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Increasing lowland rice yields of smallholder farmers through the adoption of good agricultural practices in the forest agro-ecological zone of Ghana

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ABSTRACT

Rice is an important food crop in Ghana. However, its production has constantly been below 40% of the demand, and most of the requirements meet from imports. Such low production level is largely attributed to farmers' sub-optimal crop and water management practices. As an effort toward sustainably improving rice yield, three-season on-farm participatory experiments were conducted within the Biem watershed in Ghana to determine the potential of good agricultural practices (GAP) for closing the rice yield gap with agronomic and economic sustainability. Good agricultural practices were compared with 23 farmers' traditional practices on lowland rice growth and yield, profitability, and nutrient use efficiency. The effect of alternate wetting and drying (AWD) with GAP on grain yield of rice was also determined. Rice yield was on average 28% higher under GAP than farmers' practices (FP). Alternate wetting and drying did not have significant effect on rice yield when compared to continuous flooding. However, when GAP was combined with AWD, rice yield was 13% higher than under FP. Furthermore, the results of the study indicate that major gains in nitrogen use efficiency (+1.48 kg grain kg^{-1} N; +2.4%), and net profit (+694.35 USD ha^{-1}; +59%) were achievable through the adoption of GAP. There is therefore, a high potential to close the lowland rice yield gap and achieve rice self-sufficiency through the adoption of GAP in the lowlands of the Inland valley of Ghana and similar rice production regions of West Africa.

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1. Introduction

Rice (*Oryza sativa* L.) is an important staple in most parts of West Africa (Arouna et al., 2020) and the second most important cereal crop after maize in Ghana (Buri et al., 2015). Rice consumption per capita in West Africa has thus shown an uptrend over the past six decades (Arouna et al., 2020). In Ghana, rice consumption was 45 kg per capita in 2020 (NAFCO, 2022). Despite these, local production meets less than 40% of the consumption requirement of the country (Alhassan et al., 2015) leading to large annual imports of over USD 400 million. Since 2019, governments in sub-Saharan Africa (SSA) have collaborated with international partners such as Coalition for African Rice Development (CARD) (a Japanese initiative) to implement several interventions to increase production from 28 million to 56 million tons in 10 years (2030) (Arouna et al., 2021a). Efforts are still underway to achieve this new target as reports show that the contribution of CARD to paddy rice production after the first phase (2008–2018) was 10.2 million tons, equivalent to 74% of the 14 million ton target set. Despite the increase in rice production from 14 million to 28 million tons in 2018, its level of estimated importation continues to rise in SSA (Arouna et al., 2021a). For instance, though rice production in Ghana increased from 301,000 tons in 2008 to 733,000 tons in 2018, the level of estimated rice import was 700,000 tons in 2019 (Ouédraogo et al., 2021). In 2022–2023, Ghana's rice imports have been projected to increase to 1 million ton, an increase of about 11% over the current year (Mwangi, 2022; Nathan & Bonnie, 2022). Currently, the average grain yield of rice is only 2.8 t ha^{-1}, while the attainable yield is over 6.5 t ha^{-1} (Buri et al., 2015).

Reasons for low rice yields in the country have been attributed to climate-socio-economic conditions, inherent poor soils, and sub-optimal soil management practices (Buri et al., 2015; Nakamura et al., 2016), which have been aggravated by the COVID-19 pandemic-induced constraints in recent times (Ankrah et al., 2021). Some of these sub-optimal soil management constraints

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include but not limited to poor land preparation, low fertilizer use, ineffective fertilizer management, inappropriate water management, and the impact of climate change (Buri et al., 2015).

The country has a great potential for sustainable intensification of rice-based systems in inland valleys (IVs) to enhance rice self-sufficiency, especially in the high rainforest and semi-deciduous forest agro-ecological zones because of the comparative advantage of better rainfall distribution and water availability throughout the year (Buri & Issaka, 2019). In the quest to increase rice production in Ghana and reduce its importation to the country, some policy interventions, among which are promoting good agricultural practices (GAP), including alternate wet-dry (AWD) irrigation aimed at addressing some of the production constraints, have been proposed (Ouédraogo et al., 2021).

