



RESEARCH ARTICLE

Integrated nutrient management enhances soil physico-chemical properties, yield and grain quality of wheat (*Triticum aestivum* L.)

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Abstract

Nutrient imbalance and over-reliance on chemical fertilisers remain major constraints to sustaining wheat productivity and grain quality. To address this issue, a two-year field experiment was conducted during the rabi seasons of 2021–22 and 2022–23 at the Student Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh. The study evaluated the effects of integrated nutrient sources on soil physico-chemical properties and wheat grain quality. The experimental design followed a randomised block layout, incorporating 11 distinct treatments replicated thrice. The integrated treatment comprising 100 % recommended nitrogen-phosphorous-potassium (NPK) + sulphur (S) (40 kg ha⁻¹), zinc (Zn) (5 kg ha⁻¹), iron (Fe) (10 kg ha⁻¹), *Azotobacter* + phosphate-solubilising bacteria (PSB) + farmyard manure (FYM) (5 t ha⁻¹) (T10) significantly improved grain yield, soil organic carbon and nutrient availability. Grain quality parameters, including protein, lysine and methionine contents, were also significantly enhanced under integrated nutrient management across both years.

Keywords: biofertilisers; integrated nutrient management; micronutrients; quality and soil health; soil fertility; wheat quality; yield

Introduction

Wheat (*Triticum aestivum* L.) is a major staple crop in India and ranks second after rice in total food grain production. It is a member of the family Poaceae (Graminae). It serves as a staple food for nearly two billion people worldwide, accounting for approximately 36 % of the global population. It ranks second in global cereal output, with a productivity of 2.98 Mt ha⁻¹. Wheat serves as an excellent nutritious supplement for the human body, with 8.0–15.0 % protein, 60–68 % carbohydrates, 1.5–2.0 % fat, 2.0–2.5 % cellulose and 1.5–2.0 % minerals and vitamins (B complex and vitamin E) and is utilised as feed for both humans and animals (1, 2). Wheat is a crop that may be cultivated in various soil types and climatic conditions. The crop is most effectively cultivated between latitudes 30° to 60° N and 27° to 40° S, at altitudes ranging from sea level to 3658 m.

Application of chemical fertilisers enhances crop growth, biomass accumulation and yield (3). However, excessive and

unbalanced use of chemical fertilisers adversely affects soil physico-chemical and biological properties, leading to declining soil fertility and environmental degradation (4–6). Despite their role in achieving high productivity, reliance on chemical fertilisers alone is unsustainable due to rising input costs and degradation of soil and environmental quality (7).

Chemical fertiliser enrichment in agricultural products is effective in food security, environmental protection and the health of human communities (8). Nitrogen (N) is an essential component of wheat yield (9). The efficiency of wheat cultivars to N usage has become increasingly significant to allow a reduction in N fertiliser use without lowering yield. Phosphorus (P) is critical for improving seed maturity and seed development (10). Phosphorus plays a crucial role in various critical tasks such as photosynthesis, the transformation of sugar to starch, protein development, nucleic acid generation, N fixation and the manufacture of oil. It is also part of all metabolic cycles in plants (11). Potassium (K) is of peculiar importance due to

its live role in biochemical functions of the plant like activating various enzymes, improvement of amino acids, carbohydrate and fat concentration, developing tolerance against drought and resistance to frost, lodging, diseases and insect attack (12). Biofertilisers can fix N from the atmosphere in the available form for plant and have good influence upon plant growth by synthesis of antibiotic. *Azotobacter* is employed as biofertiliser in the production of most crops (13).

Despite the importance of integrated nutrient management, limited information is available on its combined effect on soil health and grain quality of wheat under the agro-climatic conditions of Kanpur, Uttar Pradesh. Therefore, the present study was undertaken to evaluate the impact of integrated use of chemical fertilisers, organic manures and biofertilisers on soil properties, crop productivity and grain quality. It was hypothesised that the combined application of these nutrient sources would improve soil fertility, enhance nutrient availability and result in higher yield and better grain quality of wheat compared to conventional fertilisation practices.

