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Original Article

Optimizing Fertilizer and Nutrient Management for Wheat (*Triticum aestivum* L.) Cultivation in Ghana

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Abstract

Introduction:

Wheat production in Ghana is recent, and evidence-based fertilizer recommendations suitable for the semi-deciduous agroecological zone are limited. This study evaluated the effects of varying mineral fertilizer rates and their integration with organic amendments on wheat productivity, nutrient use efficiency, and soil fertility.

Methods:

Pot experiments were conducted at the CSIR-Crops Research Institute, Ghana, over two consecutive seasons using wheat (*Triticum aestivum* L., cv. Pride 999). In the first season, sole N-P_2O_5-K_2O fertilizer rates (100-50-50, 150-50-50, 200-50-50, and 90-60-60 kg ha^{-1}) were tested. In the second season, mineral fertilizer was integrated with fermented organic fertilizer (FOF) at 6 mg ha^{-1} or compost at 9 mg ha^{-1}. Grain yield, growth parameters, partial factor productivity (PFP), and post-harvest soil fertility were assessed.

Results:

In season one, maximum grain yields of 3.35 and 3.37 mg ha^{-1} were obtained at 200-50-50 and 150-50-50 kg ha^{-1} N-P_2O_5-K_2O, respectively, significantly exceeding the control (2.16 mg ha^{-1}) and 90-60-60 kg ha^{-1} (2.27 mg ha^{-1}). Wheat yield increased linearly with nitrogen up to 200 kg ha^{-1}, while optimal P_2O_5 and K_2O rates of approximately 30.5 kg ha^{-1} each produced yields of 3.31-3.33 mg ha^{-1}. Partial factor productivity declined from 14.9 to 11.2 and 10.8 kg grain kg^{-1} nutrient at 100-50-50, 200-50-50, and 90-60-60 kg ha^{-1}, respectively. In the second season, integrated fertilizer treatments averaged 3.14 mg ha^{-1}, outperforming average sole mineral fertilizer (2.81 mg ha^{-1}) in the first season. The highest yield (3.77 Mg ha^{-1}) was achieved with 100-50-50 N-P_2O_5-K_2O plus compost. Compost-based integrations averaged 3.35 mg ha^{-1}, while FOF-based integrations averaged 3.20 mg ha^{-1}. PFP ranged from 3.16 to 5.63 kg grain kg^{-1} nutrient, with the highest value recorded for 100-50-50 NPK + FOF. Post-harvest soil fertility showed no significant changes, although integrated treatments tended to increase soil organic carbon (up to 1.47%).

Conclusion:

Nitrogen is the most limiting nutrient for wheat production in the semi-deciduous agroecological zone of Ghana, with optimal yields requiring more than 200 kg ha^{-1} N, while modest P and K inputs (~30 kg ha^{-1}) are sufficient. Under the conditions of this study, combining mineral fertilizer with organic amendments improved nutrient use efficiency and grain yield. However, the absence of sole-organic amendment treatments in the second season precludes confirmation of synergistic interactions.

Categories: Food security and sustainability, Soil nutrition, Sustainable climate smart agriculture

Keywords: wheat production, nitrogen fertilization, integrated nutrient management, soil fertility, partial factor productivity

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in the world, contributing approximately 20% to global calorie and protein intake [1]. It is a critical component of food and nutritional security due to its long shelf life and widespread use in a variety of food products, including bread, pasta, and noodles. However, in Ghana, wheat production has been negligible, resulting in an over-reliance on imports to meet rising domestic demand. The country imports nearly all the wheat it consumes (approximately 1 million metric tons annually), which significantly contributes to the national food import bill and exposes the economy to international market shocks [2,3].

This challenge underpins the growing national interest in exploring the feasibility of cultivating wheat under local agro-ecological conditions. As part of the efforts to enhance domestic food production and reduce our over-dependency on imports, the Crops Research Institute (CRI) of the Council for Scientific and Industrial Research (CSIR), in collaboration with ARIMA Farms in India, has led the introduction and cultivation of wheat in Ghana since 2023. This collaborative initiative aims to develop a viable wheat production system by identifying suitable varieties, determining optimal agronomic practices and building the capacity of farmers and stakeholders along the value chain.

A foundational component of this initiative is the establishment of effective fertilizer management strategies tailored to local soil types, climate, and crop response. In many wheat-growing regions worldwide, fertilizer use is a key determinant of yield performance [4-6]. However, in new production environments such as Ghana, where wheat is not traditionally cultivated, data on appropriate fertilizer rates and combinations are lacking. Therefore, research-based evidence is urgently needed to guide farmers, extension agents, and other stakeholders in making informed decisions about nutrient management.

The adoption of a balanced and effective fertilization regime is critical to maximizing the productivity of wheat while ensuring environmental sustainability. Inorganic fertilizers boost cereal yields significantly; however, the excessive and unbalanced use of these inputs can lead to adverse environmental impacts such as nutrient leaching, water pollution and greenhouse gas emission [7,8]. Moreover, the rising costs and limited availability of mineral fertilizers in Ghana pose a significant constraint on the adequate use of fertilizers by smallholder farmers [9]. As a result, there is growing interest in exploring integrated nutrient management strategies that combine organic and inorganic nutrient sources [10-12]. One such organic amendment is Bokashi, an anaerobically fermented compost readily produced from locally available organic resources using effective microorganisms [13,14]. It has a short maturation period (2-5 weeks) and contains beneficial microbes that enhance soil biological activity and nutrient cycling [15]. When used in combination with inorganic fertilizer, fermented compost has been shown to improve nutrient use efficiency, increase crop yields and enhance soil health [16]. However, most studies on fermented compost have focused on vegetables and rice, with very limited work on wheat, especially under tropical conditions such as in Ghana.

