frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 12 January 2026
DOI 10.3389/fsufs.2025.1744084

OPEN ACCESS

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RECEIVED 11 November 2025
REVISED 17 December 2025
ACCEPTED 19 December 2025
PUBLISHED 12 January 2026

CITATION
Yussif IS, Addai IK, Lamptey S, Mustapha M-u, Abdulai H and Abdul Aziz AL (2026) Effects of variety, spacing, and amendment on the growth and yield of rice *(Oryza sativa* L.) in the Northern Region of Ghana. *Front. Sustain. Food Syst.* 9:1744084. doi: 10.3389/fsufs.2025.1744084

Effects of variety, spacing, and amendment on the growth and yield of rice *(Oryza sativa* L.) in the Northern Region of Ghana

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This study aimed to evaluate the effects of rice variety, plant spacing, and soil amendment on the growth and yield of rice in northern Ghana. A field experiment was conducted during the 2022 cropping season using a 5 × 2 × 4 factorial arrangement laid out in a randomized complete block design (RCBD). The treatments consisted of five rice varieties (V1 = Agra, V2 = Gbewaa, V3 = Digang, V4 = Mandii, and V5 = Moses), two spacing levels (S1 = 20 cm × 20 cm and S2 = 25 cm × 25 cm), and four soil amendment treatments (basal application of chemical fertilizer [BCF], foliar fertilizer [FF], half-recommended rate of chemical fertilizer and organic fertilizer [HRCFOF], and the recommended rate of chemical fertilizer [RCF]). The results showed significant interactions among variety, spacing, and soil amendment. The highest leaf area index (5.93) was recorded under the V1S2RCF treatment. The highest effective tiller numbers per plant were observed in V2S2RCF (20.78), V1S1RCF (18.6i7), V4S2BCF (15.94), V1S2RCF (15.64), and V2S1RCF (15.33). Grain yield was highest in treatments V4S1RCF, V1S2RCF, V2S1RCF, and V2S1HRCFOF. The results revealed that the integrated management of genotype, plant density, and nutrient source is essential for enhancing climate-resilient rice production in the Guinea Savannah zone.

KEYWORDS

amendment, fertilizer, recommended, rice, spacing, variety

1 Introduction

The global economy derives substantial benefits from the rice industry, as rice plays a critical role in economic development and food security worldwide. Rice production is vital for reducing malnutrition and sustaining livelihoods across many regions of the world (Fukagawa and Ziska, 2019). As a major staple food crop, rice significantly contributes to Ghana's economy and food system (International Food Policy Research Institute, 2020). In 2018, Ghana's agricultural sector contributed 19.7% to the national gross domestic product (GDP), with the crop sub-sector accounting for approximately 65% of this contribution (Ministry of Food and Agriculture, 2019).

Globally, rice is cultivated on approximately 155 million ha across diverse agro-ecological zones (United States Department of Agriculture, 2023). Of this total area, approximately 75% of rice-growing areas are under rainfed systems, while irrigated rice ecologies and inland swamps account for approximately 15 and 10% of the cultivated area, respectively (Ulzen et al., 2023).

China and India are currently the world's two largest producers of rice (United States Department of Agriculture, 2023). Globally, the average rice yield is estimated at approximately 6 t ha^{-1}, while yields in rainfed upland and irrigated systems average approximately 4 t ha^{-1} and 8 t ha^{-1}, respectively (Muthayya et al., 2014). However, substantially higher yields have been reported under improved management practices. For example, in India, Gordon (2013) documented rice yields of up to 22.4 t ha^{-1} achieved through the adoption of the System of Rice Intensification (SRI).

In Africa, increasing rice consumption has led to a corresponding increase in rice production, driven largely by the expansion of cultivated land rather than yield improvement (Yuan et al., 2024). Despite this growth, Africa currently meets approximately 60% of its rice consumption needs, largely because average yields are approximately 49% lower than the global average (Yuan et al., 2024). Low adoption of improved production technologies and heavy reliance on rainfed rice ecologies continue to constrain rice self-sufficiency across the continent (Yuan et al., 2024).

In Ghana, the majority of rice production occurs in lowland rainfed ecologies, which further exposes production to climatic variability and limits yield potential (Azumah and Adzawla, 2017).

The majority of Ghana's rice-producing areas are located in the Northern Region, which was the country's leading rice producer in 2012 (Ragasa et al., 2013). In this region, rice was cultivated on approximately 81,165 ha (Ghana Rice Mechanization Policy Brief, 2020). However, despite its dominance in rice production, yields in the Northern Region remain below the national average. In 2018, Ghana's average annual rice yield was 2.96 t ha^{-1}, while the Northern Region recorded a lower average yield of 2.6 t ha^{-1} (Ministry of Food and Agriculture, 2019). Notably, no district within the Northern Region exceeded the national average yield during that period (Ministry of Food and Agriculture, 2019).

In 2015, Ghana spent approximately USD $1.2 billion on rice imports, highlighting the country's heavy dependence on external rice supplies (International Food Policy Research Institute, 2020). Enhancing domestic rice production is therefore critical for achieving food security and self-sufficiency (Diagne et al., 2013). Rising demand for rice in Ghana is driven by rapid urbanization, increasing incomes, and shifts in dietary preferences toward rice over traditional staples (Eureka et al., 2023). Despite current yield constraints, rice-producing regions in Ghana have substantial potential to attain achievable yield levels of 6–8 t ha^{-1} through improved technologies and management practices, as reported by the Ministry of Food and Agriculture and the Savannah Agricultural Research Institute (SARI) (Ragasa et al., 2013).

