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Integrative Assessment of Organic, Inorganic, and Bio-fertilizers on wheat Phenological, growth and Yield Indices under Semi-Arid Agroecosystems

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Crop nutrient's major sources are organic, inorganic, and bio-fertilizers. Supplementation of beneficial microbes with organic and inorganic fertilizers is a feasible technology to improve wheat productivity. This study assessed the impact of Bioaab biofertilizer (containing *Rhodopseudomonas*, *Lactobacillus*, and *Saccharomyces* spp.), nitrogen (N) rates (80, 120, 160 kg ha^{-1}), and organic amendments poultry manure (PM), farmyard manure (FYM), and maize residues (MR) on wheat growth and yield. Two field trials, with and without Bioaab, were conducted during the 2020–2021 winter season at The University of Agriculture, Peshawar, using a randomized complete block design with ten treatments (including a control), each replicated three times. In the Bioaab trial, 60 L ha^{-1} of the extended solution was applied via irrigation before sowing. Bioaab application and higher N levels significantly improved plant height, leaf area, dry matter, and yields. Compared to the control, plant height increased by 12.8% and 19.0%, and leaf area by 7.6% and 18.1% at 80 and 160 kg N ha^{-1}, respectively. Dry matter production rose by 16.2% at 160 kg N ha^{-1}. Among organic sources, PM showed the highest increase in plant height (18.8%), leaf area (17.3%), and dry matter (16.7%). FYM and MR also enhanced growth, though to a lesser extent. PM led to the highest biological (12,158 kg ha^{-1}) and grain yield (4,110 kg ha^{-1}), reflecting increases of 54.7% and 86.5% over the control, respectively. These results underscore the benefits of integrated nutrient management, particularly poultry manure combined with 120–160 kg N ha^{-1}, in boosting wheat productivity under semi-arid conditions.
Keywords: Biofertilizer, Inorganic fertilizer, Organic fertilizers, Wheat growth, Wheat phenology, Wheat yield

Introduction:

Cereal crops are the main staple foods grown across vast regions worldwide and have historically been the foundation of agricultural systems in many countries [1]. Among these, wheat (Triticum aestivum L.) is the most widely grown cereal crop in the world, making it a critical component of food security [2].

In response to the growing demand for wheat, the application of inorganic fertilizers, especially nitrogen (N), has significantly increased. While nitrogen is essential for plant growth and is primarily absorbed in the forms of ammonium (NH_4^+) and nitrate (NO_3^-), its excessive use has led to a decline in soil fertility and has posed significant environmental risks [3][4]. Nitrogen plays a vital role in plant physiological and biochemical processes, contributing to enhanced yield and improved crop quality [5].

However, the over-application of chemical fertilizers has been associated with environmental degradation through nitrogen leaching, surface runoff, and volatilization, which adversely affect surface water, groundwater, and atmospheric quality [6].

Organic manures are gaining recognition as a sustainable alternative due to their ability to improve soil health, promote nutrient cycling, and boost crop yields [7]. Common organic sources include farmyard manure (FYM), poultry manure (PM), green manures, sewage sludge, and press mud [8]. The incorporation of organic amendments improves soil microbial activity and structure, promoting nutrient availability and long-term fertility [9].

Although organic fertilizers offer many benefits, relying on them alone often fails to supply sufficient nutrients to meet crop demands because of their lower nutrient content. Thus, integrated nutrient management, combining organic and inorganic fertilizers, has emerged as a practical strategy to enhance crop yields, particularly in regions like Khyber Pakhtunkhwa where wheat productivity remains suboptimal [10]. To enhance nutrient use efficiency and promote soil health, the application of beneficial microorganisms has increasingly attracted interest. Effective microorganisms technology, developed in the early 1980s by Professor at the University of the Ryukyus, Okinawa, Japan, is a microbial consortium that enhances soil fertility and crop performance. These beneficial microbes facilitate key processes such as increased photosynthesis, enzymatic and hormonal activity, accelerated decomposition, suppression of soil-borne pathogens, and improved nutrient uptake [11].

The synergistic use of effective microorganisms or beneficial microbes with organic materials enhances nutrient mineralization and microbial activity, especially when fresh organic matter is applied [12]. While organic sources like FYM and poultry manure support sustainable yield improvements, they may be insufficient on their own. Therefore, integrating beneficial microbes with both organic and inorganic fertilizers is considered a viable and efficient nutrient management strategy [13]. Considering the significance of integrated nutrient sources and microbial inoculants, the present study was undertaken to evaluate the effects of organic sources and nitrogen application with and without beneficial microbes (Bioaab) on wheat growth and productivity.