This research serves as a critical starting point in developing fertilizer recommendations for wheat cultivation in Ghana. The study evaluated the agronomic response of different application rates of N-P_2O_5-K_2O (NPK) fertilizers alone and their integration with Bokashi compost in two consecutive growing seasons. It aims to generate baseline data necessary for scaling wheat production under semi-deciduous agro-ecological conditions in Ghana, by assessing yield responses, nutrient use efficiencies and soil fertility statuses following organic and inorganic fertilizer applications. Although wheat is traditionally a cool-season crop and heat stress has limited its cultivation in tropical West Africa, the cultivar used in this study (Pride 999) is a heat tolerant, spring wheat type adapted to relatively warmer growing conditions. The semi-deciduous agro-ecological zone of Ghana was therefore selected because its comparatively moderate climatic conditions provide a suitable environment for evaluating the adaptation and fertilizer response of wheat under local conditions. We hypothesized that (i) wheat grain yield and nutrient use efficiency would increase with increasing mineral fertilizer application up to an optimum rate, and (ii) integrating mineral fertilizers with fermented organic fertilizer or compost would further enhance grain yield, nutrient use efficiency, and soil fertility compared with mineral fertilizer alone. The results of this study would serve as foundational knowledge for more intensive research on wheat nutrient recommendations in Ghana. In addition to addressing the immediate knowledge gap, the outcomes of this research will contribute to long-term agricultural development goals, including promoting climate-smart nutrient management, enhancing soil fertility and supporting Ghana's broader agenda of reaching food sufficiency. Insights gained from this work will provide practical guidance to farmers, government agencies and other stakeholders interested in promoting wheat as a viable crop option in Ghana.

Materials And Methods

Study site description

The study was conducted over two consecutive seasons (the major and minor rainy seasons) at the Cereals Division of the CSIR-Crops Research Institute, Ghana. The Institute is located at GPS AE-0680-9724 on the Ghana Digital Address System. The area lies within the semi-deciduous forest agro-ecological zone zone of Ghana, and experiences a bimodal rainfall pattern with average annual precipitation of ~1,200 mm and mean temperatures ranging from 22°C to 32°C.

Experimental design

A pot experiment was set up in an outdoor space to investigate the effects of varying rates of NPK fertilizer and its integration with two types of organic fertilizer [fermented organic fertilizer (FOF) and conventional compost (Com)] on wheat (*T. aestivum* L.) growth and productivity. The pots were filled with thoroughly mixed topsoil collected from 0 to 15 cm depth at a fallow, never-amended site near Fumesua. Pots were filled to a height of 15 cm, leaving about 7 cm from the soil surface to the open edges. The soil surface area was 1,590 cm^2. Five samples from the mixed topsoil were collected, composited, and sent for baseline chemical status analysis. The pots were arranged in a completely randomized design with three replications.

Initial and final soil characterization.

Initial soil analyses were conducted on the composited soil sample for pH (1:10 soil-to-water ratio), available P (Bray P-1 method), Total N (Kjeldahl method), Exchangeable bases and acidity (ammonium acetate method), organic carbon/matter (Walkley-Black method), exchangeable bases (Ammonium acetate extraction method) and exchangeable acidity (KCl salt extraction followed by titration method) during the first growing season. The chemical properties of the potted soil are outlined in Table *1*. After harvest in the first and second seasons, soils were sampled from each pot and analyzed for Total N and available N. P, Exchangeable K, organic C, and Organic matter to determine the soil's fertility status following fertilizer applications and nutrient uptake. Soil chemical properties after harvest are presented in Tables *7* and 8.

Property	pH	Avail. P	Total N	Exchangeable bases (cmol kg^{-1})				Exchangeable acids (cmol kg^{-1})		%	
	(1:10)	mg kg^{-1}	%	K	Ca	Mg	Na	Al	H	Org. C	Org. matter
Value	6.96	46.33	0.15	0.095	3.00	1.80	0.047	0.32	0.34	3.22	5.55

TABLE 1: Chemical properties of the topsoil before potting for the experiment.

*** P is phosphorus; N is Nitrogen; K is potassium; Ca is calcium; Mg is magnesium; Na is sodium; Al is aluminium; H is hydrogen ions; Org. C is organic carbon; Org. matter is organic matter

Treatment application

The studies were conducted in two consecutive seasons, with slightly different treatment structures. Treatments in the first season focused solely on evaluating NPK rates. They included: T1: 100:50:50 kg NPK ha^{-1}; T2: 150:50:50 kg NPK ha^{-1}; T3: 200:50:50 kg NPK ha^{-1}; T4: 90:60:60 kg NPK ha^{-1} (Blanket NPK rate for maize in Ghana); T5: Control (no fertilizer). Treatments in the second season evaluated the effect of combining organic fertilizers with the previous NPK rates. They included T1: 150:50:50 kg NPK ha^{-1} + FOF; T2: 150:50:50 kg NPK ha^{-1} + Compost; T3: 100:50:50 kg NPK ha^{-1} + FOF; T4: 100:50:50 kg NPK ha^{-1} + Compost; T5: 200:50:50 kg NPK ha^{-1} + FOF; T6: 200:50:50 kg NPK ha^{-1} + Compost; T7: 90:60:60 kg NPK ha^{-1} + FOF; T8: 90:60:60 kg NPK ha^{-1} + Compost; T9: Control (no fertilizer). FOF and compost were applied at rates of 6 mg ha^{-1} and 9 mg ha^{-1} depending on N content. In the second season, the organic fertilizers were applied 2 weeks before planting wheat, whereas in both seasons NPK was applied in two splits at 2 weeks after planting (WAP) and 4WAP.