Unimproved rice varieties generally possess traits associated with low yield potential, and their optimal productivity remains limited. In contrast, improved rice varieties have been shown to exhibit higher yield potential, enhanced resistance to pests and diseases, and superior grain quality (Rahman and Connor, 2022). However, several studies have reported that the adoption of improved varieties alone does not necessarily result in increased rice yields (Zhang et al., 2019). Improved varieties are often expensive and require higher input levels, which can discourage adoption or result in partial and ineffective use by resource-constrained farmers (Zhang et al., 2019). Moreover, cultivating improved varieties without timely input application and appropriate agronomic practices can lead to suboptimal yields.

Plant population density is a critical agronomic factor influencing rice growth and productivity. When plant density exceeds the optimal level, intense competition for nutrients, water, and sunlight slows plant growth and reduces grain yield (Dzomeku et al., 2016). In Ghana, many farmers do not adhere to recommended plant densities, as a majority continue to establish rice crops through broadcasting rather than row planting. It is estimated that more than 50% of rice farmers in the country still rely on traditional planting methods (Ragasa et al., 2013). Optimal plant spacing enhances efficient nutrient uptake and light interception, promoting healthy plant growth and ultimately increasing yield. For instance, Tadesse et al. (2019) reported that a spacing of 25 cm × 25 cm produced the highest grain yield (3.3 t ha^{-1}) compared with drilling methods.

Soil amendment plays a vital role in increasing rice yield by reducing soil acidity, improving soil health, and enhancing the availability of essential nutrients for plant uptake. Low soil fertility has been shown to limit nutrient release and uptake by rice plants, ultimately resulting in reduced grain yield (Zhu et al., 2022). Ragasa et al. (2013) reported that the majority of local rice farmers did not apply fertilizer at the recommended rates during the 2012 cropping season, further contributing to low productivity. Research by Zhu et al. (2022) also demonstrated that manure amendments positively influenced the net photosynthetic rate and improved plant physiological resilience to unfavorable environmental conditions, leading to higher rice yields. Similarly, Dzomeku et al. (2016) found that the application of either the recommended rate of chemical fertilizer or compost resulted in favorable economic returns from rice fields.

Crop response to agronomic practices often varies by genotype. Arianti et al. (2022) reported that rice varieties exhibit distinct responses to various plant spacing, with certain variety–spacing combinations producing superior yields. Similarly, El-Katony et al. (2021) observed significant improvements in rice growth and grain yield when specific varieties were combined with appropriate soil amendment practices.

The combined use of suitable rice varieties, optimal plant spacing, and appropriate soil amendments is therefore critical for achieving improved rice productivity. Consequently, this study aimed to evaluate the effects of rice variety, plant spacing, soil amendments, and their interactions on the growth and yield of rice.

2 Materials and methods

2.1 Description of the study area

The field experiment was conducted during the 2022 cropping season at Sagnarigu Kukuo, located in the Sagnarigu Municipality of the Northern Region of Ghana. The experimental site lies at an elevation of 142 m above sea level, between latitude 09°43′N and longitude 0°53′W, within the Guinea Savannah agro-ecological zone. During the 2022 growing season (March–October), the study area received an average annual rainfall of 109.4 mm, with peak rainfall occurring in August. Mean temperatures ranged from 23.4 °C to 33.0 °C, while relative humidity varied between 63 and 81% (Savannah Agricultural Research Institute, 2022). The soils of the experimental site are classified as Planosols and belong to the Changnayili soil series Ziblim et al. (2012).

2.2 Experimental materials

Three improved varieties (Agra, Gbewaa, and Digang) and two local varieties (Mandii and Moses), along with Deco compost, Yara

NPK, Falcon ammonium sulfate, Foliar Plus Complete NPK, and urea, were used.

2.3 Experimental design and treatments

This study was conducted as a $5 \times 2 \times 4$ factorial experiment arranged in a randomized complete block design (RCBD) with three replications. The experimental factors comprised five varieties—V1 = Agra, V2 = Gbewaa, V3 = Digang, V4 = Mandii, and V5 = Moses; two plant spacing levels—S1 = 20 cm × 20 cm and S2 = 25 cm × 25 cm; and four soil amendment treatments. The soil amendment treatments were basal application of chemical fertilizer (BCF) (37.5 kg ha^{-1} NPK [15–15–15]); foliar fertilizer (FF) application (basal application of 18.5 kg ha^{-1} N, 6 kg ha^{-1} P, and 6 kg ha^{-1} K, followed by foliar top-dressing with 18.5 kg ha^{-1} N from urea); half-recommended rate of chemical fertilizer and organic fertilizer (HRCFOF) (initial application of 10 t ha^{-1} Deco compost, followed by a basal application of 18.75 kg ha^{-1} NPK [15–15–15] and top-dressing with 13.13 kg ha^{-1} N from ammonium sulfate); and the recommended rate of chemical fertilizer (RCF) (basal application of 37.5 kg ha^{-1} NPK [15–15–15], followed by top-dressing with 26.25 kg ha^{-1} N from ammonium sulfate).