Objectives:

The main objectives of this study were to evaluate the effects of different organic amendments (poultry manure, farmyard manure, maize straw), nitrogen levels, and microbial inoculants (Bioaab) on wheat growth, phenology, and yield under semi-arid conditions.

Novelty Statement:

The novelty of this study lies in its integrated approach to nutrient management, combining organic and inorganic fertilizers with microbial inoculants, which has not been extensively evaluated in the specific context of wheat productivity under semi-arid environmental conditions. This research offers new insights into optimizing resource use for sustainable crop production.

Materials and Methods:

Experimental Design and Treatments:

Two field experiments, one with Bioaab application and one without, were conducted during the winter season of 2020–2021 at the Agronomy Research Farm, University of Agriculture Peshawar, Pakistan.

A randomized complete block design (RCBD) was employed for both experiments, comprising ten treatments (including a control), with each treatment replicated three times.

Treatment allocation within each block was done randomly to ensure unbiased results. Each experiment included two factors:

Factor A: Nitrogen (N) levels at 80, 120, and 160 kg ha^{-1}

Factor B: Organic sources (poultry manure, maize residues, and farmyard manure), each applied at 10 t ha^{-1}

The experiments were carried out under two distinct conditions: one involving the application of Bioaab and the other conducted without its use.

Experimental Materials and Cultural Practices:

Nitrogen was supplied at three different rates including 80, 120, and 160 kg ha^{-1}, while phosphorus and potassium were applied at their recommended doses of 90 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}, respectively. These nutrients were supplied through urea (46% N), single superphosphate (12% P_2O_5), and potassium chloride (60% K_2O), respectively [14]. Organic fertilizers such aspoultry manure (PM), maize straw (MS), and farmyard manure (FYM), were collected from the Agronomy Research Farm and uniformly applied at a rate of 10 t ha^{-1}. The application took place one month before sowing to facilitate partial decomposition. Following local agronomic practices, urea was applied in two splits: half at the time of sowing as a basal dose, and the remaining half during the tillering stage as a topdressing. Phosphorus and potassium sources were applied entirely at sowing. The nutrient composition of the organic amendments used is summarized in Table 1 for clarity. Poultry manure (PM) had the highest concentrations of key macronutrients, followed by farmyard manure (FYM), while maize straw (MS) had comparatively lower values [15][16]. Each plot measured 3 m × 2.4 m and consisted of ten rows spaced 30 cm apart. Wheat variety Pirsabaq-2015 was sown on November 11, 2020, at a seed rate of 150 kg ha^{-1} and harvested in the second week of June 2021. Four irrigations were administered using water from the Warsak Canal at 7, 17, 70, and 116 days after sowing (DAS). Weed control was managed using Infinity, a broad-spectrum herbicide effective against both broadleaf and grassy weeds. All other agronomic practices were carried out following standard local recommendations [17]. Before sowing, the field was plowed and pre-irrigated (lightly flooded) one month in advance to ensure uniform soil moisture and promote the decomposition and incorporation of organic materials.

Table 1. Nutrient composition of organic amendments used in the study.

Nutrient Source	Nitrogen (N) %	Phosphorus (P_2O_5) %	Potassium (K) %
Poultry Manure	2.8	2.84	2.3
Farmyard Manure (FYM)	1.08	0.2	0.45
Maize Straw	0.6	0.15	1

Bioaab Composition, Application, and Standard Procedure:

Bioaab, a liquid biofertilizer containing *Rhodopseudomonas* spp., *Lactobacillus* spp., and *Saccharomyces* spp., was prepared using a standardized protocol. A mixture was prepared by adding 20 liters of water to a 30-liter plastic drum, followed by 1 liter of Bioaab concentrate and 1 kilogram of sugar. The solution was thoroughly mixed and then placed in a shaded area to ferment for seven days. The extended solution (60 liters ha^{-1}) was applied via irrigation before sowing in the Bioaab experiment to stimulate microbial activity and facilitate organic matter decomposition. The Bioaab used in this study was obtained from the Nature Farming Research & Development Foundation (NFRDF), Faisalabad.

The formulation includes microbial genera known for producing biologically active compounds such as amino acids (glutamic acid, tryptophan), nucleic acids (DNA and RNA fragments), plant hormones (indole-3-acetic acid), enzymes (dehydrogenase, phosphatase), polysaccharides, and antimicrobial peptides.

