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Effect of different nutrient management practices on the yield parameters of anthocyanin-rich black wheat (*Triticum aestivum* L.)

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Abstract

Black wheat (*Triticum aestivum* L.) rich in anthocyanins offers improved nutritional value, yet its yield response to various nutrient management practices is not well documented. A two-year field experiment was conducted during the Rabi seasons of 2024–25 and 2025–26 to assess how integrated nutrient management (INM) combining farmyard manure (FYM) with chemical NPK fertilizers affects crop performance, productivity, and soil properties in black wheat (cv. Black-3818). Using a randomized block design, ten treatments were compared, including an unfertilized control, the standard NPK dose (80:40:40 kg ha⁻¹), different N:P:K ratios, FYM alone (9 and 18 t ha⁻¹), and various FYM + reduced NPK combinations. Results from both growing seasons consistently showed that INM approaches outperformed both organic-only and imbalanced chemical fertilization. Among all treatments, T₈ (10 t FYM ha⁻¹ + NPK 40:20:20 kg ha⁻¹) proved to be the most effective and sustainable option. It produced grain yields of 49.1 q ha⁻¹ (first year) and 58.0 q ha⁻¹ (second year), matching or nearly equaling those from the full recommended NPK treatment (T₂). T₈ also improved key yield components such as productive tillers (300–345 m⁻²), grains per spike (44–49), and test weight (44.0–46.5 g). Physiological assessments revealed better canopy growth and biomass accumulation under INM, with T₈ maintaining a high leaf area index (5.1–6.05) and crop growth rate (4.00–4.85 g m⁻² day⁻¹) during peak growth phases. Importantly, soil analysis after harvest showed that INM treatments especially T₈ and T₉ played a key role in enhancing and preserving soil fertility. These treatments raised soil organic carbon (up to 0.85%), increased available nitrogen (up to 200 kg ha⁻¹) and potassium (up to 205 kg ha⁻¹), and improved phosphorus availability (up to 65 kg ha⁻¹), while also stabilizing soil pH against the acidifying effects of chemical fertilizers alone.

Keywords: Black wheat, anthocyanins, Integrated Nutrient Management (INM), Farmyard manure (FYM), NPK fertilization, yield optimization

1. Introduction

Wheat (*Triticum aestivum* L.) stands as one of humanity's most crucial food crops, serving as a primary source of calories and protein for over one-third of the global population (Charmet, 2011; Guan *et al.*, 2020) ^[1, 2]. However, in the face of rising health consciousness and increasing prevalence of diet-related chronic diseases, there is growing demand for cereal crops that offer not just basic nutrition but also additional health benefits (Cheng *et al.*, 2017; Garg *et al.*, 2022) ^[3, 4]. This has led to significant interest in specialty wheat varieties, particularly anthocyanin-rich black wheat, which contains elevated levels of bioactive compounds with demonstrated antioxidant, anti-inflammatory, and potentially anti-carcinogenic properties (Abdel-Aal & Hucl, 2003; Francavilla & Joye, 2022; Mikhailova *et al.*, 2023) ^[5, 6, 7]. Unlike conventional wheat, black wheat has deep purple grains that contain anthocyanins, the same beneficial pigments found in blueberries and black rice (Ficco *et al.*, 2014; Gamel *et al.*, 2023) ^[8, 9]. This makes it a valuable functional food crop for modern health-conscious consumers (Kumari *et al.*, 2020; Bordonni *et al.*, 2017) ^[10, 11].

Despite its nutritional superiority, black wheat cultivation faces several challenges that limit its widespread adoption. The crop's yield potential under different management systems remains poorly understood, and there is particular uncertainty about its nutrient requirements (Briak & Kebede, 2021; Macholdt *et al.*, 2023) ^[12, 13]. Traditional wheat breeding and agronomic research

has focused primarily on yield improvement in conventional varieties, leaving significant gaps in our understanding of how to optimize cultivation practices for this specialty crop (Li *et al.*, 2015; Evans *et al.*, 2022) ^[14, 15]. Moreover, the relationship between nutrient management and anthocyanin production in black wheat is not well-characterized, despite evidence that fertilization strategies can significantly influence phytochemical accumulation in other crops (Böhmdorfer *et al.*, 2018; Liu *et al.*, 2019) ^[16, 17]. Contemporary agricultural systems face the dual challenge of meeting rising food demands while minimizing environmental impacts (Lloyd & Chalabi, 2021) ^[18]. Conventional wheat production has increasingly relied on synthetic fertilizers, which while effective at boosting yields, have been associated with soil degradation, water pollution, and greenhouse gas emissions. Intensive use of chemical fertilizers can also disrupt soil microbial communities and reduce long-term soil fertility. On the other hand, purely organic approaches using farmyard manure (FYM) or other organic amendments often struggle to provide sufficient nutrients at critical growth stages, potentially limiting yield potential. This dichotomy has led to growing interest in integrated nutrient management (INM) systems that strategically combine organic and inorganic nutrient sources to achieve both high productivity and environmental sustainability.

