

Response of wheat (*Triticum aestivum*) to poultry manure rates in Maiduguri, Nigeria

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Abstract. *Saddiq AA, Mahmud AA, Lassa IA, Bukar A, Gubio MT, Abdulrahman MD. 2025. Response of wheat (Triticum aestivum) to poultry manure rates in Maiduguri, Nigeria. Asian J Agric 9: 800-807.* Wheat (*Triticum aestivum*) production in semi-arid Nigeria is limited by poor soil fertility and high fertilizer costs. This study assessed the effects of poultry manure on wheat performance during two dry seasons (2022/2023 and 2023/2024) at the University of Maiduguri Teaching and Research Farm in Maiduguri, Nigeria. A randomized complete block design with three replications tested five manure rates (0, 2.5, 5, 7.5, and 10 t/ha). Growth traits (plant height, tiller number, and days to heading) and yield components (spikelets per spike, 1000-grain weight, and grain yield) were measured. Poultry manure significantly improved soil fertility and crop performance compared to the control. Grain yield rose more than six-fold, peaking at 10 t/ha (≈ 3.5 t/ha). However, 7.5 t/ha achieved nearly equivalent yields (≈ 3.2 t/ha) while delivering a more favorable cost-benefit ratio. Moderate manure rates also improved spikelet number and grain filling without nutrient imbalance observed at the highest rate. These results highlight poultry manure as a sustainable, low-cost alternative to chemical fertilizers, with 7.5 t/ha identified as the most practical rate for boosting wheat yield and profitability in semi-arid smallholder systems. In addition to yield enhancement, the study provides insight into how organic inputs can restore declining soil quality in marginal environments where resource-poor farmers struggle to afford conventional fertilizers. The observed improvements in vegetative growth and reproductive development indicate that poultry manure supplies a balanced nutrient release that supports wheat throughout its growth cycle. The two-season evaluation also demonstrates the consistency of poultry manure effects under varying dry-season conditions, confirming its reliability as an organic amendment. Overall, the findings contribute to ongoing efforts to promote climate-smart and resource-efficient agronomic practices in northern Nigeria. The recommendation of 7.5 t/ha aligns with the need for affordable strategies that enhance food security while maintaining soil health for long-term wheat production.

Keywords: Poultry manure, growth, savannah, yield, wheat

Abbreviations: C/N Ratio: Carbon to Nitrogen ratio, kg/ha: Kilograms per hectare, t/ha: Tons per hectare

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a cornerstone of global food security, supplying protein, carbohydrates, and essential micronutrients to billions of people (FAO 2012). Its adaptability across diverse agro-ecological zones has made it one of the most widely cultivated cereals worldwide (Adekiya et al. 2022). Despite this global prominence, wheat production in sub-Saharan Africa lags behind demand, leading to heavy reliance on imports to bridge consumption gaps. Nigeria, for instance, is one of the largest wheat importers in Africa, with annual demand far exceeding local production (CBN 2022). The challenge of increasing domestic wheat yields remains central to ensuring food security and reducing import dependency. Several factors contribute to Nigeria's low wheat productivity. These include inherently low soil fertility, poor irrigation infrastructure, recurrent drought, and soil

degradation in semi-arid zones (Katyar et al. 2024). The Sudan Savannah region, where Maiduguri is located, is particularly affected. The soils are sandy loams with low organic matter content and limited nutrient reserves, conditions that hinder wheat growth and yield potential. Conventional reliance on synthetic fertilizers has not provided a sustainable solution, given their high cost, limited accessibility to smallholder farmers, and associated risks of soil acidification and environmental degradation (Imran 2024). This situation underscores the need for low-cost, environmentally friendly soil fertility management practices tailored to the Nigerian context.