Materials and Methods

The present experiment was conducted on the Student Instructional Farm of Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh during rabi season of 2021–22 and 2022–23. The experiment consisted of 11 treatments (T₁: Control, T₂: 100 % NPK, T₃: 100 % NPK + 5 t farmyard manure (FYM), T₄: 100 % NPK + phosphate-solubilising bacteria (PSB) + *Azotobacter*, T₅: 125 % NPK + PSB + *Azotobacter* + 5 t FYM, T₆: 100 % NPK + S₄₀, T₇: 100 % NPK + Zn₅, T₈: 100 % NPK + S₄₀ + Zn₅, T₉: 100 % NPK + S₄₀ + Zn₅ + Fe₁₀, T₁₀: 100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 ton FYM and T₁₁: 125 % NPK). The treatments were laid in randomised block design with 3 replications. The experimental soil was sandy loam in texture and alkaline in reaction, with low organic carbon and low available N, P and K status (Table 1). The soil can be classified as an alluvial Inceptisol.

Grain N was estimated using the Kjeldahl method (14) and protein content was calculated using a factor of 6.25. Lysine and methionine contents were determined using near-infrared reflectance spectroscopy (NIRS). Soil and plant samples were analysed using standard procedures: soil pH and electrical conductivity (EC) (15), organic carbon (16), available N (17), P (18), K

(19), sulphur (S) (20) and micronutrients (21).

Yield

Grain and straw yields were recorded at harvest and expressed on a hectare basis.

Results and Discussion

Yield

Wheat grain yield was significantly influenced by integrated nutrient management treatments (Table 2). The grain yield of wheat ranged from 17.90 to 48.60 q ha⁻¹ in the first year and from 19.84 to 49.93 q ha⁻¹ in the second year, indicating substantial treatment effects. All treatments recorded significantly higher yields than the control in both years of the study. Among the treatments, T₁₀ (100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM) produced the highest grain yield, followed closely by T₉ (100 % NPK + S₄₀ + Zn₅ + Fe₁₀), showing a clear advantage over the control, suggesting synergistic effects on nutrient availability and uptake. The substantial increase in yield highlights the effectiveness of integrated use of organic, inorganic and biofertilisers. Higher yields in the second year suggest residual effects of integrated nutrient application.

Soil physico-chemical parameters

As can be seen from the Table 3, there was no significant difference in soil reaction following wheat harvests due to different treatments. Though pH was dropped from the original condition due to numerous treatments done in the wheat crop, it declined from 8.15 to 8.05 in the first year and 8.15 to 8.04 in the second year. The highest reduction in soil pH was obtained with the treatment of T₁₀ (100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM) followed by T₅ when FYM was applied. For electrical conductivity, the same result as soil pH was found. The organic carbon value was slightly greater during the second year as compared to that of the first year. There were slight but substantial changes in organic carbon during both years. Remarkably, all the treatments had higher organic carbon content than the control. It changed from 3.7 to 4.2 g kg⁻¹ in the first year and from 3.8 to 4.2 g kg⁻¹ throughout the second year. The treatment 100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM gave the highest value for both years (22).

Investigation of soil available N (Table 4) varied from 185.10 to 208.13 kg ha⁻¹ and 185.55 to 210.11 kg ha⁻¹ during the first and second

Table 1. Initial physicochemical properties of experimental soil

Soil properties	Value/ Rating		Method of determination
	2021–22	2022–23	
pH	8.14	8.15	(15)
EC	0.45 (slightly high)	0.46 (slightly high)	(15)
Organic carbon (g kg ⁻¹)	3.9 (low)	3.8 (low)	(16)
Available N (kg ha ⁻¹)	179.16 (low)	180.56 (low)	(17)
Available P (kg ha ⁻¹)	13.04 (low)	13.24 (low)	(18)
Available K (kg ha ⁻¹)	129.54 (low)	132.42 (low)	(19)
Available S (ppm ha ⁻¹)	15.98 (low)	16.10 (low)	(20)
Available Zn (mg kg ⁻¹)	0.40	0.41	(21)
Available Fe (mg kg ⁻¹)	10.35	10.38	(21)

Table 2. Effect of integrated use of nutrients on grain yield (q ha^{-1}) of wheat crop