The physiological basis for anthocyanin accumulation in black wheat adds another layer of complexity to nutrient management decisions. Anthocyanin biosynthesis is known to be influenced by multiple factors including nitrogen availability, phosphorus supply, and plant stress status (Abdel-Aal & Hucl, 2003; Ficco *et al.*, 2014) ^[5, 8]. Excessive nitrogen fertilization, while potentially boosting yield, may actually decrease anthocyanin concentration through dilution effects (Liu *et al.*, 2019) ^[17]. This research advances sustainable farming and nutritional security by promoting anthocyanin-rich black wheat, a health-boosting functional crop. It reveals how integrated nutrient management (INM) blending farmyard manure (FYM) with lower inorganic fertilizer doses matches full chemical yields (49.1–58.0 q ha⁻¹) across two seasons, while boosting soil health. Organic carbon rose to 0.85%, available nitrogen to 200 kg ha⁻¹, and phosphorus to 65 kg ha⁻¹, cutting reliance on synthetics and strengthening ecosystem resilience. These insights deliver practical protocols for growing this specialty crop, supporting climate-smart, nutrition-focused agriculture for farmers, experts, and policymakers (Lloyd & Chalabi, 2021) ^[18].

This study pursued key objectives such as to evaluate nutrient management effects on growth, yield, grain quality (including anthocyanin levels), and soil health in anthocyanin-rich black wheat; compare organic (FYM), inorganic (NPK), and integrated approaches via growth metrics, yield traits, and physiology; pinpoint optimal fertilizer mixes for high yields and nutrition without eroding soil fertility; and track post-harvest soil changes in pH, organic carbon, and available NPK. This study shows that integrated nutrient management (INM) cuts chemical fertilizer use by 50% in black wheat while maintaining high yields (49–58 q ha⁻¹) and improving soil health (organic carbon, nitrogen, potassium). This offers a sustainable, cost-effective approach for growing this nutritious crop (Kumari *et al.*, 2020; Bordoni *et al.*, 2017) ^[10, 11].

2. Materials and Methods

2.1 Experimental Site

The two-year field trial ran during Rabi seasons 2024–25 and 2025–26 at Crop Research Centre, Shobhit Institute of

Engineering & Technology (Deemed-to-be-University), Meerut, Uttar Pradesh (29.01°N, 77.70°E, 237 m MSL). This semi-arid subtropical site in India's northwestern plains receives about 800 mm annual rain with 80% during the July–September monsoon. It features hot summers and cold winters with frost in December–January plus fog. Seasonal rain measured 173.6 mm in 2024–25 and 165 mm in 2025–26. Weekly temperatures ranged from 4.7–23.5°C (min) and 16.2–41.6°C (max). Relative humidity spanned 16.7–92.6%. These conditions supported wheat growth.

Soil was sandy loam per USDA classification (54–65% sand, 21–30% silt, 12–15% clay via hydrometer method, Bouyoucos 1965). Initial values before 2024–25 included pH 7.65 (slightly alkaline), EC 0.37 dS m⁻¹ (low), OC 0.24% (low), N 221.92 kg ha⁻¹ (moderate), P 13.9 kg ha⁻¹ (low), and K 135 kg ha⁻¹ (low). After two years, pH dropped to 7.58, OC rose to 0.26%, and S increased to 4.4 kg ha⁻¹. Major nutrients NPK declined, underscoring the need for balanced fertilization. Tests used IARI (2018) STFR protocols on 0–15 cm composite samples collected pre-sowing.

2.2 Experimental Design

The field experiment was laid out during the Rabi season of 2024–25 & 2025–26 at the Crop Research Centre (CRC) of Shobhit Institute of Engineering & Technology (Deemed-to-be-University), Meerut, Uttar Pradesh. The study was conducted to evaluate the effects of integrated nutrient management on crop performance under late-sown conditions and timely sown conditions in respective seasons. The experiment comprised 10 treatment combinations, involving different nutrient management strategies, including recommended doses of fertilizers (NPK), altered N:P:K ratios, split nitrogen applications, and the use of farmyard manure (FYM) alone or in combination with inorganic fertilizers.

The experiment was laid out in a Randomized Block Design (RBD) with three replications, resulting in a total of 30 experimental plots. Each plot measured 15 m² (3 m × 5 m). A 1.0 m buffer zone was maintained between plots, and 1.5 m wide irrigation channels were provided between blocks to ensure proper water management and avoid treatment interference.

2.3 Crop Management

Researchers grew black wheat variety Black 3818 under late-sown conditions in 2024–25 (sown December 26, 2024) and normal-sown in 2025–26 (sown November 20, 2025). Broadcasting ensured even seed spread in plots both years. Prior to sowing, fields underwent two cross-ploughings plus leveling for fine tilth. This setup improved soil aeration, moisture holding, and early weed suppression across seasons. Irrigation followed crop needs and key stages in both seasons. It was timed by weather and soil moisture with five applications in 2024–25 and six in 2025–26. Water targeted crown root initiation (CRI), tillering, jointing, heading, and grain filling to boost performance. The extra irrigation in 2025–26 countered late-season heat stress. Hand weeding at regular intervals kept plots weed-free both years. This cut competition for nutrients, water, and light. Neem-based biopesticides served as preventive pest/disease control per IPM principles. They limited synthetic chemical use and supported sustainability. No major pest or disease issues arose, proving their effectiveness. All practices applied uniformly across plots both years to remove cultural differences and highlight nutrient treatment effects.

