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Response of Advanced Wheat Lines to Integrated Nutrient Management for Yield, Grain Quality and Soil Health in Semi-Arid Balochistan

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ABSTRACT

Wheat productivity in the semi-arid highlands of Balochistan, Pakistan, is constrained by low soil fertility and poor nutrient-use efficiency. A field experiment was conducted during the 2023–24 Rabi season at Quetta to evaluate the response of two advanced wheat lines (BARDC-1 and BARDC-2) to seven integrated nutrient management practices arranged in a split-plot design with five replications. Treatments included an unfertilized control, 100% recommended NP (120-60 kg N-P_2O_5 ha^{-1}), farmyard manure (FYM) @ 10 t ha^{-1}, Biozote @ 5 kg ha^{-1}, and their combinations. The integrated treatment comprising Biozote (5 kg ha^{-1}) + FYM (5 t ha^{-1}) + 50% recommended NP (T7) recorded the highest chlorophyll content, NDVI, productive tillers, 1000-grain weight, grain yield (5504 kg ha^{-1}; 112% higher than control), grain protein (14.22%), gluten and ash contents, while substantially improving post-harvest soil organic carbon, available nutrients, and microbial populations. BARDC-2 outperformed BARDC-1 in most traits. Combining Biozote and FYM with half-dose chemical fertilizer proved the most effective and sustainable strategy for enhancing wheat productivity, grain quality, and soil health under semi-arid highland conditions.

1. INTRODUCTION

Wheat (*Triticum aestivum* L.) is Pakistan's most important staple cereal, occupying 9.03 million hectares and contributing 31.44 million tonnes to national production in 2023–24 (GoP, 2024). Despite this, average national yield remains low at 3.1–3.3 t ha^{-1}, far below the potential of 6–8 t ha^{-1} achieved under optimal management (PBS, 2024). In Balochistan, wheat is grown on approximately 0.45 million hectares, yet yields stagnate at 2.1–2.4 t ha^{-1} due to arid to semi-arid climate, low and erratic rainfall (<300 mm annually), limited irrigation, and inherently poor soil fertility characterised by low organic matter (<0.5 %), high pH (>8.0), and widespread deficiencies of nitrogen, phosphorus and micronutrients (Ahmed et al., 2023). Continuous reliance on unbalanced chemical fertilizers has further accelerated soil degradation and reduced nutrient-use efficiency (Zahoor et al., 2025).

Integrated Nutrient Management (INM), combining chemical fertilizers with organic manures and microbial inoculants, has emerged as a sustainable strategy to restore soil health and boost crop productivity (Kushwah et al., 2024; Parewa et al., 2022). Studies across South Asia report 20–35 % wheat yield increases and improved grain protein content when 50 % of recommended chemical fertilizers are substituted with farmyard manure (FYM) and Azotobacter-based biofertilizers such as Biozote (Jat et al., 2018; Ali et al., 2025). Genotype × nutrient management interactions also significantly influence yield and quality, with certain advanced lines showing superior responsiveness to balanced nutrition (Salam et al., 2025; Zulfiqar et al., 2023;(Taj, 2024).

Despite these advances, location-specific research on the combined use of FYM, Biozote and reduced chemical fertilizer doses with newly developed wheat genotypes remains scarce in the highland semi-arid zone of Balochistan. The present study was therefore conducted during Rabi 2023–24 at Quetta to evaluate the performance of two advanced wheat lines (BARDC-1 and BARDC-2) under seven nutrient management practices, with emphasis on growth, physiological traits, grain yield and quality, and post-harvest soil health. The aim was to identify the most efficient and sustainable INM strategy for wheat production in the region.

2. MATERIALS AND METHODS

2.1. Experimental site

The field experiment was carried out for the Rabi season of 2023-2024 at the research farm of Balochistan Agriculture Research and Development Centre (BARDC), Quetta, Pakistan (30°12′ N, 66°58′ E, 1680 m ASL). The mean annual precipitation is around 250 mm and is predominantly received in the winter and early spring. The climate is semi-arid. During the wheat growing season, the maximum and minimum temperatures are recorded to be 4 to 37 °C and - 8 to 20 °C, respectively. The experimental soil in a depth of 0- 15 cm range is silty loam, slightly alkaline (pH 7.6), non saline (EC 0.41 dS m^{-1}), low in organic carbon (0.11 %) and available nitrogen (0.80 mg kg^{-1}). Table 1 gives detail of initial of physico-chemical and biological properties of the soil.

Table 1

Initial physico-chemical and biological properties of the experimental soil (before sowing)

Parameter	Unit	Value	Method of analysis
Soil texture	–	Silty loam	International pipette method
pH (1:2.5 soil:water)	–	7.6	pH meter
Electrical conductivity (EC)	dS m^{-1} at 25 °C	0.41	Conductivity meter
Organic carbon	%	0.11	Walkley & Black rapid titration method
Available nitrogen	mg kg^{-1}	0.80	Alkaline permanganate method (Subbiah & Asija, 1956)
Available phosphorus (P_2O_5)	mg kg^{-1}	19.5	Olsen's method
Available potassium (K_2O)	mg kg^{-1}	112	1 N NH_4OAc extractable (flame photometer)
Exchangeable sodium	mg kg^{-1}	1.63	Flame photometer
Bacterial population	$\times 10^5$ CFU g^{-1}	12.6	Serial dilution plate technique
Fungal population	$\times 10^5$ CFU g^{-1}	6.4	Serial dilution plate technique

Notes: Values are mean of three composite samples from 0–15 cm depth.