Organic amendments, particularly poultry manure, are now receiving recognition as promising alternatives. Poultry manure is not only rich in primary nutrients such as; nitrogen, phosphorus, and potassium, but also adds organic matter that enhances soil structure, microbial activity, and water retention capacity (Ahmad et al. 2021;

Zakari and Balel 2025). These benefits are especially critical in moisture-limited, sandy soils where nutrient and water losses are common. Beyond its agronomic advantages, poultry manure is widely available in Nigeria due to the growing poultry industry, making it an accessible and affordable input for smallholder farmers. Recycling farm-generated waste into crop production aligns with principles of circular and climate-smart agriculture, contributing to long-term soil health and sustainability. Research conducted in other parts of Africa and Asia has consistently shown that poultry manure improves wheat yields, soil fertility, and carbon sequestration (He et al. 2022; Washaya and Washaya 2023). However, these findings cannot be uniformly applied across regions due to differences in soil types, climatic conditions, and management practices. In Nigeria, while studies have explored organic amendments in cereals such as maize and sorghum, region-specific evidence for wheat remains sparse and fragmented (Hammad et al. 2020; Walder et al. 2023). Most available studies are short-term, location-specific, or do not adequately integrate economic analysis alongside agronomic outcomes. This creates a critical knowledge gap: how different poultry manure rates influence both wheat productivity and cost-effectiveness under the semi-arid conditions of the Sudan Savannah.

Optimizing manure application rates is especially important. While moderate doses can improve soil fertility and crop yields, excessive application may cause nutrient imbalances, nutrient leaching, or greenhouse gas emissions (Kumari et al. 2024). Smallholder farmers also face practical limitations, as transporting and applying large amounts of manure is labor-intensive and costly. Therefore, identifying an application rate that balances yield gains with economic feasibility is vital for farmer adoption and long-term sustainability. Against this backdrop, the present study investigates the response of wheat to varying poultry manure rates in Maiduguri, Sudan Savannah, Nigeria. Conducted across two consecutive dry seasons (2022/2023 and 2023/2024), the research evaluates growth parameters, yield components, and grain yield while also incorporating an economic analysis of input-output relationships. By

focusing on both agronomic and financial outcomes, the study provides region-specific recommendations that address the dual challenges of improving productivity and maintaining profitability for smallholder farmers. The results aim to contribute practical insights for sustainable wheat intensification in semi-arid Nigeria, thereby reducing dependence on imports and strengthening national food security.

MATERIALS AND METHODS

Study site and soil characterization

The field experiment was conducted over two consecutive dry seasons (2022/2023 and 2023/2024) at the Teaching and Research Farm, Faculty of Agriculture, University of Maiduguri, Borno State, Nigeria (11.83°N, 13.15°E; 355 masl), situated in the Sudan Savannah ecological zone. The region is characterized by a semi-arid climate, with temperatures ranging from 16.8°C to 41.3°C during the cropping period. The experimental soil was classified as sandy loam, with a neutral pH (6.7), low organic matter content (0.47%), total nitrogen (0.03%), available phosphorus (3.2 mg kg⁻¹), and exchangeable potassium (0.18 cmol kg⁻¹). Poultry manure, sourced from the University of Maiduguri poultry unit, was analyzed prior to application and contained 2.3% N, 1.8% P, and 1.5% K, with a C/N ratio of 12.8.

Procedures

Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Treatments consisted of five poultry manure rates: 0, 2.5, 5.0, 7.5, and 10.0 t/ha (Figure 1). Each treatment was randomly assigned to one plot per block using random number tables, ensuring unbiased allocation. Individual plots measured 3×3 m (9 m²), separated by 0.5 m alleys within blocks and 1 m between replications to minimize interference. A certified high-yielding wheat variety, LACRI WHIT-11 (Imam), was sown.