The total experimental field covered an area of 2,520 m^2 (36 m × 70 m). Each block measured 840 m^2 (12 m × 70 m), while individual treatment plots measured 21 m^2 (7 m × 3 m).

Alleys measuring 1 m and 2 m were used for adjacent treatment plots within a block and between adjacent blocks, respectively. Experimental plots were bunded to prevent water from spilling over from one plot to another. Deco compost was incorporated into the respective fields 3 weeks before transplanting.

2.4 Data collected

Data were collected on plant height, number of tillers per plant, chlorophyll content, leaf area index, days to 50% flowering, dry root weight at harvest, panicle number, spikelet and infertile spikelet per panicle, 1,000 seed weight, grain yield, and straw yield.

Grain moisture content (MC) was determined using a Dicky John multi-grain moisture meter and adjusted to 14% MC. Grain yield was then converted to kilograms per hectare (kg ha^{-1}) using the following formula:

$$\text{Grain yield}\left(\text{kg / ha}\right)\text{at 14\%MC} = \frac{\left(\begin{array}{l}\left(100 - MC\right) X\ net\ plot \\ grain\left(kg\right) X\ 1000\ \left(m^2\right.\end{array}\right)}{\left(100 - 14\right) X\ net\ plot\ area\left(m^2\right).}$$

To assess the cost-effectiveness of the treatments, data were also used to calculate the value–cost ratio for each treatment.

2.5 Data analysis

Data collected from the field experiment were subjected to analysis of variance (ANOVA) using GenStat software (18th edition). Mean differences were separated using the least significant difference (LSD) test at the 5% probability level. Pearson's correlation coefficient was employed to examine the relationships between grain yield and selected growth and yield parameters.

3 Results and discussion

3.1 Vegetative growth

V5S2HRCFOF was superior in producing tillers at the maximum tillering stage of the plants (Table 1). Studies conducted by Kashkool et al. (2020), Abdul Halim et al. (2018), and Hasanuzzaman et al. (2009) support this finding. V4S1FF and V2S1FF produced the fewest tillers. This finding implies that V4 (Mandii) and V2 (Gbewaa) responded poorly to spacing S1 (20 cm × 20 cm) and amendment FF (foliar fertilizers), producing fewer tillers (Table 1). This could be due to increased competition created by S1 and the availability of lower nutrients from the FF applied.

There was no significant ($p > 0.05$) interaction between spacing, variety, and amendment on chlorophyll content in the plants. Chlorophyll is an essential component of photosynthesis and plays a vital role in plant growth and development. Zheng et al. (2012) reported that improving conditions for spacing and nutrient availability to enhance photosynthesis or chlorophyll fluorescence can lead to a 10% increase in yield.

Plants transplanted with spacing S2 produced higher chlorophyll levels (Figure 1), which could be attributed to the spacing S2 that exposed two-thirds of the lower leaves of the rice plants to sunlight, enhancing the nitrogen status of the plants due to reduced competition and creating less overall competition among the plants in the wider spacing.

The sole chemical fertilizers or compost were superior in influencing the chlorophyll of the plants (Figure 1). This could be attributed to a better release of nutrients for plant uptake and/or the maintenance of soil health and fertility for proper plant functioning. Leaf chlorophyll concentration could also be affected by moderate potassium deficiency in rice, as Hou et al. (2020) confirmed.

Other studies presented a view contrary to the findings of this research, which indicated that there was no significant ($p > 0.05$) interaction effect on chlorophyll. The combined application of chemical and organic fertilizers has been reported by Khan (2018), Ali et al. (2020), Esfahani et al. (2019), and Gholizadeh et al. (2017) to positively influence chlorophyll formation in plants.

Plants of V4, V2, and V1 produced more chlorophyll (Figure 1), which could be attributed to their better tolerance of the soil and more efficient use of available soil resources. Junfei et al. (2017) reported that plants with reduced chlorophyll content can exhibit higher photosynthetic rates, improved canopy light distribution, and greater yields than normally pigmented plants. This finding suggests that plants with lower chlorophyll levels perform well in terms of grain yield.

Plants of the V1 and V4 varieties continued to show positive responses to the combined effect of S2 spacing and RCF amendment by producing the highest leaf area index (Table 1). This could be attributed to the superior varietal characteristics and the greater availability of nutrients, water, and light experienced by the rice plants at 63 DAP. Studies by Haque and Haque (2016), Mahajan et al. (2012), Maftukhah et al. (2019), Sen et al. (2014), and Venkatesan et al. (2023) support this finding.

10.3389/fsufs.2025.1744084

TABLE 1 Interactive effect of variety, spacing, and amendment on growth and yield parameters and grain yield.