Data Collection:

The number of days to anthesis was determined by observing the emergence of anthers on the wheat spikes across the plot, starting from the sowing date. Maturity was recorded as the number of days from sowing until the glumes had entirely lost their green coloration, indicating physiological maturity. Plant height was measured using a meter rod on 10 randomly selected tillers from each plot, and the average was computed. Leaf area per tiller (cm^2) was determined using five sample tillers at the flowering stage, following [18] using the formula:

$$\text{Leaf area tiller}^{-2} = \frac{\text{No of leaves x Leaf lenght x Leaf width}}{\text{arbitrarily tillers number}}$$

$$= \text{Correction factor } (0.65)$$

Dry matter distribution (g m^{-2}):

Dry matter distribution was recorded by harvesting a 1-meter row in each plot at the anthesis and physiological maturity stage. Harvested materials were oven-dried for 12 hours at 70°C to constant weight for dry weight determination. After drying the samples were then separated into leaves, stems, and spikes, weighted with digital balance, and then converted to g m^{-2} [19].

$$Dry\ matter\ partitioning\ (gm^{-2}) = \frac{Dry\ weight\ of\ dried\ material\ in\ 1\ meter\ row}{R\ to\ R\ (m) x Row\ length\ (m) x No.of\ Rowr} \text{X } 1$$

Biological and grain yield (kg ha^{-1}):

In each plot, the four central rows were harvested and sun-dried until a constant moisture level was reached, and the dried materials were weighed for biological yield. After recording biological yield, the harvested materials were threshed, cleaned, and weighed to determine the grain yield. Biological and grain yields (kg ha^{-1}) were calculated using the following formula:

$$Biological\ yield\ (kg\ ha^{-1}) = \frac{Biological\ yield\ of\ four\ rows}{R\ to\ R\ (m)\ x\ Row\ length(m) x\ No.of\ rows} \text{X } 100000^{-2}$$

$$Grain\ yield\ (kg\ ha^{-1}) = \frac{Grain\ yield\ of\ four\ rows}{R\ to\ R\ (m)\ x\ Row\ length(m) x\ No.of\ rows} \text{X } 100000^{-2}$$

Statistical Analysis:

All recorded data were subjected to analysis of variance (ANOVA) using the method described by [20]. Treatment means were compared using the Least Significant Difference (LSD) test at a significance level of $P < 0.05$.

Results:

Days to Anthesis:

Bioaab application, organic sources, nitrogen (N) levels, and the control vs. treatment contrast significantly ($P \leq 0.05$) influenced days to anthesis(Table 2)However, no significant difference was observed between Bioaab-treated (125.3 days) and untreated (124.8 days) plots (Figure 1C). Among N treatments, 160 kg ha^{-1} delayed anthesis (126 days), while 80 kg ha^{-1} led to earlier anthesis (124 days) (Figure 1A). Poultry manure (PM) delayed anthesis to 126 days, followed by FYM (125 days) and maize straw (MS, 124 days) (Figure 1B). Control plots reached anthesis earlier (123 days) compared to treated plots (125 days) (Figure 1D).

Days to Physiological Maturity:

Days to physiological maturity were significantly influenced ($P \leq 0.05$) by Bioaab, organic amendments, N levels, and treatment contrast (Table 1). Control plots matured earlier (163 days) than treated plots (165 days) (Figure 1D). Maturity was slightly delayed under 160 kg N ha^{-1} (165.4 days), followed by 120 kg N ha^{-1} (164.9 days), and shortest under 80 kg N ha⁻¹ (164 days) (Figure 1A). Organic sources showed delayed maturity, with PM and FYM both at 165 days and MS at 164 days (Figure 1B). Bioaab-treated plots showed slightly later maturity (165 days) compared to untreated (164 days) (Figure 1C).

Plant Height:

Plant height was significantly affected ($P \leq 0.05$) by Bioaab, N levels, organic amendments, and treatment contrast (Table 2). Bioaab application resulted in taller plants (98.0 cm) than no Bioaab (96.4 cm) (Figure 1C). Nitrogen at 160 and 120 kg ha⁻¹ produced greater heights (99.4 and 97.9 cm), compared to 80 kg ha⁻¹ (94.2 cm) (Figure 1A). PM and FYM led to taller plants (99.2 and 97.9 cm), followed by MS (94.4 cm) (Figure 1B). Control plots had the shortest plants (83.5 cm), while treated plots averaged 97.2 cm (Figure 1D).