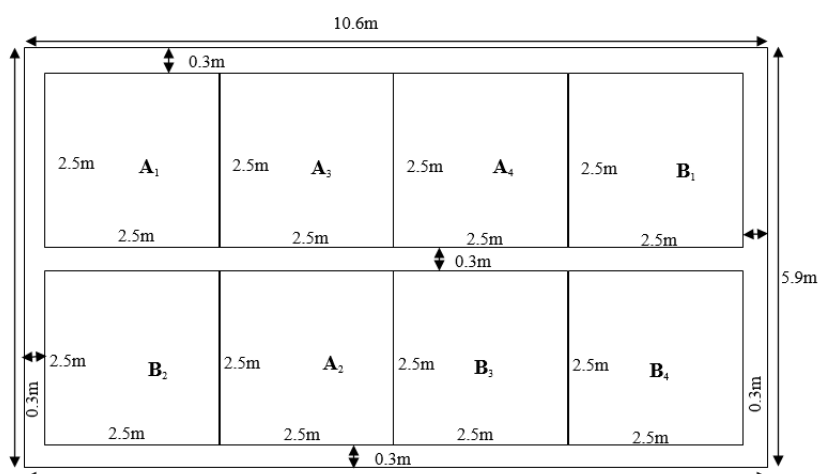


Figure 1. A layout of the Randomized Complete Block Design (RCBD) for poultry manure treatments at Maiduguri, Nigeria

Crop management

Prior to sowing, poultry manure was incorporated into the soil two weeks in advance to allow partial decomposition. Wheat was sown in rows 20 cm apart using the drilling method at the recommended seed rate. Irrigation was supplied at critical growth stages (emergence, tillering, heading, and grain filling) to avoid moisture stress. Weed control was done manually, and pests were managed through regular scouting and integrated pest management. Standard agronomic practices were followed uniformly across treatments to maintain crop health and minimize confounding effects.

Data collection

Growth parameters recorded include: plant height (cm), which was measured at maturity from the soil surface to the tip of the spike (excluding awns). Number of tillers per plant: an average of five randomly selected plants per plot. Days to first heading: number of days from sowing until 50% of plants in a plot produced spikes. Similarly, the yield and yield components measured were the number of spikelets per spike: mean of five randomly selected spikes per plot. 1000-grain weight (g): determined from clean, sun-dried grains using an electronic balance. Grain yield (kg/ha): obtained by harvesting each plot at physiological maturity, threshing, cleaning, weighing, and adjusting to 12% moisture content, then converted to a hectare basis.

Statistical analysis

Data were subjected to Analysis of Variance (ANOVA) using Statistix 8.0 (Analytical Software, Tallahassee, FL, USA). Treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% probability level ($p \leq 0.05$). Standard error (\pm SE) was used to express variability, and significance groupings are presented in the tables.

RESULTS AND DISCUSSION

The study investigates the effects of varying poultry manure application rates on the growth, yield, and reproductive traits of wheat (*T. aestivum*) in the Sudan Savannah region of Nigeria across two seasons, characterized by nutrient-deficient sandy loam soils. The results highlight the significant role of organic amendments, particularly poultry manure, in enhancing the agronomic performance of wheat under semi-arid conditions. The findings provide valuable insights into the potential of poultry manure as a sustainable alternative to chemical fertilizers in the region.

Soil fertility improvement through poultry manure

The sandy loam soils of Maiduguri, with a neutral pH of 6.7 and a low organic matter content of 0.47%, posed challenges for wheat cultivation. According to Hammad et al. (2020), this is typical in many semi-arid regions with nutrient-deficient soils. Poultry manure, rich in essential nutrients such as nitrogen (2.3%), phosphorus (1.8%), and potassium (1.5%), serves as an effective resource for

improving soil fertility, replenishing nutrient stocks, and stimulating microbial activity (Adekiya et al. 2022). The high nitrogen content is particularly critical for supporting vegetative growth, chlorophyll production, and overall plant health, thereby promoting healthier wheat plants. From our study, application of poultry manure significantly improved wheat vegetative growth, as evidenced by increases in plant height, tiller number, and grain yield (Figure 2). Organic amendments such as poultry manure have been widely documented for their ability to improve soil structure, increase water retention capacity, and boost nutrient cycling (Rayne and Aula 2020). These improvements enhance root penetration and facilitate better nutrient uptake and water absorption, which are crucial for dryland agriculture. This is especially pertinent in regions like Maiduguri, where moisture stress is a major limiting factor during the growing season.