Branding of GAPs in rice production has been widely explored in Thailand, Vietnam, Indonesia, Sri Lanka, Myanmar, and other Southeast Asian countries (Devkota et al., 2019; Mkanthama, 2013). A review conducted by Senthilkumar (2022) also showed that the majority of the studies on GAPs were from SSA countries, notably Benin, Cote d'Ivoire, Nigeria, and Senegal. However, not much research and policy on bundling and branding of such integrated agricultural practices has been carried out in Ghana for closing the rice yield gap. GAP is an integrated crop production package comprising bundled practices including major determinants of yield such as land clearing and preparation, land levelling, bunding and puddling, seedling and crop establishment, choice of variety and seeds, thinning/gap filling, fertilizer management, weed and water management, crop protection, and harvesting (Ouédraogo et al., 2021). If adoption of a full production package is difficult, in this context, a few key 'MUST DO' packages can be defined and bundled and encourage farmers to adopt. The adoption of GAP is a good intervention for increasing rice grain yields in any rice growing environment (Senthilkumar, 2022), where it increased rice yield by 28% in Nepal Terai (Devkota et al., 2021), and by 1.0 to 2.7 t ha^{-1} in Tanzania (Senthilkumar et al., 2018). Compared to farmers' practice (FP), GAP farmers had a higher panicle number and improved harvest index mainly due to timely weed control (Senthilkumar et al., 2018). In SSA, bundling of four major practices, i.e. use of improved cultivars, good crop establishment by proper levelling, bunding and puddling, increased fertilizer rate, and nutrients management (Arouna et al., 2021b).

In the face of climate change with its impact on irrigation water availability for crop production, it is important to explore water-saving technologies for rice production such as alternate wetting and drying (AWD) irrigation (Chapagain et al., 2011; Devkota et al., 2013; Dossou-Yovo et al., 2022; Lampayan et al., 2015; Sekyi-Annan et al., 2018). AWD is a water management practice that does not prescribe to flood the field continuously but allows it to dry periodically (i.e. water level declines to a specific threshold before the field is re-flooded) (de Vries et al., 2010; Devkota, 2011; Sibayan et al., 2018; Sudhir-Yadav et al., 2014). Previous studies on AWD in Africa showed significant water saving of 20–50%, but inconsistent effects on rice yield due to factors such as timing and severity of irrigation and weed management practices (de Vries et al., 2010; Djaman et al., 2017; Dossou-Yovo & Saito, 2021; Krupnik et al., 2012a, 2012b). However, little is known about the combined effects of GAP including AWD for improving rice yield and nutrient use efficiencies in the rainfed lowland of inland valleys of Ghana and SSA. Thus, this study aimed to determine the effect of sole GAP, and GAP including AWD on rice growth and yield, profitability, and sustainable rice production indicators such as nutrient use efficiency in rainfed lowland rice in Ghana.

2. Materials and methods

2.1. Experimental site

The study was conducted during the 2019 dry season and repeated in the 2020 wet season and 2020 dry seasons at Biemso No.1 (latitude 06° 52' 53.2" N and longitude 01° 50' 47.3"W) within the Biem watershed in the Ashanti region of Ghana. On-farm experimental sites were located within the deciduous rainforest agro-ecological zone, which is characterized by a bimodal rainfall pattern. The wet season occurs from March to July with a seasonal rainfall of 1,630 mm, while the dry season is from September to November with seasonal rainfall of 1,250 mm. Yearly maximum annual temperature was in the range of 27.5–37.4°C. The total amount of rainfall received during the 2019 dry, 2020 wet, and 2020 dry cropping seasons of this study were 219.08 mm, 617.21 mm, and 294.42 mm, respectively (Figure 1).

2.2. Soil characterization of the experimental sites

The predominant soil types of the valley bottoms of the Biem watershed are Eutri-Gleyic and Eutri-Gleyic Fluvisol (Buri et al., 2008). The experimental site had predominantly sandy loam and moderately acidic soil with a very low level of total organic carbon and total nitrogen (Table 1). The site was also characterized by low available phosphorus and exchangeable calcium and potassium. Exchangeable magnesium, however, was rated moderate and exchangeable sodium was rated low to moderate. Generally, the fertility status at the experimental site