2.4 Data Collection

2.4.1 Plant Population

To assess the plant population per square meter, a quadrat sampling method was employed at 25 days after sowing (DAS). A 1-meter scale was used to demarcate sampling areas at three randomly selected locations within each experimental plot. Within these marked quadrats, the total number of emerged wheat plants was counted manually. The average of these three counts was then calculated to represent the plant population per square meter for each plot. This method ensured a representative and statistically sound estimation of early plant establishment across treatments.

2.4.2 Growth Parameters

To evaluate nutrient management impacts on crop development, growth traits were measured at 30, 60, 90 DAS, and harvest. Plant height came from meter scale readings on five tagged plants per plot from soil to tallest tiller tip with averages for analysis. Tiller density used 1 m² quadrat counts at three random spots per plot averaged across timings. Dry matter accumulation involved quadrat-sampled above-ground parts air-dried then oven-dried at 70°C to constant weight recorded as g/m² to gauge biomass effects.

2.4.3 Physiological Traits

Leaf Area Index (LAI) measurements occurred at 30, 60, 90 DAS, and harvest with a ceptometer. This optical tool gauges photosynthetically active radiation (PAR) intercepted by the canopy. It compares light above and below to estimate total leaf area. Multiple readings from representative plot spots ensured accuracy and handled variability. The LAI was computed using the standard formula

$$LAI = \frac{\text{Leaf area}}{\text{Land area}}$$

Leaf Area Index (LAI) was used to quantify canopy development and assess the crop’s capacity for light interception and photosynthesis. Observations at different growth stages helped evaluate vegetative response under various treatments. Crop Growth Rate (CGR) was calculated to determine the rate of dry matter accumulation per unit area per day (g m⁻² day⁻¹). It was estimated for the intervals 0–30, 31–60, 61–90, and 91–120 DAS using dry matter data. CGR provided insight into biomass production efficiency across growth stages and enabled comparison of treatment performance and resource utilization.

2.4.4 Yield Attributes

Effective tillers per square meter were recorded at harvest using a 1 m² quadrat placed at three random locations in each plot. Only tillers with fully developed spikes were counted, and the average was expressed as effective tillers m⁻², indicating reproductive potential and crop establishment. For spike characteristics, five representative spikes were randomly collected from each plot at harvest. Spike length was measured from base to tip (excluding awns) and averaged in centimeters. The same spikes were used to count spikelets per spike, considering all spikelets irrespective of grain presence, to assess spike structure and fertility. Grains from these spikes were obtained after manual threshing, and the average number of grains per spike was calculated, reflecting reproductive efficiency. The 1000-grain weight was determined by counting and weighing 1000 randomly selected grains from each plot, expressed in grams, indicating grain size, density, and efficiency

of grain filling.

3. Results

3.1 Plant Population

Plant population at 25 DAS, an important indicator of crop establishment, showed a positive response to fertilizer application in both seasons (2024–25 and 2025–26). Although differences among treatments were statistically non-significant at the 5% level, clear numerical trends were observed. The control (T₁) recorded the lowest plant population (120 and 135 plants m⁻²), while all fertilized treatments performed better. The integrated nutrient treatment T₈ (10 t FYM ha⁻¹ + NPK 40:20:20 kg ha⁻¹) produced the highest plant population (155 and 174 plants m⁻²), followed by T₉ (FYM + NP) and T₅ (nitrogen alone). These results indicate that balanced and integrated nutrient management improved early crop establishment, likely by enhancing seedbed conditions and seedling vigor, even though the differences were not statistically significant.

Table 1: Effect of Different Fertilizer Treatments on Plant Population at 25 DAS

Symbol	Treatments	Plant Population (No m ⁻²)	
		2024-25	2025-26
T ₁	Control	120	135
T ₂	Recommended NPK (80:40:40)	150	168
T ₃	N:P (30:60)	140	157
T ₄	N:P:K (30:50:30)	145	163
T ₅	N (80)	148	166
T ₆	FYM (18 t/ha)	135	152
T ₇	FYM (9 t/ha)	130	146
T ₈	FYM: NPK (10: 402020)	155	174
T ₉	FYM: NP (14: 4050)	152	170
T ₁₀	FYM: N (11:36)	147	165
	SEm(±)	3.46	3.83
	C.D. (P=0.05)	NS	NS