From a sustainability perspective, the use of poultry manure contributes not only to crop productivity but also to environmental stewardship. It reduces dependency on synthetic fertilizers, mitigates soil degradation, and enhances soil organic carbon content. Walder et al. (2023) emphasized that organic inputs like poultry manure enhance soil physical properties and microbial diversity, which are essential for maintaining soil health in arid and semi-arid regions. Moreover, by promoting the use of farm-generated waste, this study aligns with circular agriculture principles and climate-smart farming approaches.

Trends in vegetative growth parameters

Poultry manure application had a substantial impact on the vegetative growth of wheat, with the most notable effects observed in plant height and tiller count (Table 1), more so application of poultry manure significantly influenced wheat reproductive traits, notably increasing the number of spikelets per spike and accelerating days to heading (Figure 3). Plant height, a direct indicator of plant growth, increased with higher poultry manure rates, with 5, 7.5, and 10 t/ha producing statistically similar heights in both seasons (Table 1). Initially, in the 2022/2023 season, wheat plants at this rate grew to an average height of 49.8 cm, while in the 2023/2024 season, they reached 50.7 cm. These values were significantly higher than the control (32.6 cm and 34.9 cm, respectively), indicating that poultry manure plays a critical role in promoting vegetative growth. This aligns with previous studies such as Ahmad et al. (2021), Thapa et al. (2023), and Kumari et al. (2024), Mahmoud and Abdulrahman (2025) which have shown that poultry manure can effectively support vegetative growth by supplying readily available nitrogen and improving soil structure. Interestingly, the data also revealed a diminishing effect on plant height at the highest application rate of 10 t/ha. In the 2023 season, plant height was recorded at 46.9 cm, and in the 2024 season, it was 47.4 cm. Although still higher than the control, these values are lower compared to the 5 t/ha application, suggesting that excessive manure application may lead to nutrient imbalances or even toxicity. High nitrogen levels, in particular, may cause excessive vegetative growth at the expense of other important yield components such as tillering and

reproductive development. This indicates that there is a threshold beyond which additional poultry manure does not further enhance vegetative growth and may even become detrimental. Similarly, tiller count, a key determinant of wheat productivity, increased with poultry manure application. The highest tiller counts were observed at 5 t/ha in 2023 (2.0 tillers) and at 10 t/ha in 2024 (1.9 tillers). Since each tiller can contribute to the formation of additional spikes and, ultimately, more grains, the positive response in tiller count reflects improved nutrient availability, particularly nitrogen and phosphorus, which are vital for tiller initiation and development. While 10 t/ha showed a slight increase in tiller count in 2024 compared to 5 t/ha, the overall trend suggests that moderate manure rates are more effective for optimizing vegetative growth and tillering. Excessive manure application at 10 t/ha may result in a nutrient distribution shift that favors vegetative growth without proportionally increasing reproductive traits or grain yield.