Treatment combination	TC @ 63 DAP	LAI @ 63	LAI @ 84	TC @ 84 DAP	Panicle number	Spikelet	Infertile pikelet	Yield
V1S1BCF	34.2	3.59	3.94	40.0	10.43	117.7	9.39	2,961
V1S2BCF	51.4	4.47	4.92	28.4	16.09	124	NS	1,252
V2S1BCF	31.0	3.49	3.55	24.0	11.55	109.1	17.94	5,781
V2S2BCF	61.5	4.49	4.94	59.4	16.70	142.7	NS	4,101
V3S1BCF	40.5	3.17	3.49	38.4	15.63	66	7.00	4,291
V3S2BCF	43.2	3.81	4.19	39.1	13.29	109	NS	2,178
V4S1BCF	51.7	3.65	4.01	31.0	17.26	145.1	30.44	4,588
V4S2BCF	61.2	4.70	5.17	63.8	17.05	162.7		2,288
V5S1BCF	56.2	3.08	3.39	45.6	12.79	60.5	9.77	3,772
V5S2BCF	83.7	3.82	4.20	29.7	21.98	122.5		2,470
V1S1FF	54.4	3.47	3.82	40.8	16.80	81.9	18.56	5,231
V1S2FF	70.2	4.37	4.81	53.7	26.16	107		1,513
V2S1FF	24.7	3.41	3.44	28.0	10.95	100	4.28	4,298
V2S2FF	28.5	4.26	4.69	40.0	16.58	146.5		3,667
V3S1FF	30.0	3.09	3.39	20.5	22.41	112.7	3.56	5,322
V3S2FF	50.4	3.96	4.36	22.9	13.20	100		2,396
V4S1FF	40.9	3.50	3.85	24.5	8.07	121.1	15.83	3,167
V4S2FF	33.0	4.61	5.07	37.6	17.69	257		1,302
V5S1FF	22.9	3.06	3.37	24.4	7.36	104.7	4.19	3,082
V5S2FF	59.4	3.66	4.03	53.5	10.87	130		2,176
V1S1HRCFOF	49.0	4.47	4.91	41.3	20.50	109.7	16.67	4,439
V1S2HRCFOF	74.0	5.70	6.27	58.7	18.18	206.2		2,839
V2S1HRCFOF	51.7	4.39	4.42	50.2	15.22	88.9	5.94	6,210
V2S2HRCFOF	38.5	5.60	6.19	36.7	23.69	152.7		5,058
V3S1HRCFOF	51.0	3.95	4.35	36.6	19.43	109.2	4.39	5,343
V3S2HRCFOF	67.2	4.85	5.34	34.4	23.62	124.8		5,801
V4S1HRCFOF	64.3	4.52	4.97	48.0	13.63	126.1	13.5	5,902
V4S2HRCFOF	68.4	5.80	6.38	44.9	17.50	205		2,720
V5S1HRCFOF	49.9	3.89	4.28	52.0	35.96	142.8	7.00	3,875
V5S2HRCFOF	118.8	4.76	5.24	36.2	22.56	119.5		3,179
V1S1RCF	78.7	4.56	5.02	74.7	16.43	118.6	10.83	5,002
V1S2RCF	82.8	5.93	6.52	62.6	27.37	178.5		7,172
V2S1RCF	36.4	4.52	4.52	61.3	10.24	184.4	9.17	6,003
V2S2RCF	77.5	5.71	6.28	83.1	16.93	218.7		3,894
V3S1RCF	60.0	4.03	4.43	40.2	16.85	84.3	3.06	4,289
V3S2RCF	43.8	5.31	5.84	19.2	30.41	91.2		2,782
V4S1RCF	51.7	4.55	5.00	34.0	17.57	110.4	11.61	8,169
V4S2RCF	78.0	5.85	6.44	51.5	16.89	223.2		2095
V5S1RCF	38.7	4.00	4.40	24.0	17.66	132.2	8.50	3,849
V5S2RCF	67.2	4.86	5.35	44.0	16.74	153.5		3,335
LSD	24.6	0.13	0.14	16.43	7.968	44.01	9.411	4368.6

V1 = Agra, V2 = Gbewaa, V3 = Digang, V4 = Mandii, and V5 = Moses. S1 = 20 cm x 20 cm and S2 = 25 cm × 25 cm. BCF = basal application of chemical fertilizer; FF = foliar fertilizer; HRCFOF = half-recommended rate of chemical fertilizer and organic fertilizer; and RCF = half-recommended rate of chemical fertilizer.

V3S1FF, V5S1BCF, and V5S1FF produced the lowest leaf area index (Table 1). The poor quantity and arrangement of leaves in V3 and V5 likely contributed to their weak response to the combined effect of solely basal chemical fertilizers or foliar organic fertilizers. This may have resulted in limited nutrient availability and, coupled with narrow spacing, increased competition among plants for nutrients, ultimately leading to a low leaf area index in these treatments.

Plants of V1 and V4 likely exhibited superior genetic characteristics, including greater leaf quantity and arrangement, as well as higher numbers of stems and ears, during both the vegetative and reproductive stages of the rice plants. Spacing S2 and RCF amendment also showed better performance than others during the transition from the vegetative stage to the reproductive stage of the plant due to available nutrient release. Several studies support this