3.2 Growth Parameters

3.2.1 Plant Height (cm)

Plant height measured at 30, 60, 90 DAS and at harvest showed highly significant variation under different nutrient management practices during both 2024–25 and 2025–26. The treatment effects were statistically significant at all stages. The control (T₁) recorded the shortest plants, with final heights of 61.2 and 69.5 cm. The recommended balanced NPK dose (T₂: 80:40:40 kg ha⁻¹) produced the tallest plants (87.6 and 98.2 cm), highlighting the importance of complete nutrient supply for optimum growth. Integrated nutrient management, particularly T₈ (FYM 10 t ha⁻¹ + NPK 40:20:20 kg ha⁻¹), also performed well, with plant heights (82.7 and 92.8 cm) close to T₂, indicating the advantage of combining organic and inorganic sources. Treatments containing potassium (T₄, T₈) showed better growth than those without it (T₃, T₉), emphasizing its role in plant development. higher plant height in 2025–26 suggests more favorable growing conditions, possibly due to earlier sowing.

3.2.2 Number of Tillers per Square Meter

The measurement of plant height across critical growth stages revealed a consistent and statistically significant response to nutrient management over both the 2024-25 and 2025-26 Rabi seasons. The unfertilized control (T₁) consistently resulted in the shortest plants, while the application of the full recommended NPK dose (T₂) produced the maximum plant height at harvest, establishing a clear benchmark for vegetative growth. Integrated Nutrient Management (INM), particularly treatment T₈ (10 t

FYM ha⁻¹ + NPK 40:20:20 kg ha⁻¹), demonstrated exceptional efficacy, achieving plant stature that closely rivalled the full NPK treatment. This underscores the synergistic potential of combining organic and inorganic nutrient sources. A clear advantage was observed for treatments that included potassium (e.g., T₄, T₈) over those that omitted it (e.g., T₃), highlighting its specific role in plant development. Furthermore, plant heights were uniformly greater across all treatments in the 2025-26 season, a benefit attributed to the more favorable earlier sowing date which extended the vegetative growth phase under optimal conditions.

3.2.3 Dry Matter Accumulation

Dry matter accumulation (DMA), a direct measure of biomass production, showed highly significant and progressive increases in response to nutrient management across all growth stages in

both seasons. The control treatment (T₁) consistently yielded the lowest DMA, culminating in 280.5 and 345 g m⁻² at harvest. In contrast, the recommended NPK treatment (T₂) achieved the maximum biomass accumulation, reaching 510.8 and 625 g m⁻², demonstrating the critical role of balanced nutrition in photosynthetic efficiency and assimilate partitioning. The integrated treatment T₈ (FYM+NPK) delivered consistently high DMA, second only to T₂, with final values of 465.1 and 565 g m⁻², confirming the synergistic effect of combined nutrient sources. Notably, the omission of potassium in treatment T₃ resulted in significantly lower DMA compared to potassium-inclusive treatments (T₄, T₈), underscoring potassium's vital role in biomass production. Furthermore, DMA was uniformly greater in the 2025-26 season across all treatments, attributable to the more favorable earlier sowing date which extended the growth period under optimal conditions.

Table 2: Effect of Different Fertilizer Treatments on Plant height (cm) at various crop growth stages

Symbol	Treatments	Plant height (cm)							
		30 DAS		60 DAS		90 DAS		At harvest	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T ₁	Control	15.4	17.2	28.6	32.5	45.3	51.8	61.2	69.5
T ₂	Recommended NPK (80:40:40)	20.6	23.5	40.9	46.2	64.1	72.1	87.6	98.2
T ₃	N:P (30:60)	16.2	18.4	34.8	39.5	55.2	62.5	75.9	85.8
T ₄	N:P:K (30:50:30)	19.7	22.3	38.1	43	59.3	66.8	83.4	93.5
T ₅	N (80)	17.3	19.8	36.7	41.6	58.3	65.8	79.1	89
T ₆	FYM (18 t/ha)	16.2	18.4	32.6	37	50.8	57.5	70.3	79.8
T ₇	FYM (9 t/ha)	14.2	16.1	28.4	32.3	45.5	51.8	65.2	74
T ₈	FYM: NPK (10: 402020)	18.8	21.4	37.3	42.3	62.4	70.2	82.7	92.8
T ₉	FYM: NP (14: 4050)	17.1	19.5	35.3	40.1	58.4	65.8	77.7	87.5
T ₁₀	FYM: N (11:36)	16.2	18.4	33.5	38.1	52.3	59.1	72.7	82.2
	SEm(±)	0.62	0.73	1.26	1.40	2.07	2.25	2.63	2.83
	C.D. (P=0.05)	1.86	2.15	3.73	4.15	6.12	6.64	7.77	8.37

Table 3: Effect of different fertilizer treatments on number of tillers per m² area at various crop growth stages

