF (100%)	100.40	26.83	31.46	37.38	8.15	124.38
T_4	RDF (75%) + FYM @ 10t ha^{-1}	81.95	20.58	25.33	29.25	5.48	106.05
T_5	RDF (75%) + VC @ 5t ha^{-1}	93.57	24.83	29.27	34.37	7.27	116.35
T_6	RDF (100%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	113.56	31.01	36.02	46.31	9.97	136.08
T_7	RDF (75%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	108.47	28.92	32.22	42.65	9.09	129.37
T_8	RDF (50%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	63.76	17.79	18.90	27.09	4.12	98.96
T_9	RDF (50%) + FYM @ 10t ha^{-1}	58.48	16.55	17.61	25.07	3.41	85.48
T_{10}	RDF (75%) + *Azotobacter* @ 6kg ha^{-1}	87.13	22.51	27.09	30.79	6.1	107.78
T_{11}	RDF (100%) + VC @ 5t ha^{-1} + FYM @ 10t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	143.54	39.19	42.90	53.52	11.98	170.16
SE (m)±		2.38	0.82	1.38	1.14	0.39	2.41
CD (0.05)		7.01	2.41	4.08	3.36	1.15	7.10

3.2 Plant Analysis

At harvest, nutrient contents in grain and straw were analysed separately and showed non-significant variation among treatments. The maximum grain nutrient contents were recorded under T_{11} [100% RDF + VC at 5 t ha^{-1} + FYM at 10 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1}], with N, P, and K contents of 2.71%, 0.74%, and 0.81%, respectively, which were higher than those under the other treatments. Similarly, the maximum straw nutrient contents were recorded under T_{11}, with N, P, and K contents of 0.67%, 0.15%, and 2.13%, respectively, which were higher than those under the other treatments. Under integrated nutrient management, the increased nutrient contents in grain and straw may have resulted from the immediate supply of N, P, and K through RDF, the gradual and continuous release of nutrients from FYM and vermicompost throughout crop growth, and enhanced microbial activity associated with *Azotobacter*, a free-living N-fixing bacterium (Gupta et al., 2023). The synergistic use of organic and inorganic nutrient sources with biofertiliser application may have improved soil physical properties and root proliferation, resulting in greater nutrient accumulation in plant parts. Similar improvements in N, P, and K contents under INM were reported by Bhadauria et al. (2016), Singh and Jat (2016), Nishant et al. (2016), Lodhi et al. (2024), Maskey et al. (2024), and Patel et al. (2026).

Table 7. Influence of integrated nutrient management on total NPK (kg ha^{-1}) uptake by wheat

	Treatments	N	P	K
T_1	Control	62.23	13.79	79.63
T_2	RDF (75%)	105.96	23.95	127.94
T_3	RDF (100%)	137.78	34.98	155.84
T_4	RDF (75%) + FYM @ 10t ha^{-1}	111.21	26.06	131.38
T_5	RDF (75%) + VC @ 5t ha^{-1}	127.94	32.10	145.62
T_6	RDF (100%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	159.87	40.98	172.10
T_7	RDF (75%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	151.12	38.01	161.59
T_8	RDF (50%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	90.85	21.91	117.86
T_9	RDF (50%) + FYM @ 10t ha^{-1}	83.55	19.96	103.09
T_{10}	RDF (75%) + *Azotobacter* @ 6kg ha^{-1}	117.92	28.61	134.87
T_{11}	RDF (100%) + VC @ 5t ha^{-1} + FYM @ 10t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	197.06	51.17	213.06
SE (m)±		2.54	0.68	3.15
CD (0.05)		7.48	2.02	9.29