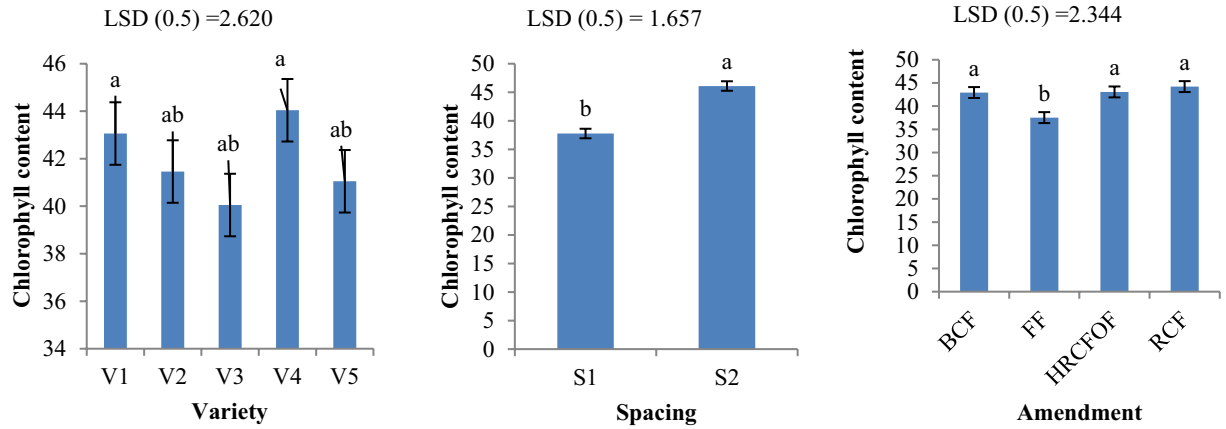

FIGURE 1
Effects of variety, spacing, or amendment on chlorophyll content at 63 Days after planting. Error bars indicate ± SEM. Means with the same letters are not significantly ($p > 0.05$) different at the 5% level of significance.

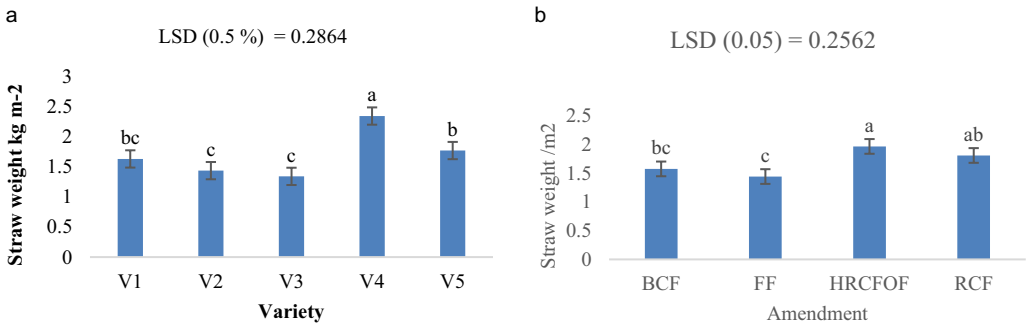

FIGURE 2
(a) Effects of variety on straw weight (kg m^{-2}). Error bars indicate ± SEM. Means with the same letters are not significantly ($p > 0.05$) different at the 5% level of significance. **(b)** Effects of amendment on straw weight (kg m^{-2}). Error bars indicate ± SEM. Means with the same letters are not significantly ($p > 0.05$) different at the 5% level of significance.

finding; for example, Yu et al. (2020) reported that, as nitrogen application increases, the leaf area index, biomass, and other indicators related to nitrogen uptake in rice plants also increase.

3.2 Components of yield (straw weight, panicle number, and spikelet number)

Straw weight was not significantly ($p > 0.05$) affected by the interaction of variety, spacing, and amendment. Variety significantly ($p < 0.05$) affected the straw weight, with V4 recording the highest value of 2.34 kg (Figure 2). The lowest values were recorded in V2 and V3, with values of 1.43 kg and 1.34 kg, respectively. The amendment had a significant ($p < 0.05$) influence on straw weight at harvest. Plants on plots where HRCFOF and RCF were applied produced the highest weights of 1.97 kg and 1.81 kg, respectively (Figure 2b). These two amendments ensured better release of nutrients at different times, which were readily accessible to the plants, thereby enhancing plant biomass production. These findings are consistent with studies by Kashkool et al. (2020) and Abdul Halim et al. (2018).

Compared to non-adopting farmers, V1S1FF, V2S1FF, and V2S2FF achieved the highest value–cost ratios of 2.51, 2.24, and 2.03 (Table 2), respectively. The cost of foliar fertilizers (FF) was significantly lower than that of other inputs, contributing to higher VCR values. This may explain the low adoption of fertilizer technology in the study area, as farmers may be unable to afford the recommended rates of fertilizers for optimal production. Adzogah (2023) corroborated this finding by indicating that the rising cost of fertilizers significantly affected crop production and the profitability of farmers.

4 Conclusion and recommendation

The results from the field experiment showed that rice growth, yield components, and grain yield were significantly influenced by the combined effects of variety, spacing, and soil amendment. The treatment combination Mandii × 20 cm × 20 cm × recommended rate of chemical fertilizer (V4S1RCF) produced the highest grain yield (8,169 kg ha^{-1}). This yield was statistically comparable to yields obtained from Agra × 25 cm × 25 cm × recommended rate of chemical fertilizer (V1S2RCF),

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TABLE 2 Value cost assessment of rice production based on variety, spacing, and amendment at Sagnarigu Kukuo in the Guinea Savannah zone of Ghana.