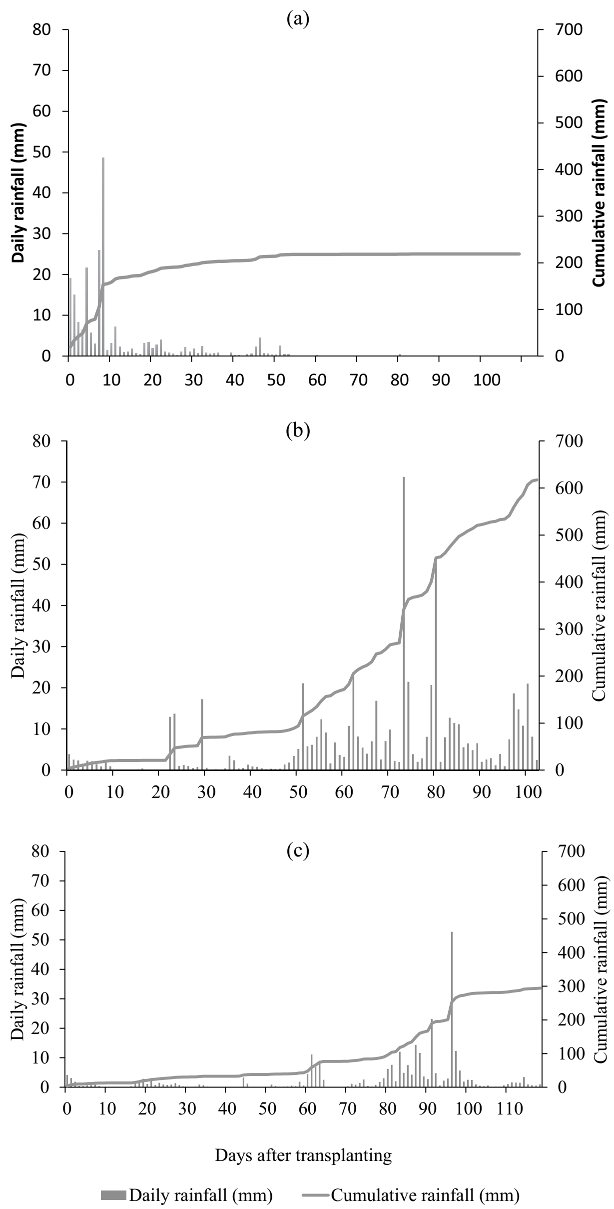

Figure 1. Daily and cumulative rainfall during the crop-growing period in dry season 2019 (a), wet season 2020 (b), and dry season 2020 (c) in the experimental site at Biemso No.1.

Table 1. Soil physicochemical properties at the experimental site before the start of the experiment.

Soil properties	0–20 cm	20–40 cm
Soil physical properties		
Sand (%)	77	77
Silt (%)	9	13
Clay (%)	14	10
Soil textural class	Sandy loam	Sandy loam
Soil chemical properties		
Soil pH (1: 2.5, water)	6.27	6.53
Total soil organic carbon (g kg $^{-1}$)	0.71	0.44
Total nitrogen (g kg $^{-1}$)	0.09	0.05
Available Bray-1 P (mg kg $^{-1}$)	5.40	3.68
Exchangeable bases (cmol$_{(+)}$ kg $^{-1}$)		
Ca^{2+}	3.34	2.80
Mg^{2+}	1.21	1.21
K^{+}	0.05	0.05
Na^{+}	0.25	0.45

was poor with most of the analyzed soil properties lower than the critical values required for crop growth. As categorized by Landon (2014), soil nutrient levels of <0.2% N, <5 mg kg^{-1} Olsen P, <0.15 $cmol_{(+)}$ kg^{-1} K, <1 $cmol_{(+)}$ kg^{-1} Ca, and <1 $cmol_{(+)}$ kg^{-1} Mg for rice production are reported as low.

2.3. Treatments, experimental design, and crop management practices

The treatments comprised paired comparison of integrated GAP with farmers' practices (FP). A total of 23 paired on-farm experiments (8 in 2019 minor, 8 in 2020 major, and 7 in 2020 minor) were conducted. An integrated package of four agronomic practices was considered as GAP in this study: (i) proper land preparation (bunding, puddling, levelling); (ii) the use of healthy seed and seedlings coupled with line transplanting (in order to raise healthy seedlings, seeds were obtained from certified seed producers. A germination test was then conducted, after which seeds were sown in a nursery bed using optimal seed rate. Early plant nutrition involving the use of NPK fertilizer in the nursery bed was practiced. Healthy (vigorous) seedlings based on visual observation were then transplanted to the main rice plots, unlike FP where most farmers practice broadcasting); (iii) adoption of recommended mineral fertilizer rates and timely application; (iv) effective water and weed management (Effective water management means water management through the construction of bunds, irrigation, and drainage canals, levelling for appropriate water control in the rice fields. Effective weed management refers to the combination of herbicide and manual weeding to keep the plots weed free). The FP comprised: (i) broadcasting, transplanting, or both crop establishment methods; (ii) bunding, puddling, and levelling land preparation methods; (iii) farmers' rate and method of mineral fertilizer application; and (iv) continuous flood irrigation. A detailed description of the crop management practices are presented in Table 2. In another set of comparisons, i.e. AWD including GAP vs FP, was compared in three farmers' fields. In the AWD treatment, a 30-cm pipe perforated to a height of 15 cm from the base was installed in the field for monitoring water levels to schedule irrigation (Stuart et al., 2018), whereas continuous flood irrigation was applied in FP.