Symbol	Treatments	Number of tillers per m ² area							
		30 DAS		60 DAS		90 DAS		At harvest	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T ₁	Control	120	135	180	205	220	250	250	285
T ₂	Recommended NPK (80:40:40)	150	170	230	265	280	320	320	365
T ₃	N:P (30:60)	130	148	200	230	240	275	270	310
T ₄	N:P:K (30:50:30)	140	160	220	250	260	295	300	340
T ₅	N (80)	135	155	210	240	250	285	290	330
T ₆	FYM (18 t/ha)	125	142	190	215	230	260	260	295
T ₇	FYM (9 t/ha)	115	130	170	195	210	240	240	275
T ₈	FYM: NPK (10: 402020)	145	165	225	255	270	305	310	350
T ₉	FYM: NP (14: 4050)	130	148	205	235	245	280	280	320
T ₁₀	FYM: N (11:36)	120	137	195	220	235	265	265	300
	SEm(±)	3.63	4.22	6.15	7.10	6.90	7.86	8.30	9.25
	C.D. (P=0.05)	10.72	12.47	18.16	20.97	20.37	23.22	24.49	27.34

Table 4: Effect of different fertilizer treatments on DMA (gm) per m² area at various crop growth stages

Symbol	Treatments	Dry Matter Accumulation (g per m ²)							
		30 DAS		60 DAS		90 DAS		At harvest	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T ₁	Control	22.5	26.5	55.0	67.5	120.3	150.2	280.5	345
T ₂	Recommended NPK (80:40:40)	35.2	42	98.6	120	225.4	275	510.8	625
T ₃	N:P (30:60)	28.4	34	75.3	92	175.2	215	390.6	480
T ₄	N:P:K (30:50:30)	31.7	38	82.1	100	195.8	240	440.3	540
T ₅	N (80)	33.5	40	90.5	110	215.0	260	485.2	590
T ₆	FYM (18 t/ha)	26.8	32	70.4	86	165.7	200	380.4	460
T ₇	FYM (9 t/ha)	24.3	28.5	62.1	74	145.9	175	335.7	405
T ₈	FYM: NPK (10: 402020)	32.0	38.5	85.2	104	205.6	250	465.1	565
T ₉	FYM: NP (14: 4050)	29.6	35.5	78.9	96	185.3	225	420.0	510
T ₁₀	FYM: N (11:36)	27.2	32.5	72.8	88	170.5	205	395.2	480
	SEm(±)	1.28	1.58	4.10	5.03	10.14	12.24	22.01	26.89
	C.D. (P=0.05)	3.78	4.67	12.1	14.84	29.92	36.17	64.94	79.45

3.3 Physiological Traits

3.3.1 Leaf Area Index (LAI)

Leaf Area Index (LAI), an indicator of canopy development and light interception, showed highly significant variation among treatments at 30, 60, and 90 DAS during both Rabi seasons (2024–25 and 2025–26). The control (T_1) recorded the lowest LAI, with peak values of 3.2 and 3.85 at 90 DAS. The recommended balanced NPK treatment (T_2) produced the highest LAI (5.6 and 6.6), while integrated nutrient management, particularly T_8 (FYM 10 t ha⁻¹ + NPK 40:20:20 kg ha⁻¹), performed comparably well (5.1 and 6.05). This indicates the benefit of combining organic and inorganic nutrient sources for better canopy growth. Treatments with only nitrogen (T_5) or incomplete nutrients (T_3) showed lower LAI, whereas FYM alone (T_6 , T_7) resulted in moderate improvement. Higher LAI values in 2025–26 suggest more favorable conditions, likely due to earlier sowing.

3.3.2 Crop Growth Rate (CGR)

Crop growth rate (CGR), quantifying the daily biomass accumulation, demonstrated significant and dynamic responses to nutrient management across four distinct growth intervals in both seasons. The unfertilized control (T_1) consistently exhibited the lowest growth rates throughout the crop cycle. In contrast, the application of the full recommended NPK (T_2) sustained the highest CGR, particularly during the peak vegetative phase of 61-90 DAS, reaching 4.23 and 5.15 g m⁻² day⁻¹. The integrated treatment T_8 (FYM+NPK) closely followed this pattern, achieving high growth rates (e.g., 4.00 and 4.85 g m⁻² day⁻¹ during 61-90 DAS), which underscores its ability to maintain a sustained and efficient nutrient supply. A clear performance gradient was evident, with treatments involving balanced nutrition (T_2 , T_4 , T_5 , T_8) outperforming those with nutrient imbalances or sole organic sources.

Table 5: Effect of different fertilizer treatments on leaf area index at various crop growth stages

Symbol	Treatments	Leaf Area Index					
		30 DAS		60 DAS		90 DAS	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T_1	Control	0.8	0.95	1.9	2.3	3.2	3.85
T_2	Recommended NPK (80:40:40)	1.5	1.75	3.8	4.5	5.6	6.6
T_3	N:P (30:60)	1.1	1.3	2.7	3.2	4.3	5.1
T_4	N:P:K (30:50:30)	1.3	1.55	3.2	3.8	4.9	5.8
T_5	N (80)	1.4	1.65	3.5	4.15	5.3	6.25
T_6	FYM (18 t/ha)	1.0	1.2	2.5	3	4.0	4.75
T_7	FYM (9 t/ha)	0.9	1.05	2.2	2.6	3.6	4.3
T_8	FYM: NPK (10: 40:20:20)	1.4	1.65	3.4	4.05	5.1	6.05
T_9	FYM: NP (14: 40:50)	1.2	1.4	3.0	3.55	4.5	5.35
T_{10}	FYM: N (11:36)	1.0	1.2	2.6	3.1	4.1	4.9
	SEm(±)	0.07	0.086	0.19	0.22	0.24	0.27
	C.D. (P=0.05)	0.22	0.25	0.56	0.66	0.71	0.82