Application of organic amendments

FOF and compost were applied 2 weeks before planting wheat at rates of 6 mg ha^{-1} and 9 mg ha^{-1}, respectively, due to the higher N content of the FOF (Table *2*). The FOF was made with palm kernel cake, leaves of *Glyricidia sepium*, fish waste, honey, and effective microorganisms (*Lactobacillus* culture and yeast), and fermented for 21 days. (The FOF is a pilot product of the CSIR-Crops Research Institute known as "CRIFert." Owing to its ongoing product development, the detailed production protocol and ingredient proportions are proprietary and are therefore not disclosed in this study.) Compost was obtained from "Asaase Gyefo" Company Limited in Ghana. The chemical properties of the organic fertilizers are outlined in Table *2*. These properties were determined by the following methods: N - Kjeldahl method; P - Molybdenum blue method; K - Flame Photometer method, C - Walkley and Black method; pH - 1:10 soil to water ratio using pH meter; EC - 1:5 soil: water ratio using EC meter.

Organic fertilizer	Total N	P	K	C	C: N Ratio	EC (µScm^{-1})	pH (1:10)
	%						
FOF	3.362	1.621	1.488	44.39	13.20	4260	5.15
Compost	2.130	1.838	1.827	20.88	9.80	2840	6.42

TABLE 2: Chemical properties of fermented organic fertilizer and compost before application to wheat.

*** N is Nitrogen; P is phosphorus; K is potassium; C is carbon; EC is electrical conductivity.

Crop management, fertilizer application, and data collection

Wheat seeds (cv. Pride 999) were sown at 2 g pot^{-1} (126 kg ha^{-1}). The seeding rate corresponded to an equivalent seeding rate of approximately 126 kg ha^{-1} based on the pot surface area (1590 cm^2). Since Ghana does not currently have an officially recommended seeding rate for wheat, this rate was selected because it falls within the globally recommended range of 120-150 kg ha^{-1} for wheat cultivation. Wheat seeds were obtained from ARIMA Farms in India. Pride 999 is a heat tolerant, climate-resilient wheat cultivar engineered to bypass the typical winter requirements of traditional wheat. Its potential yield is estimated at 3.5-4 mg ha^{-1} in India and 2.5-3 mg ha^{-1} in Ghana [17]). It has a short duration spring wheat cycle of 90-100 days. It is highly insensitive to photoperiod, hence does not require long summer months to trigger flowering. It has a high tillering capacity of 4-6 tillers per plant under optimal conditions. The soil was irrigated regularly to maintain optimal moisture. Inorganic fertilizers applied were NPK 15:15:15 and Sulphate of Ammonium (SOA, 21% N). The quantities of fertilizer to be applied were calculated based on the nutrient content and surface area of the soil in the pots. Basal NPK application was made 2 WAP, while SOA was used as top-dress, 4 WAP. The experiment was protected from pests and diseases using standard practices. Weeds were manually removed as needed. Data were collected on plant height at 2 and 6 WAP, and on total seed weight/pot and grain yield (mg ha^{-1}) after drying, following physiological maturity. Grain yield was measured at a moisture content of 12%. Yields measured per pot were converted to mg ha^{-1} by extrapolating from the surface area of each experimental pot (1,590 cm^2). (This conversion was performed solely to facilitate comparison with field-based studies and does not imply that the measured yields represent actual field productivity.)

Evaluated data

The efficiency of fertilizer use across treatments was assessed in the first season using partial factor productivity (PFP) functions. PFP factor productivity was calculated as follows:

PFP = (Grain yield (kg ha^{-1})/Total NPK applied (kg ha^{-1})) Eqn 1 (adapted from Wawire et al. [18])

Yield response of wheat to nitrogen, phosphorus and potassium fertilizers

Yield curves in response to N, P_2O_5 and K_2O increments were estimated using Excel.

The curves were either linear: $Y = a + b(x)$, or quadratic: $Y = a + b(x) - c(x^2)$

Where:

Y = wheat yield

x = fertilizer rate

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a = intercept (baseline yield without fertilizer)

b = linear coefficient (initial positive response to fertilizer)

c = quadratic coefficient (rate of diminishing returns after optimum fertilizer rate is reached, usually negative)

Optimum N, P_2O_5 and K_2O levels for wheat were calculated as follows, using the quadratic function:

Xopt = $(-b/2c)$

Where:

Xopt = optimum fertilizer rate

b = linear coefficient

c = quadratic coefficient

NB: The maximum yield possible was calculated by putting Xopt back in the quadratic function.

Data analysis

All data were analyzed using IBM SPSS Statistics 20. Significant means were separated using Fischer's least significant difference (l sd) test at 5% probability. The experiments conducted in the first and second growing seasons were designed to address different research objectives. The first season evaluated mineral fertilizer rates, whereas the second season assessed the performance of integrated mineral and organic fertilizer combinations based on the findings of the first season. Consequently, the two experiments were analyzed separately.

Results And Discussion

Wheat growth and yield response to fertilizer application

In the first growing season, plant height was not significantly affected by the fertilizer treatments at 2 and 6 WAP (Table *3*). Seed weight and grain yield, however, showed clearer treatment effects (Table *3*). The highest grain yields were observed under 200:50:50 kg ha^{-1} NPK (3.35 mg ha^{-1}) and 150:50:50 kg ha^{-1} NPK (3.27 mg ha^{-1}); these were statistically similar but significantly higher than 100:50:50 kg ha^{-1} (2.98 mg ha^{-1}). The 90:60:60 kg ha^{-1} NPK treatment (2.27 mg ha^{-1}) and the control (2.16 mg ha^{-1}) produced the lowest yields, which did not differ statistically from each other (Table *3*). Similarly, the highest seed weight was recorded under 200:50:50 kg ha^{-1} NPK and 150:50:50 kg ha^{-1} NPK around 52 g pot-1, followed by 47 g pot-1 from 100:50:50 and lastly, 34-36 g pot^{-1}. The positive response of wheat yield to N fertilization observed in the first season reflects Liebig's Law of the Minimum, which states that crop yield is constrained by the most limiting nutrient [19]. In the tested soils, N limitation is clearly a constraint, as yields increased linearly up to the highest applied rate (200:50:50 kg NPK ha^{-1}) with no plateau reached. The linear regression further suggested that the agronomic optimum lies beyond the tested range, confirming acute soil N deficiency. Such responses are consistent with reports from wheat introduction trials in sub-Saharan Africa (SSA), where wheat yields remain far below global averages (~2-4 mg ha^{-1} in SSA vs. 4-6 mg ha^{-1} globally) due largely to nutrient limitations [20]. Phosphorus and potassium responses, on the other hand, followed quadratic patterns, with optima of approximately 31 kg ha^{-1} for both nutrients. These findings illustrate the Law of Diminishing Returns, in which incremental yield gains decline as nutrient application exceeds crop demand. In nutrient response theory, such patterns are well-described by the Mitscherlich model (exponential yield response approaching a maximum) or the quadratic response model (yield increases to an optimum and then declines at higher nutrient rates) [21]. The observed response was best described by the latter, showing positive responses at low P and K rates but potential yield depression at higher levels, possibly due to ionic imbalance or reduced nutrient availability in the constrained pot environment [22,23].