Treatment combination	Yield kg ha $^{-1}$	Total revenue (GH₵ ha^{-1})	Total cost (GH₵ ha^{-1})	Value–cost ratio
V1S1BCF	2,918	12,014	11,887	1.01
V1S2BCF	1,253	5,158	9,977	0.52
V2S1BCF	5,784	23,818	15,175	1.57
V2S2BCF	4,103	16,896	13,247	1.28
V3S1BCF	4,293	17,679	13,465	1.31
V3S2BCF	2,179	8,973	11,040	0.81
V4S1BCF	4,591	18,903	13,806	1.37
V4S2BCF	2,289	9,427	11,166	0.84
V5S1BCF	3,774	15,541	12,869	1.21
V5S2BCF	2,471	10,176	11,375	0.89
V1S1FF	5,234	21,552	8,572	2.51
V1S2FF	1,514	6,234	5,880	1.06
V2S1FF	4,300	17,708	7,897	2.24
V2S2FF	3,669	15,108	7,440	2.03
V3S1FF	3,524	14,511	7,335	1.98
V3S2FF	2,397	9,872	6,520	1.51
V4S1FF	3,169	13,048	7,078	1.84
V4S2FF	1,303	5,364	5,728	0.94
V5S1FF	3,084	12,698	7,016	1.81
V5S2FF	2,177	8,965	6,360	1.41
V1S1HRCFOF	4,442	18,289	13,497	1.35
V1S2HRCFOF	2,841	11,697	11,661	1.00
V2S1HRCFOF	6,214	25,585	15,530	1.65
V2S2HRCFOF	5,061	20,839	14,208	1.47
V3S1HRCFOF	5,346	22,013	14,535	1.51
V3S2HRCFOF	3,803	15,660	12,765	1.23
V4S1HRCFOF	5,905	24,316	15,176	1.60
V4S2HRCFOF	2,722	11,206	11,524	0.97
V5S1HRCFOF	3,877	15,965	12,850	1.24
V5S2HRCFOF	3,181	13,097	12,051	1.09
V1S1RCF	5,005	20,608	13,531	1.52
V1S2RCF	7,176	29,549	16,021	1.84
V2S1RCF	6,006	24,732	14,680	1.68
V2S2RCF	3,896	16,043	12,259	1.31
V3S1RCF	4,291	17,671	12,713	1.39
V3S2RCF	2,784	11,462	10,983	1.04
V4S1RCF	8,174	33,656	17,166	1.96
V4S2RCF	2096	8,631	10,194	0.85
V5S1RCF	3,851	15,858	12,208	1.30
V5S2RCF	3,337	13,740	11,618	1.18

V1 = Agra, V2 = Gbewaa, V3 = Digang, V4 = Mandii, and V5 = Moses. S1 = 20 cm × 20 cm and S2 = 25 cm × 25 cm. BCF = basal application of chemical fertilizer; FF = foliar fertilizer; HRCFOF = half-recommended rate of chemical fertilizer and organic fertilizer; and RCF = half-recommended rate of chemical fertilizer.

Gbewaa × 20 cm × 20 cm × half the recommended rate of chemical fertilizer combined with organic fertilizer (V2S1HRCFOF), and Gbewaa × 20 cm × 20 cm × recommended rate of chemical fertilizer (V2S1RCF).

Straw biomass yield was highest in plots receiving the half-recommended rate of chemical fertilizer and organic fertilizer (HRCFOF), with values of 1.969 and 1.811 kg m^{-2}. The highest value–cost ratios were recorded for Agra × 20 cm × 20 cm × foliar fertilizer (V1S1FF), Gbewaa × 20 cm × 20 cm × foliar fertilizer (V2S1FF), and Gbewaa × 25 cm × 25 cm × foliar fertilizer (V2S2FF), with values of 2.51, 2.24, and 2.03, respectively.

Based on these findings, farmers in the study area and similar agro-ecological zones are advised to adopt Mandii × 20 cm ×

20 cm × recommended rate of chemical fertilizer (V4S1RCF), Agra × 25 cm × 25 cm × recommended rate of chemical fertilizer (V1S2RCF), Gbewaa × 20 cm × 20 cm × half the recommended rate of chemical fertilizer combined with organic fertilizer (V2S1HRCFOF), or Gbewaa × 20 cm × 20 cm × recommended rate of chemical fertilizer (V2S1RCF) to achieve higher rice productivity.

The treatment combinations Agra × 20 cm × 20 cm × foliar fertilizer (V1S1FF), Gbewaa × 20 cm × 20 cm × foliar fertilizer (V2S1FF), and Gbewaa × 25 cm × 25 cm × foliar fertilizer (V2S2FF) are recommended for adoption to enhance profitability in rice farming.

Further research is warranted across various agro-ecological zones, as the present study was conducted under lowland rainfed conditions. In addition, the efficiency and nutrient uptake of the half-recommended rate of chemical fertilizer and organic fertilizer (HRCFOF) and foliar fertilizer (FF) treatments merit further investigation under both rainfed and irrigated production systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author/s.