2.2. Treatments and experimental design

The experiment was laid out in a split-plot design with five replications. Two advanced wheat lines developed at BARDC (BARDC-1 and BARDC-2) were assigned to main plots, while seven integrated nutrient management (INM) treatments were allocated to sub-plots measuring 4 m × 2 m (ten rows at 25 cm spacing). The treatments were:

T1 – Absolute control (no fertilizer/manure)

T2 – 100 % recommended NP (120-60 kg N-P_2O_5 ha^{-1}) – split dose

T3 – Farmyard manure (FYM) @ 10 t ha^{-1} alone (at sowing)

T4 – FYM @ 10 t ha^{-1} + 50 % recommended NP (at sowing)

T5 – Biozote @ 5 kg ha^{-1} alone (at sowing)

T6 – Biozote @ 5 kg ha^{-1} + 50 % recommended NP (at sowing)

T7 – Biozote @ 5 kg ha^{-1} + FYM @ 5 t ha^{-1} + 50 % recommended NP (at sowing)

Nitrophos fertilizer (23 % N + 23 % P_2O_5) served as the sole inorganic source of nitrogen and phosphorus. Farmyard manure and Biozote were applied only at sowing and thoroughly incorporated into the topsoil along with the basal portion of nitrophos using a rotavator. In treatment T2, the remaining half of the recommended NP dose was broadcast at the crown root initiation stage and immediately followed by irrigation.

2.3. Crop Husbandry

The experimental field was ploughed twice with a tractor-drawn cultivator followed by planking. Wheat was sown on 14 November 2023 using a seed rate of 100 kg ha^{-1} with a tractor-mounted seed drill. Three irrigations (crown root initiation, tillering, and grain-filling stages) were applied uniformly to all plots. Weeds were controlled manually twice during the season. No pesticide was sprayed as insect-pest incidence remained below economic threshold level. The crop was harvested manually at physiological maturity.

2.4. Soil Sampling and Analysis

Before sowing and after wheat harvest, soil samples (0-15 cm depth) were collected from each plot using a tube auger made of stainless steel. The samples were air-dried, lightly crushed, and sieved to a 2 mm mesh. Soil pH and electrical conductivity were measured using a calibrated glass-electrode pH meter and conductivity meter, respectively, in a 1:2.5 soil:water suspension (Jackson, 1973). The Walkley-Black Method (Walkley and Black, 1934) was used to measure the soil's organic carbon. Available nitrogen was measured using the alkaline KMnO4 method (Subbiah and Asija, 1956). Available phosphorus was measured using 0.5 M NaHCO3 (pH 8.5) which extracts the phosphates and then measured colorimetrically (Olsen et al., 1954). The quantity of potassium and sodium was measured after extraction with 1 N neutral ammonium acetate and then measured with flame photometry. The soil physiochemical properties after harvest are shown in Table 2.

Fresh soil samples were used for microbial enumeration. Serial dilutions were prepared in sterile distilled water, and 1 mL aliquots were pour-plated in triplicate. Bacteria were grown on nutrient agar and fungi on potato dextrose agar (PDA) amended with streptomycin (30 mg L^{-1}) to inhibit bacterial growth. The plates were placed in an incubator at 28 ± 2 °C for 48 hours (for the bacteria plates), and for 5-7 days (for the fungi plates). A manual electronic colony counting device from Suntex 650 was used for colony counting. The results were presented as colony-forming units (CFU) g^{-1} of oven-dried soil. The soil biological properties after harvest are presented in Table 3.

2.5. Data collection

2.5.1 Growth, physiological, and yield parameters

Growth, physiological, and yield traits were assessed as follows: days to 50% seedling emergence were recorded from sowing until half the plot seedlings emerged; plant population was counted in a 1-m^2 quadrat at the 3-leaf stage; plant height (soil surface to spike tip, excluding awns) and coleoptile length were measured on representative main stems/seedlings; productive (fertile) tillers per square meter were counted at maturity; flag-leaf chlorophyll content (SPAD units) was determined with a SPAD-502 meter (Minolta, Japan) at anthesis and mid-grain filling; canopy NDVI was measured using a handheld Green Seeker (Trimble Navigation Ltd., USA) at the same stages; at harvest, spike length (excluding awns), grains per spike, and 1000-grain weight (adjusted to 12% moisture) were taken from randomly selected spikes; total above-ground dry matter, grain yield (from a central $1m^2$ area, adjusted to 12% moisture), straw yield (after threshing and oven-drying), and harvest index (grain yield/total dry matter) were calculated.

2.5.2 Grain Quality Analysis

Cleaned grain samples (≈ 500 g per plot) were sent to the Wheat Research Institute, AARI, Faisalabad, Pakistan. Protein content (%), gluten (%), ash (%), and moisture (%) were measured using a calibrated near-infrared transmittance seed analyser (Infratec™ 1241 Grain Analyzer, FOSS Analytical, Denmark) according to ISO 12099:2017.

2.6. Statistical Analysis

The experiment was designed using a split-plot design with main plots as genotypes and sub-plots as integrated nutrient management practices, replicated five times. Data was analyzed using two-way ANOVA as per the split-plot design using Statistix 8.1 (Analytical Software, Tallahassee, USA). Means were separated using the Least Significant Difference (LSD) test at a 5% probability level for significant F-values (Steel et al., 1997). Pearson's correlation coefficients for some selected variables were calculated using Jamovi (Version 2.3) (The Jamovi Project, 2023). Graphs and figures were made using Microsoft Excel 365.

3. RESULTS

3.1 Post-harvest soil physico-chemical properties

Post-harvest soil analysis significant differences were observed between wheat genotypes and INM treatments (Table 2). BARDC-2 showed higher organic carbon (0.118%), available N (0.90 mg kg^{-1}), P_2O_5 (53 mg kg^{-1}), K_2O (133.6 mg kg^{-1}), and Na (1.68 mg kg^{-1}) compared to BARDC-1, while EC was non significant. Among treatments, The integrated treatment T7 (Biozote 5 kg ha^{-1} + FYM 5 t ha^{-1} + 50 % recommended NP) recorded the highest soil organic carbon (0.145 %), available nitrogen (0.100 mg kg^{-1}), available phosphorus (57 P_2O_5 mg kg^{-1}) and exchangeable potassium (1.71 mg kg^{-1}), followed by T6 (Biozote + 50 % NP). In contrast, the unfertilized control (T1) exhibited the lowest values: organic carbon 0.078 %, available N 0.69 mg kg^{-1}, P_2O_5 41 mg kg^{-1} and K_2O 128.2 mg kg^{-1}. Soil pH ranged from 7.2 (T1) to 7.9 (T7), with integrated treatments slightly increasing pH due to organic matter addition. Electrical conductivity was highest under FYM-based treatments (0.835–0.882 dS m^{-1} in T3 and T4), while T7 recorded the lowest EC (0.315 dS m^{-1}) among fertilized treatments. Exchangeable sodium was highest in T5 (2.37 mg kg^{-1}).