Treatments (kg NPK ha^{-1})	Plant height @ 2WAP	Plant height @ 6WAP	Total seed weight	Grain yield
	cm		(g pot^{-1})	(mg ha^{-1})
100:50:50	16.80 ± 2.04	63.33 ± 3.18	47.33 ± 2.46 b	2.98 ± 0.15 b
150:50:50	16.60 ± 1.77	65.00 ± 4.16	52.00 ± 5.80 a	3.27 ± 0.36 ab
200:50:50	17.10 ± 1.23	73.00 ± 5.57	53.33 ± 7.95 a	3.35 ± 0.50 a
90:60:60	16.30 ± 0.31	74.00 ± 4.36	36.17 ± 6.36 c	2.27 ± 0.40 b
Control	18.57 ± 0.37	59.00 ± 19.98	34.33 ± 7.72 c	2.16 ± 0.49 b

TABLE 3: Wheat growth and yield parameters following inorganic application in the first growing season.

Numbers following the "±" signs are standard errors of the means for each treatment ($n = 3$). Different lower-case letters attached to treatment means within a column shows that the means are statistically different at $P < 0.05$.

Regression analysis (yield curve; Figure *1*) further supported this observation. Grain yield increased linearly with N application ($R^2 = 0.79$; $P = 0.02$), confirming that optimal N levels were not reached within the tested range. However, Phosphorus and Potassium responses followed quadratic patterns, with optimum application rates of approximately 30.5 kg ha^{-1} for both nutrients ($R^2 = 0.94$; $P = 0.04$ for both curves), corresponding to maximum yields of 3.3 mg ha^{-1}, respectively (Figures *2* and 3). Beyond these levels, yield gains declined, consistent with the Law of Diminishing Returns and nutrient response theory. Such nutrient rate behavior aligns with the Mitscherlich or quadratic-plateau models [21]. The decline at higher P and K levels may be attributed to nutrient imbalances or fixation under pot conditions [22,23]. The relatively low optimum rates of P_2O_5 and K_2O may reflect the characteristics of the experimental soil and the controlled pot environment, where nutrient losses through leaching are minimized and nutrient availability may differ from field conditions. Because only the cultivar Pride 999 was evaluated, the present study cannot determine whether the observed response is cultivar specific. Further field studies across different soil types and wheat cultivars are therefore required to validate these findings under Ghanaian production conditions.

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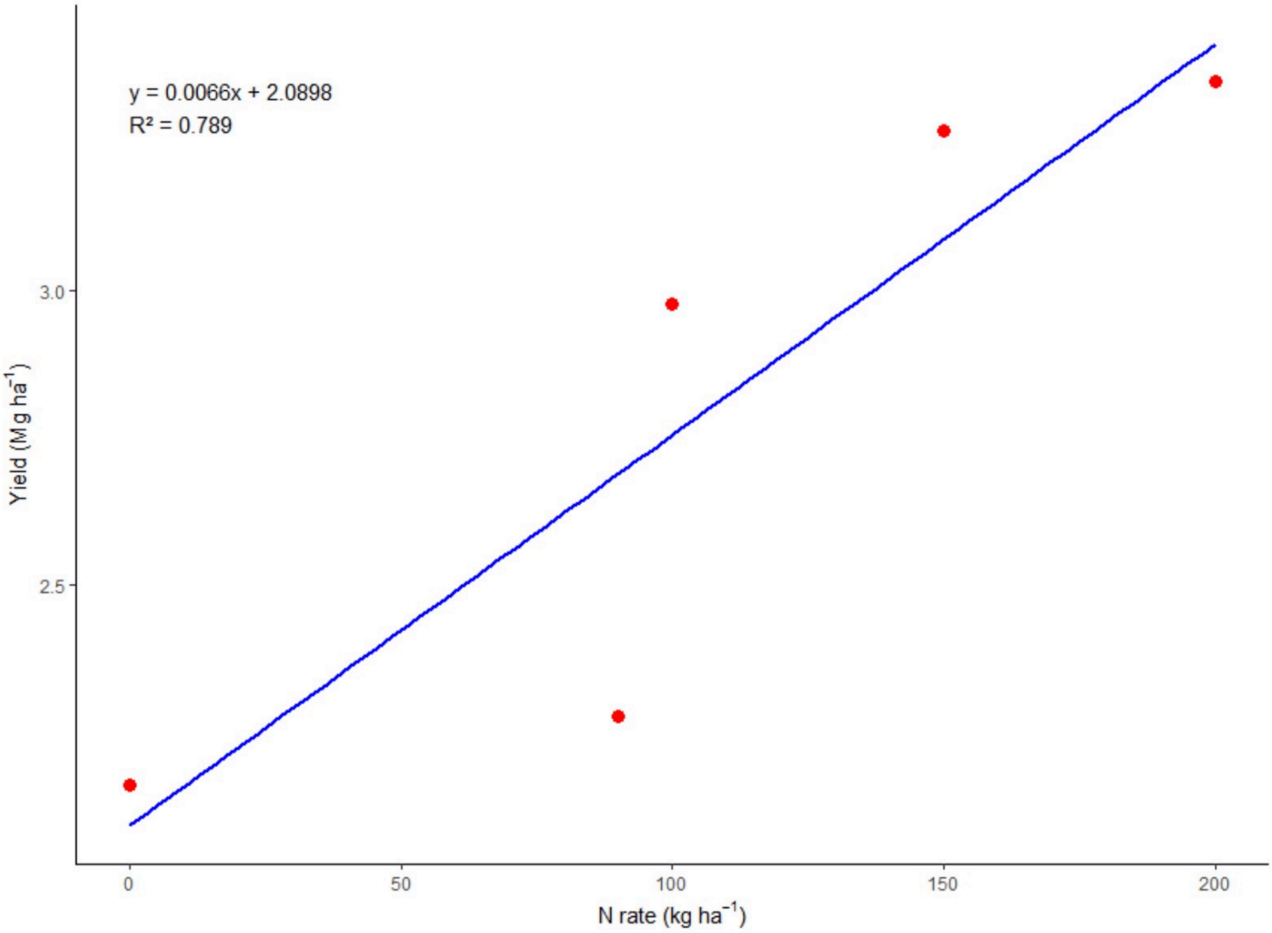