In both comparisons, plots measuring 10×10 m^2 were demarcated on each farmers' field. In all plots, three-week-old rice seedlings were transplanted at a spacing of 20×20 cm^2 using two seedlings per hill and an aromatic rice variety (AGRA) with a yield potential of over 8.0 t ha^{-1} and a maturity period of 125–130 days was used. Mineral fertilizers used under GAP were NPK 15-20-20 and urea fertilizers. The application rates were 90-60-60 of N-P_2O_5-K_2O kg ha^{-1}, respectively. NPK was applied as basal fertilizer at 300 kg ha^{-1} while urea was applied as top dressing at 100 kg ha^{-1} at panicle initiation. At physiological maturity stage of crop growth, a field survey was conducted to collect demographic information from farmers across the site, and a farmer field day was organized by inviting farmers and stakeholders within the municipality to compare crop performance in the two sets of GAP vs FP evaluation to facilitate farmer learning through an adaptive research approach (Flor et al., 2016; Senthilkumar et al., 2018). The selected respondents comprised 85 farmers including 35 females from the farmers' organizations of the lowlands

Table 2. Description of good agricultural practices and farmers' practices.

Management practice	GAP	FP
Source of seed	Certified seed producers	Seed growers
Crop establishment	Line transplanting with 20 cm x 20 cm spacing	Broadcasting, direct seeding or transplanting with irregular spacing
Bunding	Yes and regular	Yes and/or irregular
Puddling	Yes	Yes
Leveling	Yes	No
Water management	CF and AWD for some plots	CF
Weed management	Manual weeding: ponding the field with water and removing a few water-resistant weeds were manually done	Manual weeding and herbicide
Fertilizer application	Split application of 300 kg ha^{-1} recommended rate of 15:20:20 N:P:K fertilizer at 1st application (basal fertilizer) and 100 kg ha^{-1} of Urea at 2nd application (panicle initiation)	Irregular and insufficient quantities of fertilizer applied as and when available
Quantity of nitrogen fertilizer application	90 kg ha^{-1}	0–90 kg ha^{-1}
Quantity of phosphorus fertilizer application	60 kg ha^{-1}	0–45 kg ha^{-1}
Quantity of potassium fertilizer application	60 kg ha^{-1}	0–45 kg ha^{-1}
Timing of first fertilizer application (Days after transplanting)	5 DAT	14 DAT or seeding
Timing of second fertilizer application (Days after transplanting)	30 DAT	Not applicable

GAP = good agricultural practices; FP = farmer's practice; DAT = days after transplanting; AWD = alternate wet drying; CF = continuous flooding.

and 15 Agricultural Extension Officers from across the study district who were randomly selected to evaluate the GAP as compared to the FP. The farmers selected used the FP in their fields.

In all plots, plant height was measured at 2 weeks intervals. At physiological maturity, rice grain yield and aboveground dry biomass yield were determined from three (3) randomly selected areas of 1 m^2 each located away from the borders of each plot using a square quadrant per treatment per farmer. The crop was harvested manually using a sickle. Harvested panicles were carefully threshed, winnowed, and dried to 14% moisture content. Rice grains were then weighed using an electronic balance, and paddy rice yield per hectare was reported at 14% moisture content. From all plots, rice aboveground dry biomass samples were oven dried at 65°C for 48 h to have the dry aboveground biomass, which was used to extrapolate dry aboveground biomass per hectare. The weight of 1000-grains was determined by counting filled grains and drying them in the oven until reaching constant weight.