Leaf Area per Tiller:

Leaf area per tiller (cm^2) responded significantly ($P \leq 0.05$) to Bioaab, nitrogen levels, organic fertilizers, and control vs. treatment (Table 1). Bioaab-treated plots had larger leaf area (112.0 cm^2) than untreated (102.9 cm^2) (Figure 1C). Control plots recorded the lowest leaf area (95.0 cm^2), while treated plots averaged 107.7 cm^2 (Figure 1D). Nitrogen at 160 and 120 kg ha⁻¹ produced 112.2 and 107.8 cm^2, respectively, while 80 kg ha⁻¹ yielded 102.2 cm^2 (Figure 1A). Among organic sources, PM resulted in the highest leaf area (111.4 cm^2), followed by FYM (108.3 cm^2) and MS (102.5 cm^2) (Figure 1B).

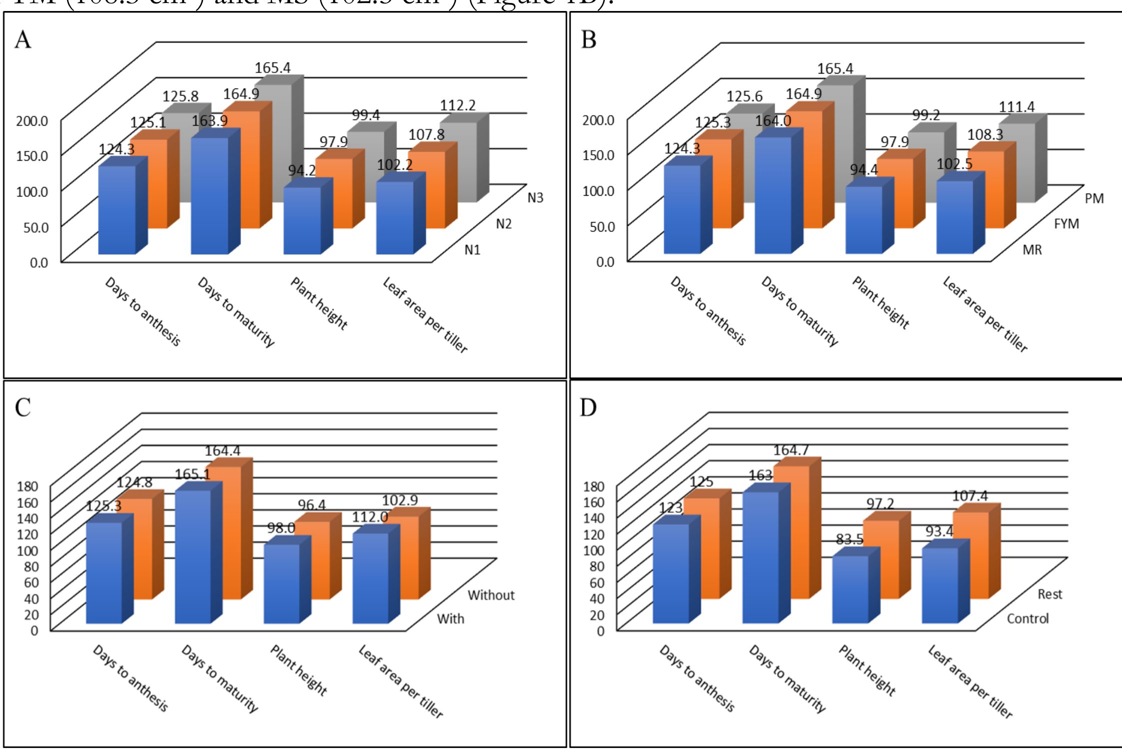

Figure 1. Effects of nitrogen levels (N1 = 80, N2 = 120, N3 = 160 kg ha⁻¹) and organic sources (MS = maize straw, FYM = farmyard manure, PM = poultry manure) on phenological and growth traits of wheat. Part A: nitrogen levels; Part B: organic sources; Part C: Bioaab application (with vs. without); Part D: control vs. all other treatments. Data represent means of three replicates.

Total Dry Matter Production:

Total dry matter at anthesis and maturity was significantly influenced ($P \leq 0.05$) by all treatments (Table 2). Bioaab application produced higher dry matter (483.4 g m⁻²) than untreated plots (452.7 g m⁻²) (Figure 2C). The highest N level (160 kg ha⁻¹) produced the greatest dry matter at both anthesis (498.5 g m⁻²) and maturity (526.2 g m⁻²), compared to 120 and 80 kg N ha⁻¹ (Figure 2A). PM resulted in maximum dry matter (501.4 and 528.1 g m^{-2}), followed by FYM and MS (Figure 2B). Treated plots outperformed control in all comparisons (Figure 2D).