FIGURE 1: Relationship between nitrogen (N) application rate and wheat yield (Mg ha^{-1}) in the first growing season. Red points represent observed yields at different N rates, while the solid blue line shows the fitted linear regression (y = 0.0066x + 2.0898). The model explains 78.9% of the variation in yield (R^2 = 0.789), indicating a strong positive linear yield response to increasing N input within the tested range.

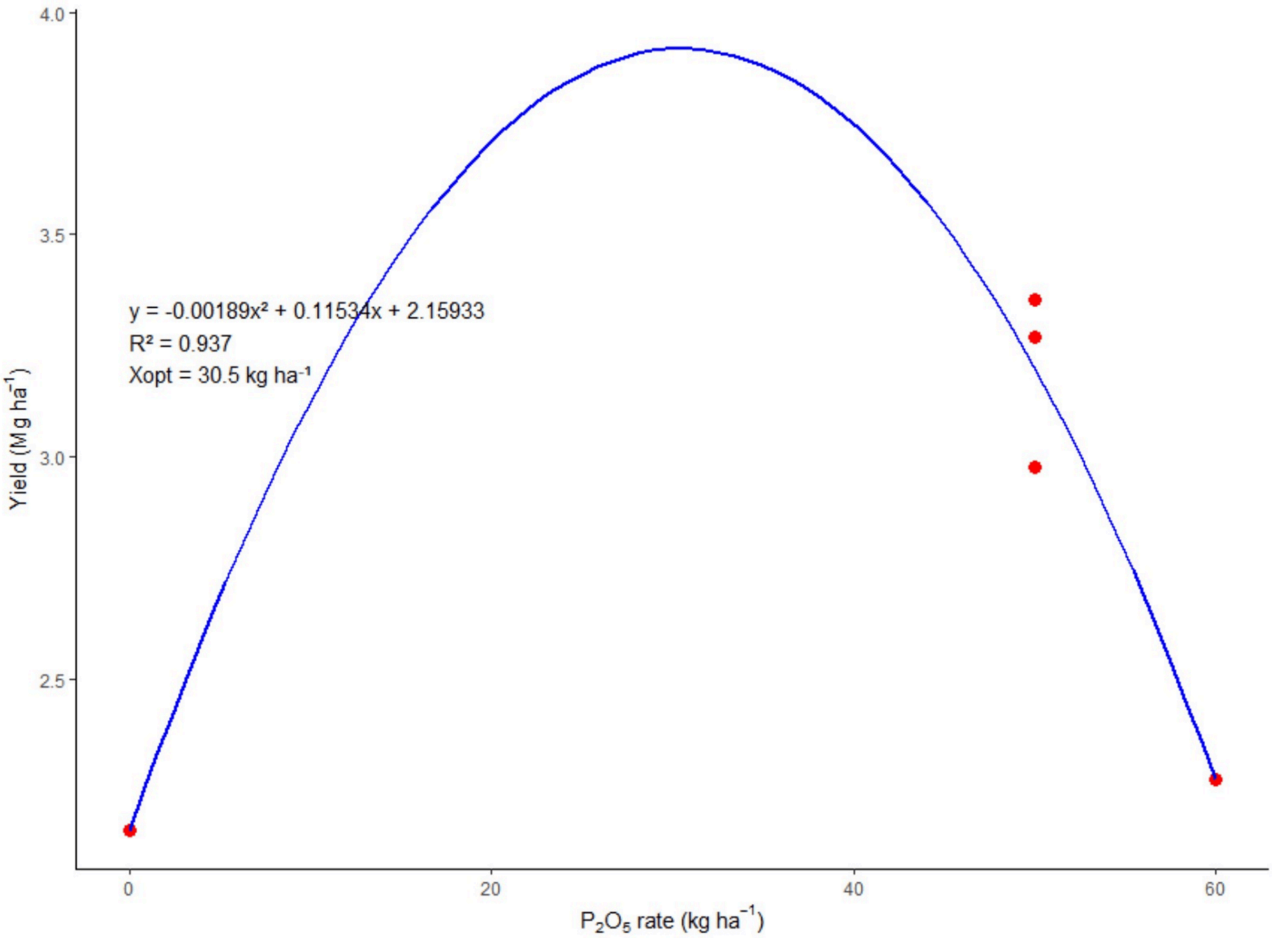

FIGURE 2: Quadratic response of wheat yield (mg ha^{-1}) to phosphorus application rate (P_2O_5, kg ha^{-1}) in the first growing season. Red points indicate observed yields, and the blue curve represents the fitted quadratic regression model ($y = -0.00189x^2 + 0.11534x + 2.15933$). The model explains 93.7% of the yield variability ($R^2 = 0.937$), with an estimated optimum P_2O_5 rate of 30.5 kg ha^{-1} for maximum yield, demonstrating a strong curvilinear yield response to phosphorus fertilization.