Physiological mechanism

The increase in plant height and tiller count can be attributed to enhanced nitrogen availability from poultry manure, which is crucial for chlorophyll synthesis, cell elongation, and vegetative growth. The gradual release of nutrients from organic matter also supports sustained nutrient availability throughout critical growth stages. Organic inputs like poultry manure improve microbial biomass and enzyme activity, accelerating mineralization of nutrients. This increases the bioavailability of N and P, supporting early establishment and root development in wheat. The organic matter from poultry manure likely improved the soil's water-holding capacity, which is particularly beneficial in Maiduguri's semi-arid conditions, where moisture stress can reduce grain filling. Our findings corroborate with Rayne and Aula (2022) and Saeed et al. (2024), who both observed increased yield components in wheat under integrated organic nutrient management. However, unlike studies in loam-rich soils, the optimum yield here was achieved at 7.5-10 t/ha due to lower baseline fertility (Table 1). On the other hand, Poultry manure plays a significant role in enhancing soil fertility through its influence on nutrient cycling, water retention, and microbial activity. Rich in organic nitrogen, phosphorus, potassium, and micronutrients, poultry manure contributes to improved nutrient availability via microbial-driven processes such as mineralization and nitrification (Rasool et al. 2023). As soil microorganisms decompose the organic matter in the manure, nutrients are gradually converted into plant-available forms, notably ammonium and nitrate, which support sustained crop uptake (Mahmoud and Abdulrahman 2025). Moreover, organic acids released during decomposition aid in solubilizing bound phosphorus, thereby improving its availability in alkaline and phosphorus-fixing soils (Ibrahim et al. 2022). The manure also enhances the soil's Cation Exchange Capacity (CEC), which improves nutrient retention and reduces leaching losses (Dhaliwal et al. 2023).

In terms of soil physical properties, poultry manure contributes to improved water retention by increasing soil

organic matter content, which enhances aggregate stability and porosity. These changes promote better water infiltration, reduce evaporation, and increase the soil's ability to retain moisture, particularly in coarse-textured or degraded soils typical of dryland regions (Mohammed et al. 2024). The improved soil structure also limits surface crusting, supporting root proliferation and plant water uptake. Furthermore, poultry manure stimulates microbial activity by supplying readily available carbon and nutrients that fuel microbial growth and enzymatic processes. It enhances the activity of key soil enzymes such as urease, phosphatase, and dehydrogenase, which are integral to nitrogen and phosphorus transformations (Arshad et al. 2024). The amendment also fosters the proliferation of beneficial microorganisms, including Plant Growth-Promoting Rhizobacteria (PGPR) and mycorrhizal fungi, which improve nutrient uptake efficiency and plant resilience. Over time, microbial succession leads to the buildup of humus-forming decomposers, contributing to long-term soil health and fertility (Li et al. 2024). Collectively, these mechanisms underscore the value of poultry manure as a sustainable input for improving soil quality and crop productivity in dryland agriculture.

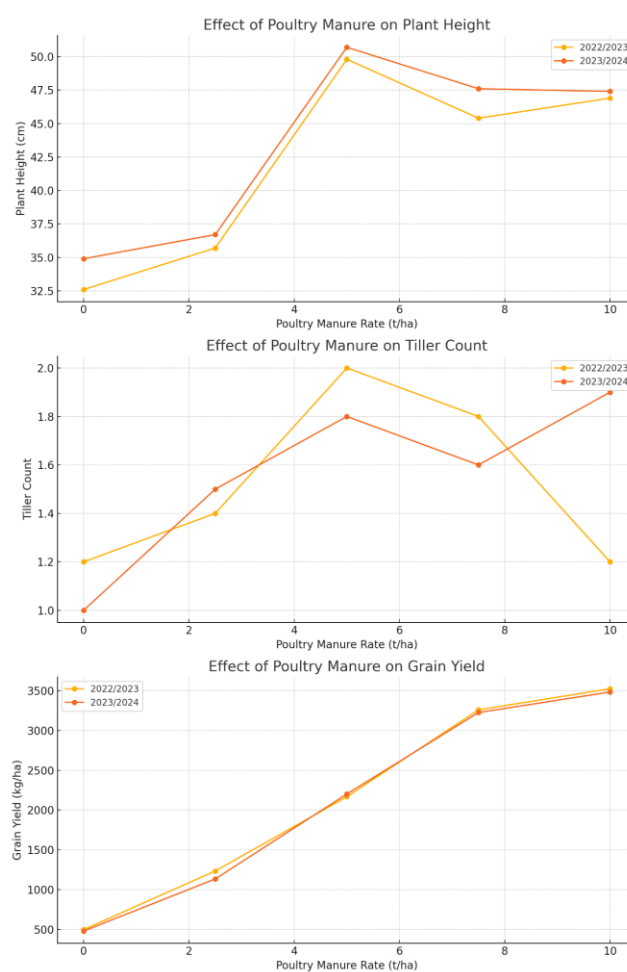


Figure 2. Effect of poultry manure on wheat growth parameters (plant height, tiller count, and grain yield)