Treatment symbol	Treatment combination	Grain yield (q ha^{-1})	
		2021-22	2022-23
T1	Control	17.90	19.84
T2	100 % NPK	38.90	39.75
T3	100 % NPK + 5 t FYM	42.23	42.29
T4	100 % NPK + PSB + <i>Azotobacter</i>	40.96	41.89
T5	125 % NPK + PSB + <i>Azotobacter</i> + 5 t FYM	42.31	42.98
T6	100 % NPK + S ₄₀	42.58	43.56
T7	100 % NPK + Zn ₅	42.95	45.08
T8	100 % NPK + S ₄₀ + Zn ₅	44.35	45.19
T9	100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀	45.90	47.16
T10	100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀ + <i>Azotobacter</i> + PSB + 5 t FYM	48.60	49.93
T11	125 % NPK	42.49	43.36
	S.E. (m) ($\pm$)	0.31	0.34
	C.D. ($p = 0.05$)	0.93	1.00

NPK: Recommended dose of nitrogen, phosphorus and potassium; FYM: Farmyard manure; PSB: Phosphate-solubilising bacteria; S₄₀, Zn₅ and Fe₁₀ denote sulphur (40 kg ha^{-1}), zinc (5 kg ha^{-1}) and iron (10 kg ha^{-1}), respectively. S.E. (m): Standard error of mean; CD ($p = 0.05$): Critical difference at 5 % level of significance.

Table 3. Effect of integrated use of nutrients on soil pH, electrical conductivity (dSm^{-1}) and organic carbon (g kg^{-1}) after harvest of the crop

Treatments	pH		EC		Organic carbon	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T ₁ : Control	8.15	8.15	0.45	0.45	3.9	3.8
T ₂ : 100 % NPK	8.13	8.12	0.46	0.46	4.0	4.0
T ₃ : 100 % NPK + 5 t FYM	8.11	8.10	0.44	0.44	4.1	4.2
T ₄ : 100 % NPK + PSB + <i>Azotobacter</i>	8.07	8.06	0.44	0.43	4.0	4.1
T ₅ : 125 % NPK + PSB + <i>Azotobacter</i> + 5 t FYM	8.05	8.04	0.43	0.43	4.1	4.3
T ₆ : 100 % NPK + S ₄₀	8.10	8.10	0.46	0.46	4.0	4.0
T ₇ : 100 % NPK + Zn ₅	8.10	8.10	0.46	0.46	3.8	4.0
T ₈ : 100 % NPK + S ₄₀ + Zn ₅	8.09	8.08	0.47	0.46	4.0	4.1
T ₉ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀	8.09	8.08	0.47	0.47	4.0	4.1
T ₁₀ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀ + <i>Azotobacter</i> + PSB + 5 t FYM	8.05	8.04	0.43	0.42	4.2	4.2
T ₁₁ : 125 % NPK	8.13	8.12	0.48	0.49	4.1	4.1
S.E. (m) ($\pm$)	0.01	0.01	0.01	0.01	0.01	0.01
C.D. ($p = 0.05$)	NS	NS	NS	NS	0.02	0.02

NPK: Recommended dose of nitrogen, phosphorus and potassium; FYM: Farmyard manure; PSB: Phosphate-solubilising bacteria; S₄₀, Zn₅ and Fe₁₀ denote sulphur (40 kg ha^{-1}), zinc (5 kg ha^{-1}) and iron (10 kg ha^{-1}), respectively. EC: Electrical conductivity. S.E. (m): Standard error of mean; CD ($p = 0.05$): Critical difference at 5 % level of significance; NS: Non-significant.

years, respectively and treatment 125 % NPK + PSB + *Azotobacter* + FYM yielded the highest value, which was closely followed by 125 % NPK. The values of both the treatments were at par statistically. The trends and outcomes were comparable for both years. However, the overall values are much higher during the second year than the first year. Available status of phosphorus within all the treatments varied from 13.09 to 16.21 and 13.29 to 19.41 kg ha^{-1} during the first and second years, respectively, whereas treatments with 125 % NPK + PSB + *Azotobacter* + FYM offered the highest value. Integrated application of organic, inorganic and biofertilisers demonstrated the best increase in available P in comparison to inorganic fertilisers without organic treatment during both years. Potassium is a primary nutrient and increases in the experimental soil due to varied treatment combinations over both years of the experiment. Plot-wise study of soil for accessible K varied from 130.69 to 140.13 kg ha^{-1} and 133.21 to 150.03 kg ha^{-1} during the first and second years, respectively, while treatment 125 % NPK + PSB + *Azotobacter* + FYM gave the greatest result. This was quickly followed by 125 % NPK. The values of both therapies were at par statistically. The trends in outcomes were comparable in both years. However, the overall values are much higher during second year than the first year. Similar results were observed with respect to available NPK (23).