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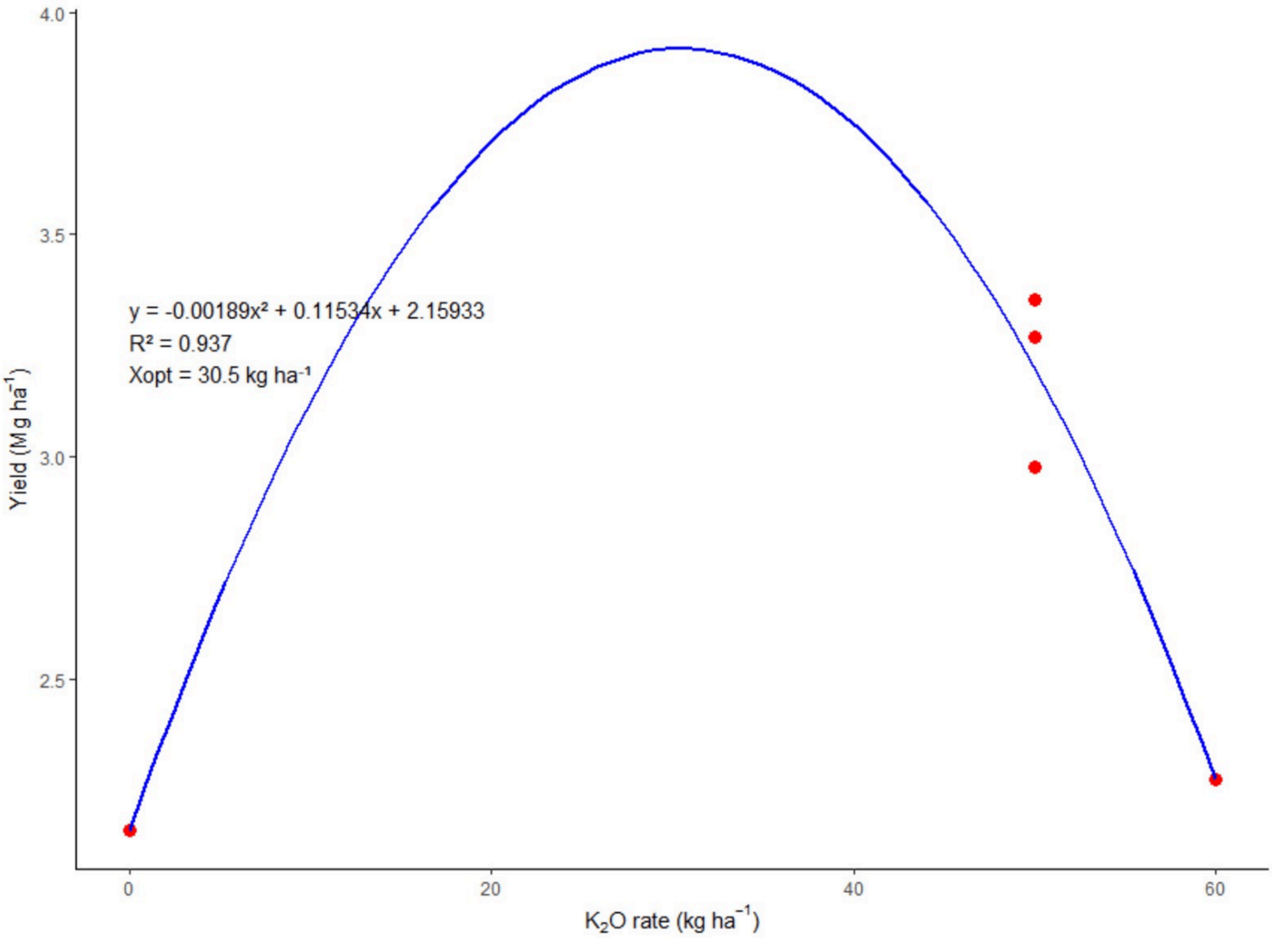

FIGURE 3: Quadratic response of wheat yield (mg ha^{-1}) to potassium (K_2O) application rate (kg ha^{-1}). Red points indicate observed yields across K_2O rates, and the solid blue curve represents the fitted quadratic regression ($y = -0.00189x^2 + 0.11534x + 2.15933$). The model accounted for 93.7% of the variation in yield ($R^2 = 0.937$), with an estimated agronomic optimum K_2O rate of 30.5 kg ha^{-1}.

Note: Phosphorus (P_2O_5) and potassium (K_2O) were applied at identical rates in all fertilizer treatments, therefore, the regression analyses for these nutrients produced identical fitted equations and R^2 values.

Effects of integrating organic and inorganic fertilizers

In the second growing season, wheat grain yield under the combined NPK and organic fertilizer treatments ranged from 2.93 to 3.77 mg ha^{-1}, with an overall average of 3.14 mg ha^{-1} (Table *4*). For context, the corresponding average yield under mineral fertilizer treatments in the first season was 2.81 mg ha^{-1} (Table *3*); however, these values were obtained under different growing conditions and are not directly comparable statistically. Within the second season, analysis of variance indicated no significant differences among treatments (F = 1.72; $P = 0.12$). However, the numerically highest yield (3.77 mg ha^{-1}) was observed under the 100:50:50 NPK + compost treatment. Similarly, compost-based treatments showed a slightly higher average yield (3.35 mg ha^{-1}) than FOF-based treatments (3.20 mg ha^{-1}); however, these differences represent descriptive trends and should not be interpreted as statistically significant treatment effects. The observed numerical trends are consistent with the concept that combining mineral fertilizers with organic amendments may provide complementary benefits. Mineral fertilizers supply readily available nutrients, whereas organic amendments can improve nutrient retention, stimulate microbial activity, and enhance soil resilience [5,24]. Such complementary effects may be particularly relevant in sub-Saharan Africa, where fertilizer use is constrained by cost and accessibility [9]. However, because treatment differences were not statistically significant and sole organic fertilizer treatments were not included, the present study cannot confirm synergistic interactions between organic and inorganic nutrient sources. Consequently, the observed yield responses should be interpreted as indicative of possible additive or complementary effects rather than confirmed synergy [25].