Table 2

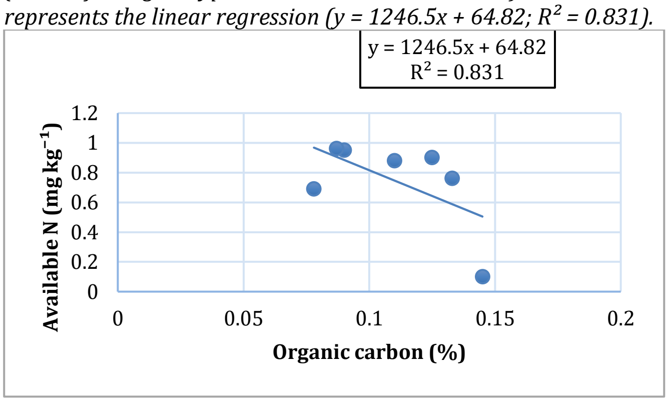
Post-harvest soil physico-chemical properties as influenced by integrated nutrient management and genotypes in wheat

Genotype	pH (1:2.5)	EC (dS m^{-1})	Organic carbon (%)	Av. N (mg kg^{-1})	Av. P_2O_5 (mg kg^{-1})	Av. K_2O (mg kg^{-1})	Na (mg kg^{-1})
BARDC-1	7.58^{a}	0.522	0.105^{b}	0.81^{b}	49^{b}	126.9^{b}	1.64^{b}
BARDC-2	7.52^{b}	0.524	0.118^{a}	0.90^{a}	53^{a}	133.6^{a}	1.68^{a}
LSD (P ≤0.05) (G)	0.03	NS	5.74	8.29	5.74	6.29	0.01
Treatment							
T1 Control	7.2^{d}	0.360^{e}	0.078^{e}	0.69^{f}	41^{f}	128.2	1.38^{d}
T2 100 % NP	7.0^{e}	0.385^{d}	0.125^{b}	0.90^{c}	58^{b}	117.0	1.39^{d}
T3 FYM 10 t ha^{-1}	7.7^{b}	0.835^{b}	0.090^{d}	0.95^{b}	47^{e}	131.0	2.12^{b}
T4 FYM + 50 % NP	7.5^{c}	0.882^{a}	0.110^{c}	0.88^{d}	40^{f}	114.2	1.39^{d}
T5 Biozote alone	7.5^{c}	0.530^{c}	0.087^{d}	0.96^{b}	54^{d}	145.6	2.37^{a}
T6 Biozote + 50 % NP	7.7^{b}	0.355^{e}	0.133^{b}	0.76^{e}	60^{a}	138.9	1.27^{e}
T7 Biozote + FYM 5 t + 50 % NP	7.9^{a}	0.315^{f}	0.145^{a}	0.100^{a}	57^{c}	136.6	1.71^{c}
LSD (P ≤ 0.05) (T)	0.05	0.017	0.01	1.55	1.07	NS	0.02

Notes: Means followed by different letters are significantly different at P ≤ 0.05 (LSD).
NS = Non-significant effect.

Figure 1

Relationship between organic carbon and available nitrogen in wheat under different integrated nutrient management practices (mean of two genotypes; n = 70; r = 0.91, P < 0.05). The solid line represents the linear regression (y = 1246.5x + 64.82; R^2 = 0.831).*



Organic carbon exhibited a strong positive linear relationship with available nitrogen (r = 0.91*, R^2 = 0.83; Figure 1).

3.2 Post-harvest soil microbial population

Soil microbial populations were significantly influenced by both genotype and treatment (Table 3). BARDC-2 recorded significantly higher bacterial and fungal populations than BARDC-1. Treatment T7 supported the maximum bacterial (30.55 × 10^5 CFU g^{-1} soil) and fungal (20.52 × 10^5 CFU g^{-1} soil) populations, showing increases of 101 % and 152 %, respectively, over the control. T6 ranked second, while sole Biozote (T5) and FYM (T3) also significantly raised microbial counts compared to the control and 100 % chemical fertilizer (T2).

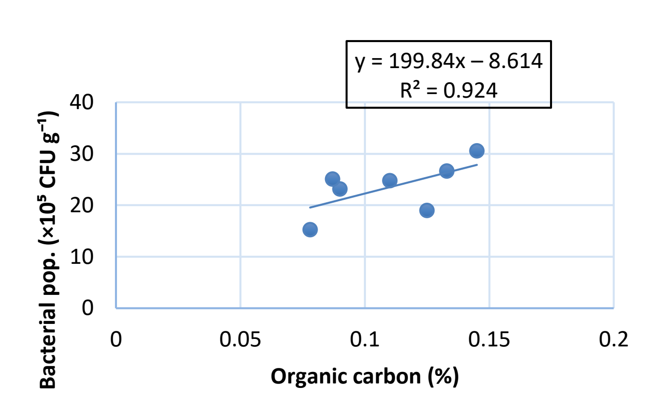
Table 3

Post-harvest soil microbial population as influenced by integrated nutrient management practices and genotypes in wheat

Genotype	Bacterial population ($\times 10^5$ CFU g^{-1} soil)	Fungal population ($\times 10^5$ CFU g^{-1} soil)
BARDC-1	22.87^{b}	13.51^{b}
BARDC-2	24.09^{a}	14.27^{a}
LSD (P ≤ 0.05) (G)	1.72	1.37
Treatment		
T1 Control	15.22^{f}	7.92^{g}
T2 100 % NP	18.97^{e}	10.57^{e}
T3 FYM 10 t ha^{-1}	23.15^{d}	18.77^{b}
T4 FYM + 50 % NP	24.77^{c}	17.67^{c}
T5 Biozote alone	25.07^{c}	9.90^{f}
T6 Biozote + 50 % NP	26.62^{b}	11.90^{d}
T7 Biozote + FYM 5 t + 50 % NP	30.55^{a}	20.52^{a}
LSD (P ≤ 0.05) (T)	3.21	2.56

Figure 2

Relationship between organic carbon and bacterial population in wheat under different integrated nutrient management practices (mean of two genotypes; n = 70; r = 0.96, P < 0.05). The solid line represents the linear regression (y = 199.84x – 8.614; R^2 = 0.924).*



Organic carbon was very strongly correlated with bacterial population (r = 0.96*, R^2 = 0.92; Figure 2).