Reproductive traits and yield components

According to Arumugam et al. (2025), reproductive traits like the number of spikelets per spike are key determinants of wheat yield. Our data clearly demonstrate that poultry manure application significantly increased the number of spikelets per spike, with the highest values recorded at the 7.5 t/ha rate (Table 2). In the 2023 season, the spikelet count reached 8.0, and in 2024, it was 7.6. This increase is attributed to the improved availability of phosphorus and potassium, essential nutrients for reproductive growth and grain formation. Phosphorus, in particular, is crucial for root development, flowering, and grain quality, while potassium plays a key role in regulating stomatal function, water uptake, and plant stress tolerance. At the 10 t/ha rate, however, the number of spikelets was slightly lower than at 7.5 t/ha, indicating that while higher manure rates improve vegetative growth, they may not necessarily enhance reproductive efficiency. This observation is consistent with other studies, such as Alkhuzai (2023) and Sani et al. (2024), which have shown that excessive organic manure applications can lead to nutrient imbalances that negatively affect reproductive traits in cereal crops. Grain yield, the most critical agronomic parameter, showed a consistent response to poultry manure application. The highest grain yield was recorded at 10 t/ha, with values of 3523.9 kg/ha in 2022/2023 and 3483.7 kg/ha in 2023/2024. However, the 7.5 t/ha rate yielded nearly equivalent results (3259.5 kg/ha and 3225.1 kg/ha, respectively). The control plots, which received no manure, produced significantly lower yields (498.8 kg/ha and 480.6 kg/ha), underscoring the essential role of poultry manure in improving wheat productivity.

Economic considerations

Following the procedure of Kocetkovs and Zvirbule (2025), we assess the economic viability of different poultry manure rates, we calculated the gross margin and Benefit–Cost Ratio (BCR) for each treatment. Grain yield values were converted to revenue using a market price of ₦250 per kg. The cost of poultry manure was estimated at ₦20,000 per ton, and labor costs for application were assumed at ₦5,000 per hectare. Gross margin was calculated as total revenue minus total costs (manure + labor), while BCR was determined as the ratio of total revenue to total costs. Although 10 t/ha produced the highest grain yield, it also incurred higher costs. For smallholder farmers in semi-arid regions, the cost of inputs, particularly organic amendments like poultry manure, can be prohibitive. In this context, the 7.5 t/ha rate emerged as the most economically viable option. It provides a favorable balance between input cost and yield benefit, delivering a yield close to the maximum while minimizing input costs. This makes the 7.5 t/ha application a practical choice for farmers seeking to maximize yield without placing undue financial strain on their resources.

Sustainability and long-term soil health

The use of poultry manure offers significant environmental and sustainability benefits compared to synthetic fertilizers. Organic amendments, such as poultry manure, help enhance soil health by increasing organic matter content, boosting microbial diversity, and promoting nutrient cycling. The long-term application of poultry manure can mitigate soil degradation, which is a common issue in semi-arid regions where continuous cultivation depletes soil nutrients and reduces soil fertility. Additionally, poultry manure contributes to soil carbon sequestration, an important aspect of sustainable farming practices. Organic inputs like poultry manure increase the soil's capacity to store carbon, helping reduce atmospheric carbon dioxide levels and mitigating climate change effects. This aligns with climate-smart agriculture principles, which aim to increase productivity while minimizing farming's environmental impact. A similar study by Gorooui et al. (2023) has indicated that substituting synthetic fertilizers with poultry manure also reduces the environmental risks associated with fertilizer runoff and greenhouse gas emissions, further enhancing the sustainability of agricultural systems.