Author contributions

IY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. M-uM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. IA: Formal analysis, Writing – review & editing. SL: Writing – review & editing. HA: Writing – review & editing. AA: Funding acquisition, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgments

The authors would like to thank the Crop Science Department of the University for Development Studies, Tamale, Ghana; Puzuri Certified Agroseed Dealers, Tamale, Ghana; and Savannah Agricultural Research in the Northern and Upper West Regions of Ghana for crucial services rendered, which made this study a success.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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References

Abdul Halim, N. S. A., Abdullah, R., Karsani, S. A., Osman, N., Panhwar, Q. A., and Ishak, C. F. (2018). Influence of soil amendments on the growth and yield of rice in acidic soil. *Agronomy* 8:165. doi: 10.3390/agronomy8090165

Adzogah, A. S. (2023). Rising cost of farm inputs adversely affecting crop production. *Agribusiness*.

Ali, I., Ullah, S., He, L., Zhao, Q., Iqbal, A., Wei, S., et al. (2020). Combined application of biochar and nitrogen fertilizer improves rice yield, microbial activity and N-metabolism in a pot experiment. *PeerJ* 8:e10311. doi: 10.7717/peerj.10311

Arianti, F. D., Nurwahyuni, E., Minarsih, S., and Amri, A. F. (2022). Growth and yield response of rice based on different planting distances in rainfed field. *E3S Web Conf.* 361:04002. doi: 10.1051/e3sconf/202236104002

Azumah, S. B., and Adzawla, W. (2017). Effect of urea deep placement technology adoption on the production frontier: evidence from irrigation rice farmers in the northern region of Ghana. *Int. J. Biol. Biomolec. Agric. Food Biotechnol. Engin.* 11, 288–294.

Diagne, A., Alia, D. Y., Wopereis, M. C., Saito, K., Nakelse, T., and Seck, P. A. (2013). "Impact of rice research on income, poverty and food security in Africa: an ex-ante analysis" in Realizing Africa's rice promise (Wallingford, UK: CABI), 390–423.

Dzomeku, I. K., Sowley, E. N. K., and Yussif, I. S. (2016). Evaluation of system of rice intensification (SRI) for enhanced rice (*Oryza sativa* L.) production in the Guinea Savannah zone of Ghana. *Curr. Agric. Res. J.* 4, 84–93. doi: 10.12944/CARJ.4.1.09

El-Katony, T. M., Ward, F. M., Deyab, M. A., and El-Adl, M. F. (2021). Algal amendment improved yield and grain quality of rice with alleviation of the impacts of salt stress and water stress. *Heliyon* 7:e07911. doi: 10.1016/j.heliyon.2021.e07911

Esfahani, A., Niknejad, Y., Fallah, H., and Dastan, S. (2019). Integrated management of organic manures and chemical fertilizers for enhancing paddy yield and the nutrient content of rice cultivars. *Commun. Soil Sci. Plant Anal.* 50, 1–16. doi: 10.1080/00103624.2019.1573248

Eureka, E., Adomako, A., Aboagye-Ghunney, K., and Owusu, P. (2023). Survey of rice (*Oryza sativa* L.) production ecosystems in northern Ghana confirms low risk of exposure to potential toxic elements from local grain consumption. [Epub ahead of print] doi: doi: 10.1101/2023.04.08.536104.

Fukagawa, N. K., and Ziska, L. H. (2019). Rice: importance for global nutrition. *J. Nutr. Sci. Vitaminol. (Tokyo)* 65, S2–S3. doi: 10.3177/jnsv.65.S2

Ghana Rice Mechanization Policy Brief (2020). Opportunity to influence and impact policy on mechanization and infrastructure delivery for rice production: Set targets and

report return on investments (ROI) in infrastructure, and machinery in rice value chains disaggregated district, Ghana.

Gholizadeh, A., Saberioon, M., Borůvka, L., and Wayayok, A. Mohd Soom M. A. 2017 Leaf chlorophyll and nitrogen dynamics and their relationship to lowland rice yield for site-specific paddy management Inf. Process. Agric. 4 256–268 doi: 10.1016/j.inpa.2017.08.002

Gordon, C. G. (2013). Rice production records set with new method. *World Affairs J.*

Haque, M. A., and Haque, M. (2016). Growth, yield, and nitrogen use efficiency of new rice variety under variable nitrogen rates. *Am. J. Plant Sci.* 7, 612–622. doi: 10.4236/ajps.2016.73054

Hasanuzzaman, M., Nahar, K., Roy, T. S., Rahman, M. L., Hossain, M. Z., and Ahmed, J. U. (2009). Tiller dynamics and dry matter production of transplanted rice as affected by plant spacing and number of seedling per hill. *Acad. J. Plant Sci.* 2, 162–168.

Hou, W., Tränkner, M., Lu, J., Yan, J., Huang, S., Ren, T., et al. (2020). Diagnosis of nitrogen nutrition in Rice leaves influenced by potassium levels. *Front. Plant Sci.* 11:165. doi: 10.3389/fpls.2020.00165

International Food Policy Research Institute (2020). Ghana's rice market. MoFA-IFPRI market brief 2. Washington, DC: International Food Policy Research Institute (IFPRI).