Early establishment and growth parameters

In growth parameters the genotype BARDC-2 showed significantly higher coleoptile length (8.3 cm) than BARDC-1 (7.3 cm), plant population also showed significant result between genotypes, while differences in tillers, days to germination, days to physiological maturity, and plant height were non-significant (Table 4). Among INM treatments also significantly affected growth. T7 (Biozote + FYM 5 t + 50% NP) recorded the highest tillers (464.9 m^{-2}), plant height (102.5 cm), and days to physiological maturity (190.7). Treatments T6 and T7 consistently enhanced plant population, coleoptile length (non-significant), and tillering compared to chemical-only (T2) or control (T1).

Table 4

Growth parameters of wheat as influenced by integrated nutrient management and genotypes

Genotypes	Days to germination	Plant population (plants m^{-2})	Coleoptile Length (cm)	Tillers m^{-2}	Days to Physiological Maturity	Plant height (cm)
BARDC-1	14.7	81.6^{b}	7.3^{b}	335.3	189.06	86.0
BARDC-2	14.3	93.2^{a}	8.3^{a}	351.5	189.00	86.1
LSD (P ≤ 0.05) (G)	NS	9.54	0.89	NS	NS	NS
Treatment						
T1 Control	15.0^{a}	90.6^{a}	7.5	263.6^{d}	188.40^{bc}	74.1^{d}
T2 100 % NP	13.5^{b}	87.8^{ab}	8.0	315.4^{c}	188.10^{c}	83.5^{c}
T3 FYM 10 t ha^{-1}	14.7^{ab}	89.4^{a}	8.3	322.4^{c}	188.30^{bc}	82.3^{c}
T4 FYM + 50 % NP	15.2^{a}	93.4^{a}	6.9	331.7^{c}	188.50^{bc}	83.6^{c}
T5 Biozote alone	15.0^{a}	70.1^{b}	8.4	313.1^{c}	189.00^{b}	83.7^{c}
T6 Biozote + 50 % NP	14.7^{ab}	88.7^{a}	8.0	392.8^{b}	190.20^{a}	92.8^{b}
T7 Biozote + FYM 5 t + 50 % NP	13.6^{b}	92.0^{a}	7.6	464.9^{a}	190.70^{a}	102.5^{a}
LSD (P ≤ 0.05) (T)	1.27	17.86	NS	17.9	0.76	6.18

Notes: Means followed by different letters are significantly different at P ≤ 0.05 (LSD).
NS = Non-significant effect.

3.4 Wheat Physiological Traits

wheat physiological traits were significantly influenced by both genotype and treatment (Table 5). BARDC-2 had significantly higher chlorophyll (SPAD) than BARDC-1 at anthesis (57.5 vs 53.7) and grain filling (80.4 vs 74.5). NDVI at anthesis (0.47 vs 0.46) and grain filling (0.66 vs 0.63) were non-significant (NS) between genotypes. Among treatments, Integrated nutrient management significantly affected SPAD and NDVI. T7 (Biozote + FYM 5 t + 50% NP) recorded the highest SPAD at anthesis (58.8) and grain filling (81.7), and NDVI at anthesis (0.59) and grain filling (0.82). Treatments combining biofertilizer, organic manure, and partial NP (T4, T6, T7) consistently outperformed control (T1) and Biozote alone (T5), whereas chemical-only (T2) was intermediate.

Table 5

Physiological parameters of wheat as influenced by integrated nutrient management and genotypes

Genotypes	Chlorophyll (SPAD) at anthesis stage	Chlorophyll (SPAD) at grain filling stage	NDVI at anthesis stage	NDVI grain at filling stage
BARDC-1	53.7^{b}	74.5^{b}	0.46	0.63
BARDC-2	57.5^{a}	80.4^{a}	0.47	0.66
LSD (P ≤ 0.05) (G)	1.91	2.71	NS	NS
Treatment				
T1 Control	53.3^{cd}	74.2^{cd}	0.39^{d}	0.54^{d}
T2 100 % NP	56.5^{abc}	78.7^{abc}	0.49^{bc}	0.68^{bc}
T3 FYM 10 t ha^{-1}	56.5^{abc}	78.9^{abc}	0.47^{c}	0.65^{c}
T4 FYM + 50 % NP	57.2^{ab}	80.1^{ab}	0.53^{b}	0.73^{b}
T5 Biozote alone	52.3^{d}	72.8^{d}	0.32^{e}	0.44^{e}
T6 Biozote + 50 % NP	54.8^{bcd}	76.0^{bcd}	0.48^{c}	0.66^{bc}
T7 Biozote + FYM 5 t + 50 % NP	58.8^{a}	81.7^{a}	0.59^{a}	0.82^{a}
LSD (P ≤ 0.05) (T)	3.58	5.08	0.04	0.06

3.5 Yield attributes and productivity

Yield attributes were significantly influenced by both genotype and treatment (Table 6). BARDC-2 had significantly longer spikes (11.08 cm) and higher 1000-grain weight (41.1 g) than BARDC-1 (9.58 cm; 40.0 g), also recorded significantly total dry matter and harvest index while other traits, including grains per spike, grain yield and straw yield were non-significant (NS) between genotypes. Among treatment effect INM significantly influenced all yield traits. T7 (Biozote + FYM 5 t + 50% NP) produced the highest spike length (10.57 cm), grains per spike (54.0), 1000-grain weight (47.9 g), total dry matter (16,903 kg ha^{-1}), grain yield (5,504.2 kg ha^{-1}), and straw yield (12,302 kg ha^{-1}). Control (T1) recorded the lowest values, and intermediate treatments (T2–T6) differed significantly.