The application of poultry manure has significantly enhanced 1000-grain weight and grain yield per hectare, as shown in Table 3. The 1000-grain weight and grain yield per hectare increased with higher application of poultry manure rates, reaching a peak at 10 t/ha. At this rate, 1000-grain weights were 36.0 g in 2022/2023 and 40.9 g in 2023/2024, while grain yields reached 3523.9 kg/ha and 3483.7 kg/ha, respectively. These values contrast sharply with those of the control plots, which recorded less than 500 kg/ha in both years. The improvement in grain yield is attributed to the cumulative effect of improved soil fertility, enhanced nutrient availability throughout the growing season, and better grain filling due to sustained nitrogen and phosphorus supply. These findings corroborate the report of Ajeigbe et al. (2024), who emphasized the yield-boosting effects of poultry manure due to its slow-release nutrient profile and enhancement of soil physical properties. Similarly, Sharma et al. (2024) highlighted that the use of poultry manure improves not only yield components but also overall crop productivity under low-input agricultural systems. In Nigerian contexts, where soils are often nutrient-depleted, the use of organic manure is crucial. A recent study by Saddiq et al. (2025) stressed the importance of integrating organic sources like poultry manure to bridge yield gaps and reduce dependency on expensive synthetic fertilizers.

A cost-benefit consideration shows that while 10 t/ha yields the highest production levels, the 7.5 t/ha treatment presents an optimal trade-off between input cost and yield benefit, especially for resource-constrained smallholder farmers. With poultry manure locally available at minimal cost, the application at 7.5 t/ha can improve productivity without significant financial burden. This reinforces the value of integrating organic amendments in regions facing high fertilizer prices and economic constraints.

Table 1. Effect of poultry manure on plant height and tiller count of wheat across two dry seasons

Treatments PM (t/ha ⁻¹)	Plant height (cm)		Tiller count	
	2022/2023	2023/2024	2022/2023	2023/2024
0	32.6 ^b	34.9 ^b	1.2 ^b	1.0 ^b
2.5	35.7 ^b	36.7 ^b	1.4 ^b	1.5 ^b
5	49.8 ^a	50.7 ^a	2.0 ^a	1.8 ^a
7.5	45.4 ^a	47.6 ^a	1.8 ^a	1.6 ^b
10	46.9 ^a	47.4 ^a	1.2 ^b	1.9 ^a
SE(±)	1.22	1.78	0.24	0.18

Note: Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ (DMRT)

Table 2. Effect of poultry manure on days to heading and spikelets per spike of wheat