The available sulphur value was slightly higher during second year than the first year. There were slight but significant

differences in available sulphur during both years. Remarkably all the treatments exhibited higher available sulphur than that of control. It fluctuated from 16.03 to 18.31 kg ha^{-1} in first year and from 16.28 to 18.53 kg ha^{-1} throughout the second year. The treatment 100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM delivered the greatest value for both the years (Table 5), which was closely followed by 100 % NPK + S₄₀ + Zn₅ + Fe₁₀. The trends of outcomes were comparable during both years (24). The values of zinc were enhanced in the experimental soil due to various treatments during both the years. Maximum build-up of accessible zinc was detected with (100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM). There were slight but substantial increases in available zinc (plot wise) during both the years. Remarkably all the treatments exhibited higher available zinc content than that of control. It fluctuated from 0.42 to 0.54 mg kg^{-1} and 0.42 to 0.55 mg kg^{-1} during 2021–22 and 2022–23 correspondingly. Effect of 100 % NPK alone did not show significant superiority over control. Indicating that increasing the level of NPK from control to 100 % had no obvious positive effect (Table 4). Similar findings have also been reported by previous researchers (22, 25). The results showed that ranges of variation in available iron content were 10.39 to 16.31, 10.45 to 18.03 and 10.42 to 17.17 mg kg^{-1} of soil during the first year, the second-year analysis. The findings differed dramatically under different treatments as compared to control. T₁₀ (100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* +

Table 4. Effect of integrated use of nutrients on available nitrogen, phosphorus and potassium (kg ha⁻¹) after harvest of the crop

Treatments	Available N		Available P ₂ O ₅		Available K ₂ O	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T ₁ : Control	185.10	185.55	13.09	13.29	130.69	133.21
T ₂ : 100 % NPK	190.09	194.35	14.13	15.02	132.85	137.98
T ₃ : 100 % NPK + 5 t FYM	201.12	207.11	14.77	16.94	136.33	146.21
T ₄ : 100 % NPK + PSB + <i>Azotobacter</i>	203.45	205.63	15.09	17.66	135.50	145.32
T ₅ : 125 % NPK + PSB + <i>Azotobacter</i> + 5 t FYM	208.13	210.11	16.21	19.41	140.13	150.03
T ₆ : 100 % NPK + S ₄₀	195.00	199.92	14.61	15.63	133.21	140.67
T ₇ : 100 % NPK + Zn ₅	194.74	198.12	14.31	15.39	133.73	142.74
T ₈ : 100 % NPK + S ₄₀ + Zn ₅	197.63	201.89	14.44	15.43	134.01	144.31
T ₉ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀	198.77	203.12	14.52	15.51	134.47	144.96
T ₁₀ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀ + <i>Azotobacter</i> + PSB + 5 t FYM	205.52	209.31	15.97	18.21	138.49	147.41
T ₁₁ : 125 % NPK	207.21	209.02	14.86	16.09	138.56	147.76
S.E. (m) (±)	0.52	0.55	0.10	0.42	0.56	0.77
C.D. (p = 0.05)	1.55	1.62	0.28	1.23	1.65	2.28

NPK: Recommended dose of nitrogen, phosphorus and potassium; FYM: Farmyard manure; PSB: Phosphate-solubilising bacteria; S₄₀, Zn₅ and Fe₁₀ denote sulphur (40 kg ha⁻¹), zinc (5 kg ha⁻¹) and iron (10 kg ha⁻¹), respectively. Available N, P₂O₅ and K₂O are expressed in kg ha⁻¹. S.E. (m): Standard error of mean; CD (p = 0.05): Critical difference at 5 % level of significance.