Table 6

Yield attributes and grain yield of wheat as influenced by integrated nutrient management and genotypes

Gentypes	Spike length (cm)	Grains spike^{-1}	1000-grain weight (g)	Total dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
BARDC-1	9.58^{b}	43.3	40.0^{b}	11255^{b}	3841.6	7875.2	32.04^{b}
BARDC-2	11.08^{a}	43.5	41.1^{a}	12422^{a}	4062.4	8208.6	34.91^{a}
LSD (P ≤ 0.05) (G)	0.28	NS	0.96	1136.5	NS	NS	2.8716
Treatment							
T1 Control	9.80^{c}	34.2^{f}	32.5^{f}	8146^{e}	2599.6^{f}	5169^{d}	36.58^{a}
T2 100 % NP	10.37^{ab}	38.6^{e}	36.2^{e}	10472^{cd}	3060.0^{e}	7068^{c}	32.85^{ab}
T3 FYM 10 t ha^{-1}	10.13^{bc}	41.2^{de}	39.0^{d}	11167^{c}	3393.8^{e}	7216^{c}	35.24^{ab}
T4 FYM + 50 % NP	10.33^{ab}	44.8^{c}	42.3^{c}	13988^{b}	4360.0^{c}	9444^{b}	32.27^{b}
T5 Biozote alone	10.60^{a}	42.9^{cd}	41.2^{c}	8627de	3928.3^{d}	6205^{cd}	35.74^{ab}
T6 Biozote + 50 % NP	10.53 ^{a}	48.1^{b}	45.0^{b}	13566^{b}	4818.3^{b}	8889^{b}	34.67^{ab}
T7 Biozote + FYM 5 t + 50 % NP	10.57^{a}	54.0^{a}	47.9^{a}	16903^{a}	5504.2^{a}	12302^{a}	26.96^{c}
LSD (P ≤ 0.05) (T)	0.52	3.04	1.81	2126.1	412.93	1327.7	2.4005

Notes: Means followed by different letters are significantly different at P ≤ 0.05 (LSD).
NS = Non-significant effect.

3.6 Grain quality parameters

The Grain quality traits exhibited significant treatment and genotype effects (Table 7). BARDC-2 exhibited significantly higher protein (13.22 %), gluten (13.82 %), and ash content (1.62 a %) compared to BARDC-1 (protein 12.80 %, gluten 12.91 b %, ash 1.48 %). Moisture content was significantly higher in BARDC-1 (11.50 %) than BARDC-2 (11.36 %). Among treatment effect the INM significantly influenced all quality traits. T7 (Biozote + FYM 5 t + 50% NP) produced the highest protein (14.22 %), gluten (14.90 %), and ash content (1.82 %), while T1 (Control) recorded the lowest values.

Table 7

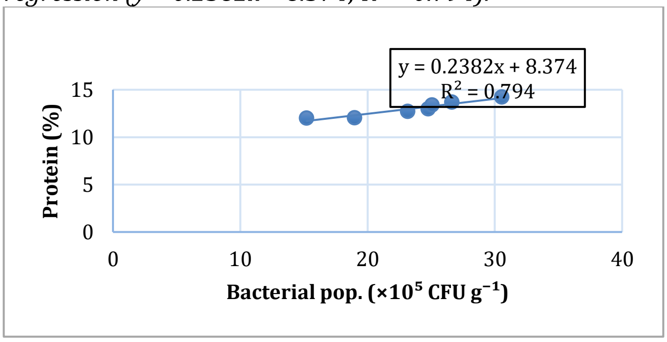
Grain quality parameters of wheat as influenced by integrated nutrient management and genotypes

Genotype	Protein (%)	Gluten (%)	Ash (%)	Moisture (%)
BARDC-1	12.80^{b}	12.91^{b}	1.48^{b}	11.50^{a}
BARDC-2	13.22^{a}	13.82^{a}	1.62^{a}	11.36^{b}
LSD (P ≤ 0.05)	0.06	0.06	0.046	0.05
Treatment				
T1 Control	12.00^{f}	12.10^{d}	1.30^{d}	11.20^{c}
T2 100 % NP	12.05^{f}	12.02^{d}	1.32^{d}	11.40^{b}
T3 FYM 10 t ha^{-1}	12.70^{e}	13.50^{c}	1.55^{c}	11.35^{b}
T4 FYM + 50 % NP	13.00^{d}	13.80^{b}	1.55^{c}	11.60^{a}
T5 Biozote alone	13.40^{c}	13.45^{c}	1.62^{bc}	11.55^{a}
T6 Biozote + 50 % NP	13.70^{b}	13.80^{b}	1.70^{b}	11.55^{a}
T7 Biozote + FYM 5 t + 50 % NP	14.22^{a}	14.90^{a}	1.82^{a}	11.40^{b}
LSD (P ≤ 0.05)	0.12	0.12	0.08	0.09

Notes: Means followed by different letters are significantly different at P ≤ 0.05 (LSD).
NS = Non-significant effect.

Figure 3

Relationship between bacterial population and grain protein content of wheat under different integrated nutrient management practices (mean of two genotypes; n = 70; r = 0.89, P < 0.05). The solid line represents the linear regression (y = 0.2382x + 8.374; R^2 = 0.794).*



Bacterial population showed a very strong positive linear relationship with grain protein content ($r = 0.89^*$, $R^2 = 0.79$; Figure 3).

3.7 Correlation among selected traits

Pearson's correlation coefficients among key growth, physiological, soil and quality parameters are presented in Table 8. Grain yield exhibited very strong positive correlations with productive tillers m^{-2} ($r = 0.94^*$), post-harvest bacterial population ($r = 0.92^*$ Figure 4), NDVI at grain-filling ($r = 0.91^*$), chlorophyll content at anthesis ($r = 0.89^*$), 1000-grain weight ($r = 0.88^*$) and protein content ($r = 0.87^*$) ($P \leq 0.05$). Post-harvest bacterial population was strongly correlated with grain protein content ($r = 0.89^*$, Figure 3), while soil organic carbon showed very strong relationships with both bacterial population ($r = 0.96^*$, Figure 2) and available nitrogen ($r = 0.91^*$, Figure 1).