Biological and Grain Yield:

Bioaab, nitrogen levels, organic sources, and treatment contrast significantly affected biological and grain yield ($P \leq 0.05$) (Table 1). Bioaab increased biological (11,647 kg ha^{-1}) and grain yield (3,756 kg ha^{-1}) compared to untreated plots (Figure 2C). Nitrogen at 120 and 160 kg ha^{-1} produced similarly high yields, with 120 kg ha^{-1} identified as potentially efficient (Figure 2A). Among organics, PM achieved the highest yields (biological: 12,158 kg ha^{-1}; grain: 4,110 kg ha^{-1}), followed by FYM and MS (Figure 2B). Control plots produced the lowest yields (Figure 2D).

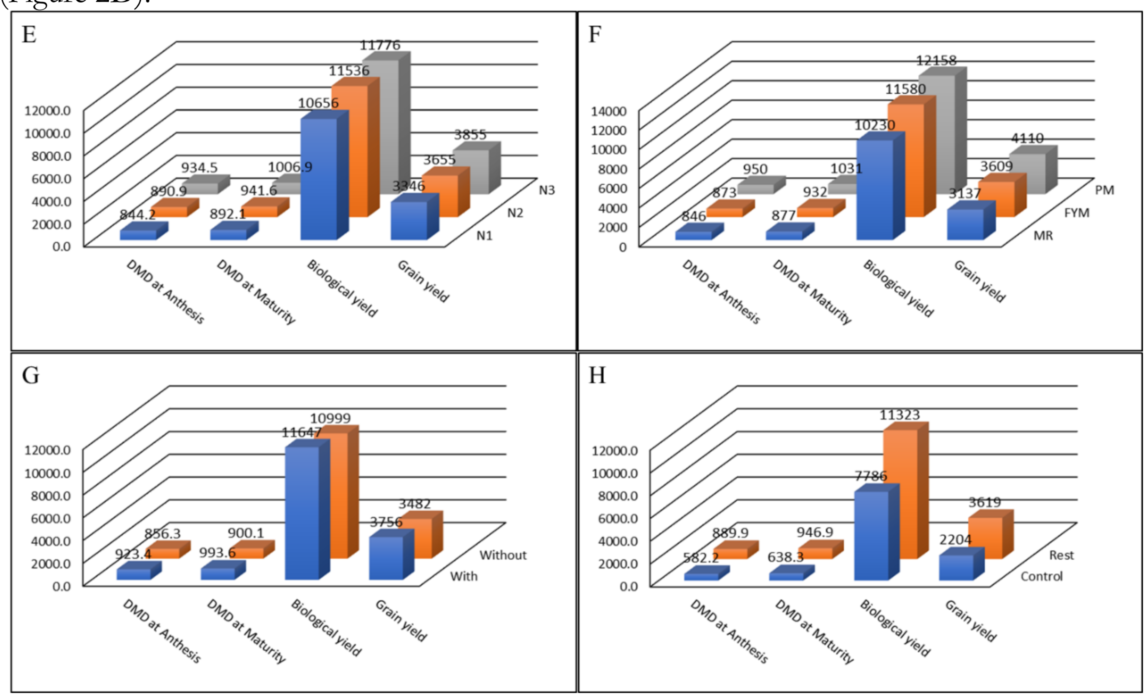

Figure 2. Effects of nitrogen levels (N1 = 80, N2 = 120, N3 = 160 kg ha^{-1}) and organic sources (MS = maize straw, FYM = farmyard manure, PM = poultry manure) on growth and yield traits of wheat. Panel E: nitrogen levels; Panel F: organic sources; Panel G: Bioaab application (with vs. without); Panel H: control vs. all other treatments. DMD = dry matter distribution. Data represent means of three replicates.

LSD$_{(\leq 0.05)}$: Least Significant Difference at 5% probability level; values sharing the same letter within a column are not statistically different. **NS**: Not significant; ***: Highly significant ($p \geq 0.001$). **CV (%)**: Coefficient of Variation. **Letters (a, b, c)**: Denote statistical groupings; means with the same letter within a treatment category (e.g., nitrogen levels) are not significantly different (Tukey's HSD or similar post-hoc test at $p \leq 0.05 p \leq 0.05$).

Table 2. Effects of nitrogen levels, organic sources, and Bioaab application (with and without) on phenological, growth, dry matter partitioning, and yield parameters of wheat.