Table 5. Effect of integrated use of nutrients on available sulphur (kg ha⁻¹), available zinc and available iron (mg kg⁻¹) after harvest of the crop

Treatments	Available S		Available Zn		Available Fe	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T ₁ : Control	16.03	16.28	0.42	0.42	10.39	10.45
T ₂ : 100 % NPK	16.51	16.61	0.43	0.44	10.60	10.69
T ₃ : 100 % NPK + 5 t FYM	17.07	17.49	0.46	0.48	13.78	13.98
T ₄ : 100 % NPK + PSB + <i>Azotobacter</i>	16.71	16.87	0.45	0.46	11.07	11.21
T ₅ : 125 % NPK + PSB + <i>Azotobacter</i> + 5 t FYM	17.28	17.81	0.47	0.48	13.89	14.07
T ₆ : 100 % NPK + S ₄₀	17.44	17.96	0.44	0.45	10.79	10.99
T ₇ : 100 % NPK + Zn ₅	16.61	16.79	0.48	0.49	10.88	11.12
T ₈ : 100 % NPK + S ₄₀ + Zn ₅	17.71	18.19	0.49	0.51	11.00	11.77
T ₉ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀	18.02	18.43	0.51	0.53	15.93	17.31
T ₁₀ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀ + <i>Azotobacter</i> + PSB + 5 t FYM	18.31	18.53	0.54	0.55	16.31	18.03
T ₁₁ : 125 % NPK	16.89	17.27	0.45	0.46	11.17	11.86
S.E. (m) (±)	0.11	0.07	0.01	0.01	0.21	0.25
C.D. (p = 0.05)	0.32	0.21	0.02	0.02	0.60	0.75

NPK: Recommended dose of nitrogen, phosphorus and potassium; FYM: Farmyard manure; PSB: Phosphate-solubilising bacteria; S₄₀, Zn₅ and Fe₁₀ denote sulphur (40 kg ha⁻¹), zinc (5 kg ha⁻¹) and iron (10 kg ha⁻¹), respectively. Available S is expressed in kg ha⁻¹, while Zn and Fe are expressed in mg kg⁻¹. S.E.(m): Standard error of mean; CD (p = 0.05): Critical difference at 5 % level of significance.

PSB + 5 t FYM) gave the maximum available iron content over both years. All the treatments except 100 % NPK exhibited considerably greater values over control. Treatment with iron addition yielded the second highest value, indicating that added iron resulted in an increase in available iron content, which delivered the next best value of Fe (26).

Quality parameters

The protein, lysine and methionine content were determined in wheat by using the Jones factor, the protein content in wheat grain is calculated by multiplying the N value by 6.25 (Jones factor). This factor considers the effects of nitrogen fertiliser on the protein content of wheat grains. The Jones factor provides a more precise estimation of the protein content of the wheat grain. The protein content varied from 9.50 % to 11.18 % during the first year and from 9.56 % to 11.31 % in the second year of the study. In the first year, the 125 % NPK treatment produced the highest protein content, whereas in the second year, the combination T₁₀ (100 % NPK + S₄₀ + Zn₅ + Fe₁₀ + *Azotobacter* + PSB + 5 t FYM) resulted in the highest levels (Table 5). The control treatment consistently exhibited the lowest protein content during both years. All treatments produced

considerably elevated protein content compared to the control, with marked variability in protein levels evident among the different treatments. Our results are in conformity with the results of other workers (27). The lysine level ranged from 3.09 to 4.06 and 3.10 to 4.11 g/16 g N during the first and second years, respectively. The treatment combination T₅ (125 % NPK + PSB + *Azotobacter* + 5 t of FYM) gave the greatest lysine content during the first and second years of field experiment. The treatment T₁ (Control) gave the lowest value of lysine content during the first and second years of research. All the therapy generated considerably greater lysine content in comparison to control. The lysine concentration varied dramatically among different integrated plant nutrition treatments (Table 6). Similar findings have also been reported by other workers in wheat (28). The methionine concentration ranged from 1.11 to 1.87 g/16 g N and 1.11 to 1.89 g/16 g N during the first and second years, respectively. The treatment combination T₅ (125 % NPK + PSB + *Azotobacter* + 5 t FYM) gave the greatest methionine content during the first and second years of the experiment (Table 6). The treatment T₁ (Control) gave the lowest value of protein content during both years of experiment. Similar finding has also been reported (29).