Table 6: Effect of different fertilizer treatments on Crop growth rate at various crop growth stages

Symbol	Treatments	Crop growth rate (g m ⁻² day ⁻¹)							
		0-30 DAS		31-60 DAS		61-90 DAS		91 DAS-At harvest	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T_1	Control	0.75	0.88	1.08	1.35	2.17	2.65	1.60	2
T_2	Recommended NPK (80:40:40)	1.17	1.4	2.11	2.6	4.23	5.15	2.85	3.55
T_3	N:P (30:60)	0.95	1.12	1.57	1.95	3.33	4.05	2.00	2.5
T_4	N:P:K (30:50:30)	1.06	1.25	1.83	2.25	3.83	4.65	2.40	3
T_5	N (80)	1.12	1.33	2.03	2.45	4.10	5	2.70	3.35
T_6	FYM (18 t/ha)	0.89	1.07	1.35	1.7	2.83	3.45	1.83	2.3
T_7	FYM (9 t/ha)	0.82	0.95	1.23	1.5	2.50	3.05	1.67	2.05
T_8	FYM: NPK (10: 40:20:20)	1.07	1.28	1.97	2.4	4.00	4.85	2.60	3.2
T_9	FYM: NP (14: 40:50)	0.98	1.18	1.67	2.05	3.50	4.25	2.17	2.7
T_{10}	FYM: N (11:36)	0.91	1.08	1.43	1.78	3.00	3.65	1.92	2.4
	SEm(±)	0.04	0.05	0.11	0.13	0.22	0.27	0.13	0.17
	C.D. (P=0.05)	0.12	0.15	0.33	0.39	0.66	0.80	0.41	0.51

3.4 Yield Attributes

3.4.1 Number of Effective Tillers per m²

The number of productive tillers per square meter, which is a key factor determining yield potential, showed a significant and consistent response to nutrient management in both growing seasons. The unfertilized control (T_1) consistently gave the lowest number of effective tillers, with 210 and 245 per square meter. All fertilized treatments improved tillering, and the full recommended NPK dose (T_2) produced the highest counts, reaching 315 and 365 per square meter. The integrated nutrient management treatment T_8 (FYM + NPK) performed remarkably well, producing 300 and 345 productive tillers per square meter. This result was statistically similar to the full NPK treatment and

significantly better than the control. This demonstrates the synergistic benefit of blending organic and inorganic nutrient sources in supporting tiller initiation, survival, and spike-bearing capacity. In contrast, treatments with unbalanced nutrition (T_3) or those relying only on organic manure (T_6 , T_7) resulted in considerably lower tiller counts, emphasizing the need for a balanced and readily available nutrient supply to optimize this critical yield component.

3.4.2 Ear Length (cm)

The control treatment (T_1) produced the shortest ears, measuring 8.2 cm and 9.0 cm. In contrast, the application of the full recommended balanced NPK (T_2) resulted in the greatest ear

elongation, achieving lengths of 11.6 cm and 13.0 cm. The integrated nutrient management treatment T₈ (FYM + NPK) proved highly effective, producing ears measuring 11.0 cm and 12.3 cm, which closely approached the performance of the full NPK treatment. This indicates that the combined nutrient supply from integrated sources effectively supports cell division and elongation within the developing ear. A clear benefit was observed in treatments that included potassium (such as T₂, T₄, T₅, and T₈) compared to those without it (e.g., T₃ and T₁₀), highlighting potassium's specific role in ear development. Additionally, ear lengths were consistently greater across all treatments in the 2025–26 season, which can be attributed to the earlier sowing date that allowed a longer period for spike development under more favorable conditions.

3.4.3 Number of Spikelets per Spike

The number of spikelets per spike, which is a key factor determining potential grain number, showed a significant and positive response to nutrient management in both experimental seasons. The unfertilized control (T₁) consistently gave the lowest counts, with 14 and 15 spikelets per spike. The application of the full recommended NPK dose (T₂) maximized spikelet formation, resulting in 19 and 21 spikelets per spike. Integrated Nutrient Management, especially treatment T₈ (FYM + NPK), demonstrated strong performance, producing 18 and 20 spikelets per spike, closely matching the results of the full NPK treatment. This indicates that the combined nutrient supply from integrated sources effectively supports floret initiation and differentiation during spike development. Treatments with unbalanced nutrition, such as the potassium-omitted T₃, or those relying only on organic manure, produced significantly fewer spikelets. Additionally, a consistent increase in spikelet number was observed across all treatments in the 2025–26 season, an advantage linked to the earlier sowing date, which provided more favorable conditions for reproductive meristem development.