Table 8

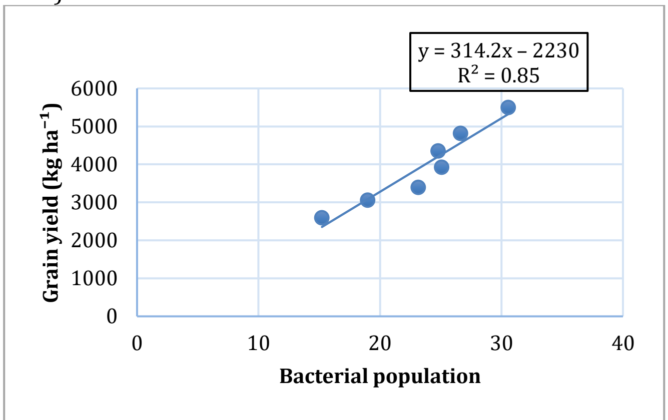
Pearson's correlation coefficients among selected growth, physiological, soil and quality parameters in wheat (mean of two genotypes; n = 70)

Parameter	Tillers m^{-2}	1000-grain wt (g)	NDVI grain filling	Chlorophyll anthesis (SPAD)	Protein (%)	Bacterial pop. ($\times 10^5$ CFU g^{-1})	Org. carbon (%)	Av. N (mg kg^{-1})	Grain yield (kg ha^{-1})
Tillers m^{-2}	1								
1000-grain weight (g)	0.85	1							
NDVI – grain filling	0.96	0.87	1						
Chlorophyll (SPAD) – anthesis	0.92	0.84	0.93	1					
Protein content (%)	0.89	0.81	0.90	0.91	1				
Bacterial population	0.93	0.86	0.94	0.90	0.89	1			
Organic carbon (%)	0.90	0.83	0.92	0.88	0.86	0.96	1		
Available nitrogen (kg ha^{-1})	0.87	0.80	0.89	0.86	0.84	0.91	0.91	1	
Grain yield (kg ha^{-1})	0.94	0.88	0.91	0.89	0.87	0.92	0.90	0.88	1

Note: All values are significant at $P \leq 0.05$

Figure 4

Relationship between post-harvest soil bacterial population and grain yield of wheat under different integrated nutrient management practices (n = 70; r = 0.92, P < 0.05). The solid line represents the linear regression (y = 314.2x – 2230; R^2 = 0.85).*



The strong linear relationship ($r = 0.92^*$, $R^2 = 0.85$) between soil bacterial population and grain yield (Figure 4) confirms that enhanced microbial activity was a key factor in the superior performance of T7.

4. DISCUSSION

4.1 Soil health improvement

The marked increase in organic carbon and available nutrients under integrated treatments, especially T7, resulted from enhanced organic matter input from FYM and accelerated microbial mineralization driven by Biozote. These findings agree with recent semi-arid studies reporting 25–40 % higher soil organic carbon and improved N and P availability when FYM is combined with microbial inoculants (Kushwah et al., 2024; Parveen et al., 2025; Parewa et al., 2022). Genotype BARDC-2 left slightly higher residual nutrients than BARDC-1, indicating superior root activity and rhizodeposition, a trait linked to nutrient-use efficiency in modern wheat cultivars under reduced fertilizer regimes (Salam et al., 2025; Zulfiqar et al., 2023). Thus, integrating Biozote and FYM with 50 % recommended chemical fertilizer (T7) offers a practical and sustainable strategy for restoring soil fertility in the high-pH, low-organic-matter soils of Balochistan's semi-arid highlands.

4.2 Enhancement of post-harvest soil microbial populations

The substantial increase in bacterial and fungal populations under integrated treatments, particularly T7, reflects the combined effect of readily decomposable carbon from FYM and growth-promoting stimuli from Azotobacter-based Biozote. These results align with recent field studies in semi-arid regions demonstrating that co-application of organic manure and microbial inoculants can raise soil bacterial counts by 80–120 % and fungal counts by 100–150 % compared with chemical fertilizer alone (Kushwah et al., 2024; Parewa et al., 2022; Jat et al., 2018). The slightly higher microbial populations associated with genotype BARDC-2 suggest greater rhizosphere competence and root exudation, a trait increasingly recognized in nutrient-efficient wheat cultivars under reduced fertilizer regimes (Salam et al., 2025; Zulfiqar et al., 2023). Thus, the integration of Biozote and FYM with 50 % recommended chemical fertilizer (T7) effectively revitalized soil microbial communities, providing a sustainable foundation for long-term wheat productivity in the semi-arid highlands of Balochistan.

4.3 Growth and physiological performance

The superior vegetative growth under integrated nutrient management, particularly T7, resulted from improved synchrony between nutrient release and crop demand, leading to higher tiller density, plant height, chlorophyll content and NDVI throughout the season. These findings are consistent with recent studies demonstrating that combined application of biofertilizers and organic amendments enhances nutrient availability, root proliferation and canopy development in wheat under semi-arid conditions (Fazily et al., 2021; Kumar et al., 2022). Genotype BARDC-2 exhibited greater coleoptile length, tillering and leaf greenness than BARDC-1, confirming its superior seedling vigor and physiological efficiency (Vukasovic et al., 2022). The prolonged availability of nitrogen and micronutrients from FYM mineralization and Biozote-mediated fixation sustained vegetative growth and delayed senescence, as reflected in higher SPAD values and NDVI at grain filling (Khan et al., 2017; Ikan et al., 2024; Ramzan et al., 2020). Overall, the synergistic effect of Biozote, FYM and 50 % recommended NP in T7 provided a balanced and sustained nutrient supply, supporting robust growth and physiological performance of wheat in the resource-limited highland environment of Quetta.