Table 6. Effect of integrated nutrient management on protein (%), lysine (g/16 g N) and methionine content in wheat grain

Treatments	Protein		Lysine		Methionine	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
T ₁ : Control	9.50	9.56	3.09	3.10	1.11	1.11
T ₂ : 100 % NPK	10.06	10.25	3.40	3.41	1.29	1.30
T ₃ : 100 % NPK + 5 t FYM	10.87	11.00	3.78	3.82	1.69	1.71
T ₄ : 100 % NPK + PSB + <i>Azotobacter</i>	10.93	11.00	3.85	3.90	1.73	1.75
T ₅ : 125 % NPK + PSB + <i>Azotobacter</i> + 5 t FYM	11.31	11.37	4.06	4.11	1.87	1.89
T ₆ : 100 % NPK+ S ₄₀	10.68	10.75	3.63	3.67	1.39	1.41
T ₇ : 100 % NPK + Zn ₅	10.62	10.68	3.56	3.59	1.50	1.51
T ₈ : 100 % NPK + S ₄₀ + Zn ₅	10.68	10.75	3.64	3.72	1.61	1.65
T ₉ : 100 % NPK + S ₄₀ + Zn ₅ + Fe ₁₀	10.75	10.81	3.71	3.79	1.65	1.69
T ₁₀ : 100 % NPK+ S ₄₀ + Zn ₅ + Fe ₁₀ + <i>Azotobacter</i> + PSB + 5 t FYM	11.12	11.31	3.98	4.07	1.83	1.87
T ₁₁ : 125 % NPK	11.18	11.25	4.02	4.05	1.85	1.86
S.E. (m) (±)	0.07	0.04	0.03	0.04	0.02	0.02
C.D. (p = 0.05)	0.20	0.12	0.09	0.11	0.05	0.07

NPK: Recommended dose of nitrogen, phosphorus and potassium; FYM: Farmyard manure; PSB: Phosphate-solubilising bacteria; S₄₀, Zn₅ and Fe₁₀ denote sulphur (40 kg ha⁻¹), zinc (5 kg ha⁻¹) and iron (10 kg ha⁻¹), respectively. Protein is expressed in %, while lysine and methionine are expressed in g per 100 g protein. S.E. (m): Standard error of mean; CD (p = 0.05): Critical difference at 5 % level of significance.

Conclusion

The findings from the two-year study clearly demonstrate that integrated nutrient management exerts a highly beneficial influence on wheat productivity, soil health and grain quality. The combined use of organic, inorganic and biofertiliser sources consistently produced superior grain yields compared to the control, with treatments such as T₁₀ and T₅ performing exceptionally well. The positive residual effects observed in the second year further emphasise the sustained benefits of balanced nutrient application. Soil physico-chemical properties, including pH, organic carbon and available Nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn) and iron (Fe), improved noticeably under integrated treatments, with farmyard manure (FYM) and micronutrient-enriched combinations showing the greatest enhancement. These changes reflect improved nutrient availability and soil fertility. Quality parameters such as protein, lysine and methionine also increased significantly under higher nutrient doses and integrated sources, confirming their role in improving the nutritional value of wheat grain. Overall, the study highlights that integrated nutrient management not only boosts yield but also enhances soil fertility and grain quality, making it a sustainable and productive strategy for wheat cultivation.

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Authors' contributions

AT conceived the study, conducted the field trials and drafted the manuscript. JP contributed to the experimental design of the study. AT, SS and VS performed the statistical analyses. HT¹ and DK assisted

in verifying the results and ensuring reproducibility. SRP, DD, HT² and AT participated in critical revision and editing of the manuscript. All authors read and approved the final manuscript [HT¹- Himanshu Trivedi and HT²- Himanshu Tiwari].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the AI tool ChatGPT was used solely for language editing, grammar correction and improving the clarity of the manuscript. The AI tool was not used for data analysis, interpretation of results, or generation of scientific content. All scientific interpretations, results and conclusions presented in this manuscript are the original work of the authors.

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