Treatments (kg NPK ha^{-1})	Plant height @ 2WAP	Plant height @ 6WAP	Total seed weight	Yield
	cm	(g pot^{-1})	(mg ha^{-1})	(mg ha^{-1})
100:50:50 NPK + Com	17.20 ± 0.78	62.33 ± 3.83	60.00 ± 8.05	3.77 ± 0.51
100:50:50 NPK + FOF	16.90 ± 0.40	61.67 ± 4.33	52.67 ± 4.95	3.31 ± 0.31
150:50:50 NPK + Com	16.83 ± 1.86	54.67 ± 7.51	38.83 ± 4.48	2.44 ± 0.28
150:50:50 NPK + FOF	17.23 ± 1.51	56.00 ± 5.51	48.83 ± 3.38	3.07 ± 0.21
200:50:50 NPK + FOF	18.00 ± 1.21	61.33 ± 4.06	56.83 ± 4.06	3.57 ± 0.26
200:50:50 NPK + Com	16.80 ± 1.26	69.00 ± 2.89	56.67 ± 1.92	3.56 ± 0.12
90:60:60 NPK + FOF	17.17 ± 1.19	58.00 ± 7.77	45.00 ± 14.25	2.83 ± 0.90
90:60:60 NPK + Com	18.00 ± 0.55	66.67 ± 1.76	57.33 ± 11.69	3.61 ± 0.74
Control	16.57 ± 0.31	59.13 ± 17.16	32.31 ± 7.13	2.13 ± 0.47

TABLE 4: Wheat growth and yield parameters following combined inorganic and organic fertilizer application in the second season.

Numbers following the "±" signs are standard errors of the mean for each treatment (*n* =3). Absence of lower-case letters attached to treatment means shows that the means are statistically similar. FOF, Fermented Organic Fertilizer

The absence of significant differences between compost and FOF treatments suggests that both organic amendments function similarly. Their performance aligns with the expected wheat yield potentials under Ghanaian conditions [17], indicating that locally available organic inputs can effectively complement mineral fertilizers in the semi-deciduous agroeco-zone of Ghana. Long-term studies in maize-wheat systems elsewhere have similarly demonstrated that integrated nutrient management improves yields and soil fertility compared to sole inputs [26].

Nutrient use efficiency (PFP)

PFP declined with increasing NPK rates in the first season, from 14.9 kg grain kg^{-1} nutrient at 100:50:50 kg ha^{-1} NPK to 11.2kg grain kg^{-1} at 200:50:50 kg ha^{-1} NPK and 10.8 kg grain kg^{-1} at 90:60:60 kg ha^{-1} NPK (Table *5*). This trend reflects diminishing nutrient use efficiency at higher fertilizer rates, consistent with nutrient response theory and the yield curves observed in this study.

Treatments (kg NPK ha^{-1})	PFP
100:50:50	14.88
150:50:50	13.08
200:50:50	11.18
90:60:60	10.83

TABLE 5: Nutrient use efficiencies of the inorganic rates applied in the first growing season.

PFP, Partial Factor Productivity

In the second season, PFP values were generally lower, ranging from 3.16 to 5.63 kg grain kg^{-1} nutrient (Table 6). The lower PFP values are primarily due to the inclusion of nutrients supplied by the organic amendments in the total nutrient application rate, which increased the denominator used in the PFP calculation. The highest efficiency was observed under 100:50:50 kg ha^{-1} NPK + FOF (5.63 kg grain kg^{-1} nutrient), followed by 100:50:50 kg ha^{-1} NPK + Compost (5.23 kg grain kg^{-1} nutrient). Despite lower absolute values, integrated treatments maintained relatively higher efficiencies compared to higher fertilizer rates.

Treatments (kg NPK ha^{-1})	PFP
100:50:50 kg NPK ha^{-1} + Com	5.226572
100:50: 50 kg NPK ha^{-1} + FOF	5.633281
150:50:50 kg NPK ha^{-1} + Com	3.163663
150:50:50 kg NPK ha^{-1} + FOF	4.813917
200:50:50 kg NPK ha^{-1} + Com	4.335695
200:50:50 kg NPK ha^{-1} + FOF	5.195382
90:60:60 kg NPK ha^{-1} + FOF	4.732758
90:60: 60 kg NPK ha^{-1} + Com	4.926052

TABLE 6: Nutrient use efficiencies of the combined inorganic and organic fertilizer rates in the second growing season.

These findings are consistent with reports from sub-Saharan Africa, where nutrient use efficiency is highest at moderate fertilizer rates and declines with increasing inputs unless balanced with organic amendments [18,25] . Given the high cost of fertilizers in Ghana, optimizing nutrient use efficiency through integrated approaches is critical for improving farmer profitability and sustainability.

Soil fertility dynamics after harvest

Post-harvest soil analysis showed no statistically significant differences among treatments in both seasons (Table *7*). In the first season, fertilized treatments showed slightly higher total N compared to the control, but differences were not significant. Similarly, in the second season, integrated treatments did not significantly improve soil parameters compared to the control, although there were slight increases in organic carbon (up to 1.47%) under some treatments (Table *8*). Although this C increase was not statistically significant, it represents a positive trend that may indicate the potential of integrated nutrient management to enhance soil organic carbon over time. The lack of significant changes in soil fertility may be due to the short duration of the experiment, as improvements in soil organic matter and nutrient dynamics typically require long-term application of organic inputs. Additionally, pot conditions may have limited root growth and soil buffering capacity, while microbial communities may require longer periods to respond fully to organic amendments [10] .