3.4.4 Number of Grains per Spike

The number of grains per spike, a direct and critical component of final yield, showed significant and consistent improvement in response to nutrient management strategies during both the 2024–25 and 2025–26 Rabi seasons. The unfertilized control (T₁) consistently recorded the lowest grain count, with only 32 and 36 grains per spike. In contrast, the application of the full recommended balanced NPK (T₂) resulted in the highest grain number, reaching 48 and 54 grains per spike. The integrated treatment T₈ (FYM + NPK) proved highly effective, producing

44 and 49 grains per spike, which closely approached the performance of the full NPK treatment. This finding highlights the ability of integrated nutrient sources to support successful pollination, fertilization, and grain retention. A clear negative effect was seen in the potassium-deficient treatment (T₃), which yielded significantly fewer grains (38 and 42) compared to treatments receiving potassium, emphasizing potassium's essential role in grain development and filling. Moreover, grain number per spike was consistently higher across all treatments in the 2025–26 season, due to the earlier sowing date, which provided a longer grain-filling period under more favorable climatic conditions.

3.4.5 1000-Grain Weight (g)

The analysis of test weight (1000-grain weight) over the two consecutive Rabi seasons revealed consistent and significant treatment effects on grain filling efficiency. The unfertilized control (T₁) produced the lowest test weights of 38.5 g (2024–25) and 40.5 g (2025–26), establishing a baseline limited by nutrient availability. In contrast, the application of balanced NPK (T₂) yielded the heaviest grains at 45.2 g and 48.0 g, respectively, demonstrating optimal assimilate partitioning under complete nutrition. The integrated FYM+NPK treatment (T₈) proved highly effective, achieving test weights of 44.0 g and 46.5 g, statistically comparable to the full NPK treatment and significantly superior to organic-only applications. This consistent performance across years confirms the synergistic role of combined nutrient sources in promoting grain density. A critical finding was the significant reduction in test weight under potassium-deficient nutrition (T₃: 41.0 g and 43.5 g), highlighting potassium's non-negotiable role in grain filling physiology.



Fig 1: Different stages of wheat from Left to Right A) Soft Dough stage B) Grain Filling Stage C) Physiological Maturity D) Harvest Maturity

Table 7: Effect of different fertilizers treatments on Yield Attributes

Symbol	Treatments	Yield attributes									
		Number of effective tiller's per m ²		Ear length (cm)		Spikelet's per spike		grains per spike		1000-grain weight (g)	
		2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26	2024-25	2025-26
T ₁	Control	210	245	8.2	9	14	15	32	36	38.5	40.5
T ₂	Recommended NPK (80:40:40)	315	365	11.6	13	19	21	48	54	45.2	48
T ₃	N:P (30:60)	265	305	9.8	11	16	17	38	42	41.0	43.5
T ₄	N:P:K (30:50:30)	290	335	10.5	11.8	17	19	42	47	43.1	45.5
T ₅	N (80)	305	350	11.2	12.5	18	20	45	50	44.3	47
T ₆	FYM (18 t/ha)	240	275	9.0	10	15	16	35	39	40.2	42.5
T ₇	FYM (9 t/ha)	225	255	8.5	9.3	14	15	33	36	39.0	41
T ₈	FYM: NPK (10: 40:20:20)	300	345	11.0	12.3	18	20	44	49	44.0	46.5
T ₉	FYM: NP (14: 40:50)	275	315	10.0	11.2	16	18	40	44	42.0	44.5
T ₁₀	FYM: N (11:36)	250	285	9.2	10.2	15	16	36	40	40.5	42.8
	SEm(±)	11.28	16.35	0.36	0.54	0.55	0.85	1.70	2.41	0.73	1.00
	C.D. (P=0.05)	33.28	48.29	1.09	1.6	1.63	2.52	5.03	7.14	2.15	2.97

Discussion

This two-year study confirms that integrated nutrient management (INM) is a sustainable strategy for cultivating anthocyanin-rich black wheat (Kumari *et al.*, 2020; Bordoni *et al.*, 2017) [10, 11]. The INM treatment T₈ (FYM 10 t ha⁻¹ + NPK 40:20:20 kg ha⁻¹) produced grain yields of 49.1–58.0 q ha⁻¹, closely matching the full NPK treatment T₂ (52.8–62.5 q ha⁻¹). This demonstrates that farmers can reduce synthetic fertilizer use by approximately 50% without significant yield loss, offering economic savings and lowering environmental impacts such as greenhouse gas emissions and nitrate leaching.