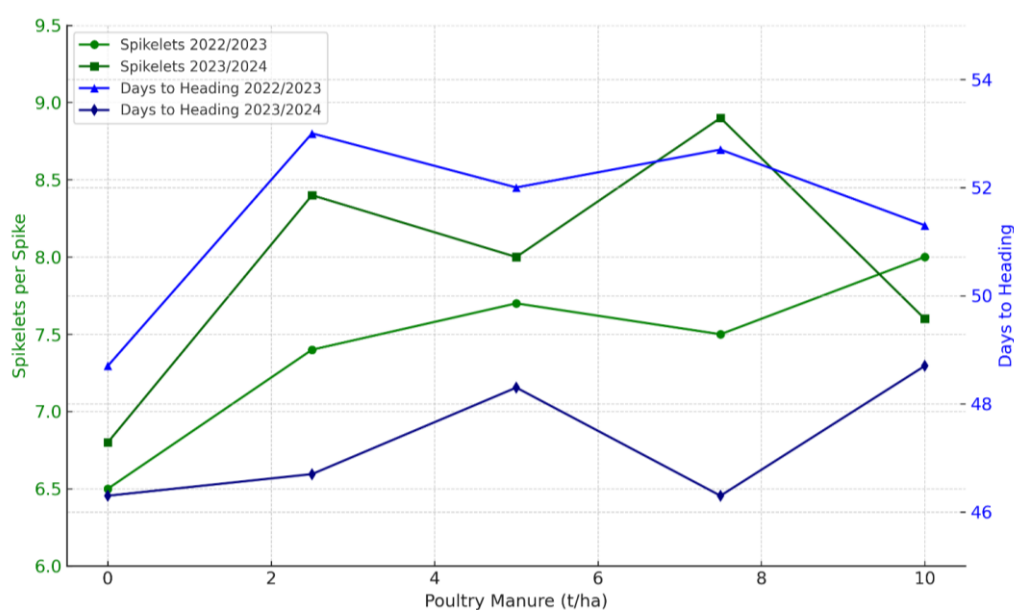
Treatments PM (t/ha ⁻¹)	Days to first heading		Number of spikelets per spike	
	2022/2023	2023/2024	2022/2023	2023/2024
0	48.7	46.3	6.5 ^b	6.8 ^b
2.5	53.0	46.7	7.4 ^a	8.4 ^a
5	52.0	48.3	7.7 ^a	8.0 ^a
7.5	52.7	46.3	7.5 ^a	8.9 ^a
10	51.3	48.7	8.0 ^a	7.6 ^a
SE(±)	2.34	1.44	0.20	0.80

Note: Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ (DMRT)

Table 3. Effect of poultry manure on 1000-grain weight and grain yield of wheat

Treatments PM (t/ha ⁻¹)	1000-grain weight		Grain yield per hectare	
	2022/2023	2023/2024	2022/2023	2023/2024
0	24.1 ^b	21.0 ^c	498.8 ^d	480.6 ^d
2.5	30.8 ^a	26.2 ^b	1234.6 ^c	1134.9 ^c
5	32.2 ^a	29.9 ^b	2167.3 ^b	2202.1 ^b
7.5	35.2 ^a	35.4 ^{ab}	3259.5 ^a	3225.1 ^a
10	36.0 ^a	40.9 ^a	3523.9 ^a	3483.7 ^a
SE(±)	2.75	1.41	577.9	580.6

Note: Means followed by the same letter within a column are not significantly different at $p \leq 0.05$ (DMRT)

**Figure 3.** Effect of poultry manure on spikelets per spike and days to heading

To conclude, our study demonstrated that poultry manure application improved wheat performance in the semi-arid Sudan Savannah of Nigeria, enhancing both growth traits and grain yield compared to unfertilized controls. Yields increased substantially with manure application, with the highest values at 10 t/ha. However, 7.5 t/ha produced nearly equivalent yields while offering a more favorable cost-benefit outcome, making it the most practical option for smallholder farmers under local conditions. While these results underscore the potential of poultry manure as a sustainable alternative to synthetic fertilizers, the findings are based on two dry seasons at a single site. This limits their generalizability across Nigeria's diverse agro-ecologies, where rainfall patterns, temperature, and soil characteristics may influence manure decomposition and nutrient release. Multi-site and multi-year trials are therefore needed to validate these outcomes, particularly with respect to soil carbon sequestration, nutrient dynamics, and environmental trade-offs. Expanded economic assessments should also incorporate labor requirements and fluctuations in manure availability and cost. Taken together, the evidence supports 7.5 t/ha as an agronomically effective and economically viable rate for wheat production in semi-arid environments, while supporting climate-smart and sustainable agricultural practices in semi-arid Nigeria. Further research will be critical for developing robust, region-wide recommendations that balance productivity, affordability, and long-term soil health. Therefore, include multi-site and multi-year trials to capture environmental variability, as well as assessments of long-term soil health, nutrient cycling, labor requirements, and environmental trade-offs such as leaching and emissions.

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