Treatments	Days to anthesis	Days to maturity	Plant height (cm)	Leaf area tiller^{-1} (cm^2)	Dry matter distribution at anthesis	Dry matter distribution at maturity	Biological yield (kg ha^{-1})	Grain yield (kg ha^{-1})
Nitrogen (kg ha^{-1})								
80	c	b	b	c	c	c	b	b
120	b	a	a	b	b	b	a	a
160	a	a	a	a	a	a	a	a
LSD$_{(P\geq0.05)}$	0.43	0.52	1.6	4.4	26	32	532	250
Organic sources (10-ton ha^{-1})								
Maize residues	b	c	b	b	c	c	c	c
Farmyard manure	a	b	a	a	b	b	b	b
Poultry manure	a	a	a	a	a	a	a	a
LSD$_{(P\geq0.05)}$	0.43	0.52	1.6	4.4	26	32	532	250
Bioaab (60 L ha^{-1})								
With	NS	a	a	a	a	a	a	a
Without	NS	b	b	b	b	b	b	b
LSD$_{(P\geq0.05)}$	NS	0.47	1.2	8.7	17	21	502	202
Control vs Rest	***	***	***	***	***	***	***	***
CV (%)	0.47	0.47	2.48	6.2	4.51	5.09	7.18	10.64

Discussion:

The results demonstrate that integrated nutrient management involving Bioaab, organic amendments, and nitrogen significantly enhances phenological traits, biomass, and yield performance in wheat under semi-arid conditions.

Although, Bioaab did not significantly alter days to anthesis or maturity, it improved other growth parameters such as plant height, leaf area, and dry matter accumulation. This aligns with findings by [21][22], who observed that biofertilizer-enhanced microbial activity facilitates nutrient availability but may not directly affect phenological development.

Nitrogen significantly delayed anthesis and maturity, consistent with [22], likely due to extended vegetative growth resulting from improved nutrient availability. Higher N levels also enhanced plant height and leaf area, supporting the observations of [23][24], which reaffirm nitrogen's role in promoting cellular expansion, leaf development, and chlorophyll synthesis. Among the organic amendments, poultry manure (PM) consistently outperformed farmyard manure (FYM) and maize straw (MS). The superior effect of PM is attributed to its higher nutrient content and faster decomposition rate, which accelerate microbial activity and nutrient cycling, as reported by [23][25]. The slight delay in maturity under organic amendments can be explained by prolonged nutrient availability, which extends the vegetative phase.

Bioaab-treated plots recorded higher dry matter accumulation and yield, indicating the role of microbial inoculants in enhancing organic matter mineralization and improving soil nutrient dynamics. These findings are consistent with [26][27], who emphasized that microbial activity significantly contributes to nutrient availability and plant productivity. Although 160 kg N ha^{-1} resulted in the highest biomass and yield, the 120 kg N ha^{-1} treatment provided nearly comparable outcomes, suggesting it was an efficient and balanced nitrogen level for optimal yield, in agreement with [28].

Control plots consistently produced inferior results, reinforcing the need for adequate fertilization under nutrient-poor, semi-arid conditions. The combination of organic and inorganic sources with microbial inoculants proved more effective than individual treatments, highlighting the value of integrated nutrient management for sustainable wheat production, as also emphasized by [29][30].

Conclusions:

The integrated use of Bioaab, poultry manure, and nitrogen (120–160 kg ha^{-1}) significantly enhanced wheat growth, yield, and nutrient use efficiency under semi-arid conditions. Poultry manure proved the most effective among the organic sources. The 120 kg N ha^{-1} rate offered an optimal balance of productivity and efficiency. These findings support integrated nutrient management as a sustainable strategy to boost wheat performance while reducing dependence on synthetic fertilizers. Further long-term, multi-location studies are recommended to validate these results for broader adoption.

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Data Availability Statement:

The data presented in the tables under the Results section represent the mean values of three replications conducted during the study. Replicated data will be made available on request.

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Conflicts of Interest:

The authors declare that they have no conflicts of interest related to the research or manuscript submission.

Author Contributions:

Siddique Ahmad conceived and designed the experiment, and conducted the fieldwork. Laiba Urooj performed the statistical analyses and handled data processing using relevant software. Basit Ullah assisted in data collection and field management. Muhammad Amjad and Mehran Ali contributed to the critical review, editing, and improvement of the manuscript's overall quality. All authors read and approved the final version of the manuscript.

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