4.4 Yield attributes and grain yield

The superior yield performance of T7 confirms that integrating biofertilizer, organic manure and partial NP substantially boosts wheat yield components through enhanced nutrient uptake and reproductive efficiency. Greater spike length, grains per spike, 1000-grain weight, grain yield and total dry matter under T7 reflect improved biomass accumulation and sink strength. These results align with recent semi-arid trials showing INM outperforms sole chemical or organic fertilization by 15–35 % in grain yield (Zulfiqar et al., 2023; Ikan et al., 2024). Genotypic differences in spike length and 1000-grain weight highlight varietal variation in sink capacity and grain-filling efficiency, while non-significant differences in total dry matter, grain yield and straw yield under T7 indicate nutrient management's dominant role over genotype in your conditions. Overall, T7 offers a sustainable approach to maximize wheat productivity in Quetta's semi-arid agro-climatic zone.

4.5 Grain quality responses

The marked improvements in grain protein, wet gluten and ash contents under T7 reflect enhanced late-season nitrogen availability and micronutrient uptake from the synergistic action of Biozote, FYM and partial NP, which promote better protein synthesis and mineral accumulation in the grain. These findings are consistent with recent semi-arid wheat studies showing INM increases protein and gluten by 10–25 % compared to sole chemical fertilization (Salam et al., 2025; Kumar et al., 2015; Kushwah et al., 2024). Genotype BARDC-2's higher protein (13.22 %), gluten (13.82 %) and ash (1.62 %) than BARDC-1 indicate superior sink strength and nutrient remobilization efficiency, while BARDC-1's higher moisture (11.50 %) suggests varietal differences in grain hydration. Non-significant moisture variation across treatments underscores INM's focus on nutritional quality over physical traits. Overall, T7 provides a sustainable means to elevate wheat grain quality for milling and baking in Balochistan's semi-arid conditions.

4.6 Mechanisms and correlations

The Pearson's correlation analysis revealed very strong positive relationships between grain yield and several key traits (Table 8). The particularly tight linear association between post-harvest bacterial population and grain yield ($r = 0.92^*$, $R^2 = 0.85$; Figure 4) provides clear evidence that improved soil microbial activity was a major driver of the superior performance observed under T7 (Parewa et al., 2022; Ikan et al., 2024; Dai et al., 2025).

The tight correlation between soil bacterial population and grain protein content ($r = 0.89^*$, $R^2 = 0.79$; Figure 3) indicates that microbial-mediated nitrogen mineralization during the post-anthesis period directly contributed to higher grain protein, a key quality parameter for milling and baking (Ramzan et al., 2020; Kumar et al., 2015).

The exceptionally strong relationship between soil organic carbon and bacterial population ($r = 0.96^*$, $R^2 = 0.92$; Figure 2) confirms that organic matter input from FYM served as the primary energy source driving microbial proliferation under integrated management (Dhaliwal et al., 2021; Kushwah et al., 2024; Parveen et al., 2025).

The significant correlation between organic carbon and available nitrogen ($r = 0.91^*$, $R^2 = 0.83$; Figure 1) demonstrates that FYM addition enhanced N mineralization, thereby sustaining crop demand and reducing reliance on chemical fertilizers (Jat et al., 2018).

These highly significant associations highlight the pivotal role of enhanced soil microbial activity and organic carbon status in driving nutrient mineralisation, photosynthetic efficiency and, ultimately, higher grain yield and quality under integrated nutrient management (Kushwah et al., 2024; Parewa et al., 2022; Jat et al., 2018; Ali et al., 2025).

4.7 Practical implications

Integration of Biozote and FYM with only 50 % of recommended chemical fertilizer (T7) offers a practical, cost-effective and environmentally sustainable alternative for wheat growers in Balochistan, reducing fertilizer requirement while doubling productivity and restoring soil health.

5. CONCLUSION

Integrated application of Biozote (5 kg ha^{-1}), farmyard manure (5 t ha^{-1}) and 50 % recommended chemical fertilizer (T7) proved the most effective and sustainable nutrient management strategy for wheat under semi-arid highland conditions of Balochistan. This practice not only doubled grain yield (5504 kg ha^{-1}) over the unfertilized control but also significantly improved grain quality and post-harvest soil fertility. Genotype BARDC-2 exhibited superior performance across traits. The study strongly recommends adoption of T7 as a resource-efficient approach to enhance wheat productivity while maintaining long-term soil health in the region. Long-term, multi-location evaluations are recommended to determine the sustained effects of this integrated nutrient management practice on soil health and wheat productivity.

REFERENCES

Ahmed, M., Hyder, S. I., Ullah, A., Khan, R. U., Ahmad, M. A., Hayat, A., & Arshad, N. (2023). Response of Integrated Nutrient Management (INM) on Growth, Yield, and Nutrient use Efficiency of Wheat under Irrigated Conditions. *Journal of Applied Research in Plant Sciences* , *4*(01), 363–369. https://doi.org/10.38211/joarps.2023.04.01.43

Ali, M., Bari, A., Ibrahim, M. *et al.* Impact of irrigation schedule and integrated nutrient management on wheat yield and nutrients uptake under semi-arid regions. *Irrig Sci* 43, 519–532 (2025). https://doi.org/10.1007/s00271-024-00986-8

Dai, Y., Wu, X., Li, S., Li, Y., Wang, L., Hu, Y., Liu, K., Yang, Z., Cai, L., Xu, K., Cui, M., Xu, X., Jia, Y., Wei, D., & Ding, J. (2025). Optimizing Resource Management with Organic Fertilizer and Microbial Inoculants to Enhance Soil Quality, Microbial Diversity, and Crop Productivity in Newly Cultivated Land. *Plants*, *14*(19), 3032. https://doi.org/10.3390/plants14193032

Dhaliwal, S. S., Sharma, S., Sharma, V., Shukla, A. K., Walia, S. S., Alhomrani, M., Gaber, A., Toor, A. S., Verma, V., Randhawa, M. K., Pandher, L. K., Singh, P., & Hossain, A. (2021). Long-Term Integrated Nutrient Management in the Maize–Wheat Cropping System in Alluvial Soils of North-Western India: Influence on Soil Organic Carbon, Microbial Activity and Nutrient Status. *Agronomy*, *11*(11), 2258. https://doi.org/10.3390/agronomy11112258

Fazily, T., Thakral, S. K., & Dhaka, A. K. (2021). Effect of integrated nutrient management on growth, yield attributes and yield of wheat. *International Journal of Advances in Agricultural Science and Technology*, *8*(1), 106-118. DOI: 10.47856/ijaast.2021.v08i1.014

Government of Pakistan. (2024). *Economic Survey of Pakistan 2023–24*. Finance Division, Government of Pakistan.