Table 8. Influence of integrated nutrient management on economics of crop

	Treatments	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C ratio
T_1	Control	2.815	4.743	43031.6	97784	54752.4	1.23
T_2	RDF (75%)	3.831	6.001	51609.6	129416.8	77807.15	1.43
T_3	RDF (100%)	4.627	6.797	52302.6	152699.8	100397.2	1.71
T_4	RDF (75%) + FYM @ 10t ha^{-1}	3.959	6.095	54109.6	132888.8	78779.15	1.49
T_5	RDF (75%) + VC @ 5t ha^{-1}	4.435	6.611	55409.6	147131.8	91722.15	1.65
T_6	RDF (100%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	5.003	7.125	58302.6	163313.8	105011.2	1.80
T_7	RDF (75%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	4.821	6.993	56809.6	158390.3	101580.7	1.78
T_8	RDF (50%) + VC @ 5t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	3.707	5.891	56116.6	125901.8	69785.15	1.30
T_9	RDF (50%) + FYM @ 10t ha^{-1}	3.523	5.699	52616.6	120455.8	67839.65	1.27
T_{10}	RDF (75%) + *Azotobacter* @ 6 kg ha^{-1}	4.169	6.159	53809.6	137863.3	83053.65	1.56
T_{11}	RDF (100%) + VC @ 5t ha^{-1} + FYM @ 10t ha^{-1} + *Azotobacter* @ 6 kg ha^{-1}	5.297	7.989	62402.6	176463.3	114070.7	1.82

Nutrient uptake by wheat grain was significantly affected by the treatments. Among the treatments, the maximum uptake of N, P, and K by grain was recorded under T_{11} [100% RDF + VC at 5 t ha^{-1} + FYM at 10 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1}] at 143.54, 39.19, and 42.90 kg ha^{-1}, respectively. Similarly, the maximum uptake of N, P, and K by straw was recorded under T_{11} at 53.52, 11.98, and 170.16 kg ha^{-1}, respectively. The maximum total crop uptake of N, P, and K at harvest was also recorded under T_{11} at 197.06, 51.17, and 213.06 kg ha^{-1}, respectively, and was significantly higher than that under the other treatments. The higher N, P, and K uptake may have resulted from the greater availability of nutrients to the crop at critical growth stages, which encouraged plant growth and grain development and ultimately increased grain yield and nutrient uptake. INM treatments increased nutrient availability to plant roots, thereby contributing to higher grain yield. The results indicate that crop nutrient uptake was greater under INM than under the sole use of chemical fertilisers. Similar improvements in N, P, and K uptake under INM were reported by Dahiya et al. (2019), Bellakki et al. (1998), Bamboriya et al. (2023), Maskey et al. (2024), and Patel et al. (2026).

3.3 Economics

The economics were calculated on the basis of prevailing market rates during 2022-23. The maximum gross return (Rs. 176,463 ha^{-1}), net return (Rs. 114,070 ha^{-1}), and B:C ratio (1.82) were recorded under T_{11} [100% RDF + VC at 5 t ha^{-1} + FYM at 10 t ha^{-1} + *Azotobacter* at 6 kg ha^{-1}], which was superior to the other treatments. The higher gross return, net return, and B:C ratio under T_{11} may be attributed to the synergistic effect of organic, inorganic, and biofertiliser sources, which improved nutrient-use efficiency, sustained nutrient availability throughout crop growth, and enhanced yield attributes. The lower cost of nitrogen fixation associated with biofertiliser inoculation, together with improved soil fertility from organic manures, resulted in a favourable cost–benefit ratio compared with the sole application of chemical fertilisers or organic manures. Similar economic responses to nutrient management were reported by Dhar et al. (2016) in wheat, Togas et al. (2017) in pearl millet, Nargave and Mandloi (2018) in maize, and Yadav et al. (2018) and Sharma and Tomar (2024) in wheat.

4. Conclusion

The study indicated that integrated nutrient management improved post-harvest soil fertility, nutrient uptake, and economic returns in wheat. Among the tested treatments, 100% recommended dose of fertiliser combined with vermicompost at 5 t ha^{-1}, farmyard manure at 10 t ha^{-1}, and *Azotobacter* at 6 kg ha^{-1} recorded the highest organic carbon, available N, P, and K, nutrient uptake, and benefit–cost ratio. This treatment also produced the highest grain and straw yields reported in the economic analysis. These results suggest that combining inorganic fertilisers with organic manures and a biofertiliser may improve nutrient-use performance and profitability in wheat under the experimental conditions.

5. Limitations

The study was conducted during one *rabi* season at a single experimental location; therefore, validation across locations and seasons is required before broad recommendations can be made. The manuscript does not provide complete details of RDF composition, plot size, irrigation schedule, sowing and harvesting dates, or crop-management practices. Long-term effects on soil health, microbial activity, and sustainability were not assessed.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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