Property	**Avail. P**	**Exchangeable K**	**Total N**	**Organic C**	**Organic matter**
Treatments (kg NPK ha^{-1})	mg kg^{-1}	Cmol kg^{-1}	%		
100:50:50	25.24 ± 6.39	0.19 ± 0.01	0.19 ± 0.02	1.32 ± 0.09	2.27 ± 0.17
150:50:50	25.68 ± 6.39	0.20 ± 0.01	0.15 ± 0.02	1.25 ± 0.09	2.16 ± 0.17
200:50:50	27.61 ± 6.39	0.21 ± 0.01	0.18 ± 0.02	1.29 ± 0.09	2.22 ± 0.17
90:60:60	23.94 ± 6.39	0.20 ± 0.01	0.18 ± 0.02	1.24 ± 0.09	2.13 ± 0.17
Control	26.98 ± 6.39	0.18 ± 0.01	0.12 ± 0.02	1.33 ± 0.09	2.31 ± 0.17

TABLE 7: Soil chemical status after wheat harvest in the first growing season.

Numbers following the "±" signs are pooled standard errors of the means (SEM). Absence of lower-case letters attached to treatment means shows that the means are statistically similar. The SEM was calculated from three replicates per treatment. Since each treatment had an equal number of replicates, the SEM for each soil parameter is identical across treatments.

Long-term field studies have demonstrated that continuous application of organic amendments enhances soil organic carbon, aggregate stability, and nutrient cycling [12,27] .Therefore, although these short-term effects were minimal, the observed trends suggest potential long-term benefits of integrated nutrient management for soil health.

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Property	Avail. P	Exchangeable K	Total N	Organic C	Organic matter
Treatments	$mgkg^{-1}$	$cmolkg^{-1}$	%		
100:50:50 kg NPK ha^{-1} + FOF	28.58 ± 6.39	0.21 ± 0.01	0.18 ± 0.02	1.38 ± 0.09	2.37 ± 0.17
100:50:50 kg NPK ha^{-1} + Com	28.84 ± 6.39	0.21 ± 0.01	0.15 ± 0.02	1.35 ± 0.09	2.32 ± 0.17
150:50:50 kg NPK ha^{-1} + FOF	25.69 ± 6.39	0.21 ± 0.01	0.23 ± 0.02	1.37 ± 0.09	2.36 ± 0.17
150:50:50 kg NPK ha^{-1} + Com	23.21 ± 6.39	0.22 ± 0.01	0.19 ± 0.02	1.42 ± 0.09	2.46 ± 0.17
200:50:50 kg NPK ha^{-1} + FOF	18.70 ± 6.39	0.21 ± 0.01	0.18 ± 0.02	1.38 ± 0.09	2.38 ± 0.17
200:50:50 kg NPK ha^{-1} +Com	29.98 ± 6.39	0.20 ± 0.01	0.22 ± 0.02	1.47 ± 0.09	2.53 ± 0.17
90:60:60 kg NPK ha^{-1} + FOF	29.49 ± 6.39	0.19 ± 0.01	0.14 ± 0.02	1.31 ± 0.09	2.25 ± 0.17
90:60:60 kg NPK ha^{-1} + Com	20.27 ± 6.39	0.21 ± 0.01	0.17 ± 0.02	1.28 ± 0.09	2.21 ± 0.17
Control	27.98 ± 6.39	0.19 ± 0.01	0.14 ± 0.02	1.35 ± 0.09	2.33 ± 0.17

TABLE 8: Soil chemical status after wheat harvest in the second growing season.

Numbers following the "±" signs are pooled standard errors of the mean. Absence of lower-case letters attached to treatment means shows that the means are statistically similar. FOF, Fermented Organic Fertilizer

Implications for wheat production in Ghana

The results demonstrate that N is the primary limiting nutrient for wheat production in the semi-deciduous agro-ecological zone of Ghana. N rates higher than 200 kg ha^{-1} may be considered while relatively modest applications of P and K (~30 kg ha^{-1}) are sufficient. Integration of organic and inorganic fertilizers improved yield performance and nutrient use efficiency without significantly altering soil fertility in the short term. These findings align with broader nutrient response theory and highlight integrated nutrient management as a practical strategy for sustainable wheat intensification in Ghana. Given the country's reliance on wheat imports and constraints in fertilizer access by farmers, applying very high nitrogen rates may not always be economically feasible. Integrating mineral fertilizers with locally available organic amendments such as fermented organic fertilizer and compost provides a practical approach to supplement fertilizer nitrogen, reduce dependence on mineral fertilizers and potentially lower production costs while sustaining crop productivity.

Conclusions

This study represents an important step toward developing fertilizer recommendations for sustainable wheat production in Ghana. Under the controlled pot conditions of this study, wheat yield remained responsive to nitrogen throughout the range of application rates evaluated, indicating that the agronomic optimum was not reached. In contrast, relatively modest phosphorus and potassium applications were sufficient to support wheat growth. Integrating mineral fertilizers with compost or Bokashi-type FOF improved grain yield and nutrient use efficiency compared with sole mineral fertilizer applications under the conditions of the second experiment. Although these improvements suggest beneficial complementary interactions, true synergistic effects could not be confirmed because sole organic fertilizer treatments were not included. Likewise, while no significant changes in soil fertility were detected after two growing seasons, the observed positive trends in soil organic carbon indicate the potential for longer-term soil health benefits. Overall, the findings demonstrate the importance of balanced nutrient management for wheat production and support integrated nutrient management as a promising strategy for improving nutrient use efficiency and sustaining wheat production in Ghana. Future field studies should validate these findings across locations and seasons, identify the agronomic optimum nitrogen rate, evaluate long-term effects on soil fertility, and incorporate economic analyses to determine economically viable fertilizer recommendations.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Plant subjects: All authors have confirmed that this study did not involve any herbarium specimen. **Human subjects:** All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** Funds and wheat seeds were provided by ARIMA Farms, India. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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