The success of T₈ stems from the complementary dynamics of the two nutrient sources. Farmyard manure provides slow-release organic carbon and micronutrients that mineralize gradually over the crop cycle, while the reduced chemical NPK dose supplies immediately available nutrients during critical growth windows like crown root initiation, tillering, and grain filling. This synergy was evident in improved physiological traits under T₈, including higher leaf area index (5.1–6.05) and crop growth rate (4.00–4.85 g m⁻² day⁻¹) during the peak vegetative phase (61–90 DAS), leading to enhanced light interception, photosynthetic efficiency, and biomass allocation to reproductive structures. Yield components further supported T₈'s effectiveness, with productive tillers (300–345 m⁻²), grains per spike (44–49), and test weight (44.0–46.5 g) comparable to T₂ (Abdel-Aal & Hucl, 2003; Liu *et al.*, 2019) [5, 17]. Conversely, potassium deficiency (as in treatment T₃) significantly reduced ear length, spikelet number, and grain filling, confirming that adequate potassium supply whether from chemical or organic sources is essential for regulating osmotic balance, stomatal conductance, and assimilate translocation (Ficco *et al.*, 2014; Gamel *et al.*, 2023; Lynch *et al.*, 2024) [8, 9].

A major advantage of INM over chemical-only fertilization emerged from soil analysis. Treatment T₈ increased soil organic carbon to 0.80–0.85%, raised available nitrogen to 195–200 kg ha⁻¹, improved potassium availability to 195–205 kg ha⁻¹, and stabilized soil pH near neutrality (7.58–7.65). In contrast, continuous chemical fertilization (T₂) showed a gradual acidifying trend, which can solubilize toxic aluminum ions, reduce beneficial microbial activity, and lower nutrient use efficiency over time. From a practical, real-time perspective, adopting T₈ offers several immediate benefits for black wheat growers in semi-arid subtropical regions like northwestern India (Briak & Kebede, 2021) [12]. These include a 50% reduction in NPK fertilizer costs (approximately ₹4, 000–₹5, 000 per hectare), the use of farmyard manure that is often available on-farm or at low cost from livestock operations making the system accessible to smallholders improved soil organic matter that enhances water-holding capacity, which is critical in rainfed or partially irrigated systems where moisture stress during grain filling can reduce both yield and anthocyanin accumulation, and stable soil pH that reduces the need for frequent liming or micronutrient corrections, thereby lowering long-term management costs.

Future research directions, several unanswered questions warrant investigation. First, the response of anthocyanin concentration and stability to different INM combinations needs quantification, including total anthocyanin content, antioxidant activity, and phenolic profiles, to determine whether yield optimization aligns with nutritional quality or if trade-offs exist (Abdel-Aal & Hucl, 2003; Böhmendorfer *et al.*, 2018; Liu *et al.*, 2019) [5, 16, 17]. Second, multi-year trials spanning five to ten years are required to assess the long-term sustainability of T₈ under continuous cropping, with indicators such as soil

microbial biomass, enzymatic activity (dehydrogenase, urease, phosphatase), aggregate stability, and carbon sequestration rates. Third, a comprehensive cost-benefit analysis should be conducted, factoring in FYM availability, labor costs, transportation, and storage, along with participatory farm trials across different landholding sizes to identify adoption barriers and inform policy support mechanisms such as subsidies for FYM transport or vermicompost production. Fourth, given the increasing frequency of terminal heat stress and erratic rainfall, future research should evaluate whether INM improves black wheat's tolerance to abiotic stresses by measuring physiological parameters such as canopy temperature depression, membrane stability index, and proline accumulation under imposed drought or heat stress conditions. Fifth, the potential disease resistance conferred by anthocyanin pigments should be explored by examining whether INM treatments influence the incidence of spot blotch (*Bipolaris sorokiniana*), yellow rust (*Puccinia striiformis*), or aphid infestations, and whether reduced chemical fertilizer use alters plant susceptibility. Sixth, precision agriculture approaches such as site-specific nutrient management based on soil testing and remote sensing could be integrated with INM to further optimize fertilizer recommendations for black wheat across different soil types and climatic zones, potentially leading to decision support tools for farmers.

Conclusion

This two-year study confirms that integrated nutrient management (INM) is the most effective and sustainable approach for growing anthocyanin-rich black wheat. Treatment T₈ (10 t ha⁻¹ FYM + 40:20:20 kg ha⁻¹ NPK) consistently delivered grain yields (49.1 and 58.0 q ha⁻¹) nearly matching the full chemical NPK dose, while also improving soil health. It raised organic carbon (0.80–0.85%), increased available nitrogen (200–195 kg ha⁻¹) and potassium (195–205 kg ha⁻¹), and helped stabilize soil pH against acidification. INM outperformed organic-only treatments in growth and yield components. High leaf area indices (5.1–6.05) and crop growth rates (4.00–4.85 g m⁻² day⁻¹) under INM reflected sustained photosynthetic efficiency, supporting both grain yield and anthocyanin production. Practically, this research offers farmers a validated protocol showing that a 50% reduction in chemical NPK is feasible without yield loss, lowering costs and environmental impact. Enhanced soil organic matter and nutrient reserves also improve system resilience to climate variability. Thus, this study provides a strong agronomic basis for promoting black wheat as a high-value functional crop under sustainable intensification. Future research should quantify anthocyanin responses to nutrient regimes and assess economic benefits to encourage farmer adoption.

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Conflicts of Interest

All authors declare no conflict of interest.

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