Junfei, G., Zhenxiang, Z., Zhikang, L., Ying, C., Zhiqin, W., and Hao, Z. (2017). Rice (*Oryza sativa* L.) with reduced chlorophyll content exhibit higher photosynthetic rate and efficiency, improved canopy light distribution, and greater yields than normally pigmented plants. *Field Crop Res.* 200, 58–70. doi: 10.1016/j.fcr.2016.10.008

Kashkool, H. R., Radhi, N. J., and Hassan, W. F. (2020). Effect of plant spacing system and soil amendment in growth and yield of rice plants (*Oryza sativa* L.). *Plant Arch.* 20, 2710–2714.

Khan, H. I. (2018). Appraisal of biofertilizers in rice: to supplement inorganic chemical fertilizer. *Rice Sci.* 25, 357–362. doi: 10.1016/j.rsci.2018.10.006

Maftukhah, R., Suli, A. S., Annisa, H. N., and Nugroho, B. D. A. (2019). Leaf area index development of local rice varieties as a response to different irrigation management. *IOP Conf. Ser. Earth Environ. Sci.* 355:012006. doi: 10.1088/1755-1315/355/1/012006

Mahajan, G., Timsina, J., Jhanji, S., Sekhon, N. K., and Kuldeep-Singh (2012). Cultivar response, dry-matter partitioning, and nitrogen-use efficiency in dry direct-seeded rice in Northwest India. *J. Crop Improv.* 26, 767–790. doi: 10.1080/15427528.2012.686473

Ministry of Food and Agriculture 2019 Agriculture in Ghana. Facts and figures, issued by Ministry of Food and Agriculture (MoFA), statistics, research and information directorate (SRID) October 2019

Muthayya, M., Sugimoto, J. D., Montgomery, S., and Maberly, G. F. (2014). An overview of global rice production, supply, trade, and consumption. *Ann. N. Y. Acad. Sci.* 1324, 7–14. doi: 10.1111/nyas.12540

Ragasa, C., Dankyi, A., Acheampong, P., Wiredu, A. N., Chapoto, A., Asamoah, M., et al. (2013). Patterns of adoption of improved rice technologies in Ghana. International Food Policy Research Institute. Working Paper 35. Ghana Strategy Support Program.

Rahman, M. M., and Connor, J. D. (2022). The effect of high-yielding variety on rice yield, farm income and household nutrition: evidence from rural Bangladesh. *Agric Food Secur* 11:35. doi: 10.1186/s40066-022-00365-6

Savannah Agricultural Research Institute (2022). 2021–2022 weather data. Tamale, Ghana: SARI-Nyankpala.

Sen, A., Sarkar, M. A. R., Begum, M., Zaman, F., and Ray, S. (2014). Effect of spacing and weed management on the growth of BRRI dhan56. *International Journal of Experimental Agriculture*, 4, 20–29.

Tadesse, Z., Tadesse, T., and Assega, H. (2019). Effect of seed rate and row spacing on yield and yield components of rain-fed lowland rice (*Oryza sativa* L.) variety. Ethiopian Institute of Agricultural Research (EIAR), Fogera National Rice Research and training center. Fogera, Ethiopia. *Int. J. Res. Stud. Agric. Sci.* 5, 18–26. doi: 10.20431/2454-6224.0512003

Ulzen, O. O., Buri, M. M., Sekyi-Annan, E., Devkota, K. P., Dossou-Yovo, E. R., Ayamba, B. E., et al. (2023). Yield potentials of improved rice varieties for increased lowland rice production within the Mankran watershed in Ghana. *Plant Prod. Sci.* 26, 17–27. doi: 10.1080/1343943X.2022.2156893

United States Department of Agriculture. 2023. Economic research service. Techpoint Africa.

Venkatesan, S., Nandhini, D. U., Senthilraja, K., Prabha, B., Jidhu, V. S., Eevera, T., et al. (2023). Traditional cultivars influence on physical and engineering properties of rice from the Cauvery deltaic region of Tamil Nadu. *Appl. Sci.* 13:5705. doi: 10.3390/app13095705

Yu, F., Feng, S., Du, W., Wang, D., Guo, Z., Xing, S., et al. (2020). A study of nitrogen deficiency inversion in rice leaves based on the hyperspectral reflectance differential. *Frontiers in Plant Science*, 11:573272.

Yuan, S., Saito, K., and Van Oort, P. A. J. (2024). Intensifying rice production to reduce imports and land conversion in Africa. *Nat. Commun.* 15:835. doi: 10.1038/s41467-024-44950-8

Zhang, Y., Li, Y., and Li, Y. (2019). Changes in soil cation exchange capacity (CEC) pre and post-six farming practice mean. *Res. Gate*. doi: 10.13140/RG.2.2.32677.70816

Zheng, R. R., Wu, Y., and Xia, Y. P. (2012). Chlorocholine chloride and paclobutrazol treatments promote carbohydrate accumulation in bulbs of *Lilium* oriental hybrids 'Sorbonne'. *J Zhejiang Univ Sci B* 13, 136–144. doi: 10.1631/jzus.B1000425

Zhu, X., Chen, J., and Huang, S. (2022). Manure amendment can reduce rice yield loss under extreme temperatures. *Commun. Earth Environ.* 3:147. doi: 10.1038/s43247-022-00481-y

Ziblim, I. A., Okai-Anti, D., and Asmah, E. A. (2012). Productivity index rating of some soils in the Tolon/Kumbungu district of the Northern region of Ghana. *J Soil Sci Environ Manage*, 3:154–63.