Hanway, J.J., Heidel, H., 1952. Soil analysis methods as used in Iowa State College Soil Testing Laboratory. *Iowa Agric. 57*, 1–31.

Ikan, C., Soussani, F.-E., Ouhaddou, R., Ech-Chatir, L., Errouh, F., Boutasknit, A., Assouguem, A., Ali, E. A., Ullah, R., Ait Barka, E., Lahlali, R., & Meddich, A. (2024). Use of Biofertilizers as an Effective Management Strategy to Improve the Photosynthetic Apparatus, Yield, and Tolerance to Drought Stress of Drip-Irrigated Wheat in Semi-Arid Environments. *Agronomy*, *14*(6), 1316. https://doi.org/10.3390/agronomy14061316

Jackson, M.L., 1973. *Soil Chemical Analysis*. Prentice Hall of India, New Delhi.

Jat, R. D., Jat, H. S., Nanwal, R. K., Yadav, A. K., Bana, A., Choudhary, K. M., ... & Jat, M. L. (2018). Conservation agriculture and precision nutrient management practices in maize-wheat system: Effects on crop and water productivity and economic profitability. *Field Crops Research*, *222*, 111-120. https://doi.org/10.1016/j.fcr.2018.03.025

Kushwah, N., Billore, V., Sharma, O. P., Singh, D., & Chauhan, A. P. S. (2024). Integrated Nutrient management for optimal plant health and crop yield. *Plant Science Archives*, *8*(3), 10-12. https://doi.org/10.51470/PSA.2023.8.2.10

Khan, M. N., Shah, H., Qureshi, A. H., & Abbasi, S. S. (2017). Biozote performance on wheat in on-farm trials: farmers' perceptions. *Science Technology and Devlopment*, *36*(3), 147-151. ISSN 0254-6418 / DOI: 10.3923/std.2017.147.151

Kumar, A., Pathak, R. K., Kumar, S., Kumar, K., Singh, D., & Pal, S. (2015). Influence of integrated nutrient management on yield, uptake and crop quality of wheat. *Int. J. Res. Appl*, *3*(6), 77-79.

Kumar, S., Sindhu, S. S., & Kumar, R. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Current Research in Microbial Sciences*, *3*, 100094. https://doi.org/10.1016/j.crmicr.2021.100094

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circ. 939*.

Pakistan Bureau of Statistics. (2024). *Agricultural statistics of Pakistan 2023–24*. Government of Pakistan.

Parveen, M., & Ghosh, S. (2025). Ecological dynamics and microbial consortia: Enhancing soil health and sustainable agriculture. *Egyptian Journal of Botany*. DOI: 10.21608/ejbo.2025.312933.2967

Parewa, H. P., Yadav, J., Meena, V. S., Sarkar, D., Meena, S. K., Rakshit, A., & Datta, R. (2022). Improved nutrient management practices for enhancing productivity and profitability of wheat under Mid-Indo-Gangetic Plains of India. *Agriculture*, *12*(9), 1472. https://doi.org/10.3390/agriculture12091472

Ramzan, Y., Hafeez, M.B., Khan, S. *et al.* Biofortification with Zinc and Iron Improves the Grain Quality and Yield of Wheat Crop. *Int. J. Plant Prod.* 14, 501–510 (2020). https://doi.org/10.1007/s42106-020-00100-w

Salam, Abdul, Atta Ullah, Ghulam Rasool, Mehwish Shoaib, Nanak Khan, Ahmed Ali, Muhammad Ejaz, Muhammad Waris, Kamran Hashim, and Honak Baloch. "Agro-Morphological Performance of Wheat (Triticum aestivum L.) Genotypes for Yield and Quality Traits." *Planta Animalia* 4, no. 3 (2025): 143-151.https://doi.org/10.71454/.

Steel, R.G.D., Torrie, J.H., Dickey, D.A., 1997. *Principles and Procedures of Statistics: A Biometrical Approach*, 3rd ed. McGraw-Hill, New York.

Subbiah, B.V., Asija, G.L., 1956. A rapid procedure for estimation of available nitrogen in soils. *Current. Sci. 25*, 259–260.

The Jamovi Project, 2023. *Jamovi* (Version 2.3) [Computer Software]. Retrieved from https://www.jamovi.org

Vukasovic, S., Alahmad, S., Christopher, J., Snowdon, R. J., Stahl, A., & Hickey, L. T. (2022). Dissecting the genetics of early vigour to design drought-adapted wheat. *Frontiers in plant science*, *12*, 754439. https://doi.org/10.3389/fpls.2021.754439

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*, *37*(1), 29-38.

Zahoor, I., Farzana, M. H. C., Shafeeq, M., Afzal, A. B., Haider, S. M. S., Arshad, E., ... & Ahmad, S. (2025). Enhancing Soil Nutrient Efficiency for Sustainable Agriculture. *Sch J Agric Vet Sci*, *7*, 232-241. https://doi.org/10.36347/sjavs.2025.v12i07.001

Zulfiqar, U., Ahmad, M., Valipour, M., Ishfaq, M., Maqsood, M. F., Iqbal, R., ... & El Sabagh, A. (2023). Evaluating optimum limited irrigation and integrated nutrient management strategies for wheat growth, yield and quality. *Hydrology*, *10*(3), 56. https://doi.org/10.3390/hydrology10030056

Taj, S. (2024). Valorization of Germinated Oats, Soybeans, and Wheat for High-Protein Food Supplementation in Low-Resource Settings. Journal of Bioscience Studies, 1(1), 1-7. https://doi.org/10.65761/jbs.v1.i1.1