2.4. Calculation of sustainable rice production indicators

The grain yield, nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), potassium use efficiency (KUE), and profitability indicators of sustainable rice production were computed. To compute the nutrient use efficiencies (NUEs), P and K fertilizers were derived to elemental form by multiplying the amount of P_2O_5 and K_2O for each fertilizer applied by a factor of 0.44 and 0.83, respectively. The NUE, PUE, and KUE were then estimated by dividing the total grain yield harvested by the elemental N, P, and K values, and the efficiencies expressed in kg grain kg^{-1} elemental N, P, or K. Similarly, economic analysis was carried out to assess the profitability of GAP compared to FP by calculating net profit and benefit-cost (B:C) ratio. Net profit was computed by subtracting total production cost (TPC; total cost except for fixed cost) from the total revenue from grain. B:C ratio was computed using equation 1.

$$B : C \text{ ratio} = \frac{B}{TPC}. \tag{1}$$

Where B = Net benefit and TPC = Total production cost. B:C ratio of more than 1.5 is considered economically viable (Sekyi-Annan et al., 2021)

The total production cost (TPC) comprised the cost of all operations for rice production from land preparation to harvesting. Costs incurred on nursery management, land preparation (ploughing, bunding, puddling, and levelling), seeds, herbicide, netting rice, PVC pipes installed for watering, harvesting, threshing, drying, NPK fertilizer, urea, and labour costs for all operations and input applications were recorded. Total income was computed from the revenue accrued from the milled rice. The price of each unit of inputs used and the price of milled grain were collected from the local market assessment. The milling recovery considered was 70% of unmilled rice (Sekyi-Annan et al., 2021).

2.5. Statistical analysis

The field data were subjected to analysis of variance (ANOVA) using Statistix 10 software. A parametric student's paired t-test analysis was also carried out to compare means using a 5% level of significance. Before conducting the ANOVA, the normality of the data distribution for each season was examined for yield using Shapiro–Wilk test. Conformity of the homogeneity of variance was also performed using Bartlett's test (Snedecor & Cochran, 2021). The survey data were subjected to descriptive statistics such as frequencies and percentages and statistically analyzed using Statistical Package for Social Sciences (SPSS Statistics Version 20). Furthermore, to compare the trade-off among the performance indicators (grain yield, NUE, PUE, KUE, and profitability) and input use between GAP and FP, radar charts with the values on each spoke normalized to 0–1 scale was used.

3. Results

3.1. Characterization of rice management practices

General characteristics of rice farmers and production practices such as farm sizes, seed sources, planting methods, land preparation, and weed control used by farmers in Biem watershed have been presented in Table 3. About 33% of the farmers cultivated rice each year in 3–4 acres area and about 83% of the farmers obtained rice seeds from seed growers. About 50% of the farmers produced rice raising nursery and later transplanted (transplanting), 33% of farmers broadcasted rice seeds (by direct seeding method) and 17% practiced both direct seeding and transplanting. For land preparation, 17% of the farmers practiced only bunding, 17% practiced both bunding and puddling, and 17% practiced both puddling and levelling. Even though all the farmers (100%) applied fertilizer to their crops, the

Table 3. Farm sizes, seed sources, planting methods, land preparation, and weed control methods used by farmers for rice cultivation in Biem watershed in Ghana.

Variables	Percentage (%)
Total land area cultivated to rice	
<1 acre	33.3
1–2 acres	16.7
3–4 acres	33.3
5–6 acres	16.7
Source of rice seeds	
Seed growers	83.3
Research Institutes	16.7
Crop establishment method	
Broadcasting (direct seeding)	33.3
Transplanting	50.0
Both	16.7
Land preparation method	
Bunding	16.7
Bunding and puddling	16.7
Puddling and levelling	16.7
Bunding, puddling and leveling	50.0
Fertilizer application on farmers' fields	
Yes	100.0
No	0
Weed management method used by farmers	
Herbicide application only	33.3
Manual weeding and herbicide application	66.7

application rate was inadequate and was applied as and when available. The common weed management methods adopted by the majority of the farmers (67%) were manual weeding and herbicide application.

3.2. *Effect of crop management practices on plant height*

Figure 2 shows the effects of crop management practices on plant height measured in 2019 dry season. Throughout the cropping season in all growth stages, plant height was significantly higher ($p \leq 0.05$) under GAP than under FP.

3.3. *Effect of crop management practices on yield and yield attributes of rice*

Results of the effect of crop management practices on yield and yield attributes such as aboveground dry biomass, number of tillers, and 1000 grain weight for the three cropping periods are presented in Table 4. The results show that the grain yield of rice was significantly higher under GAP than under FP in all three seasons. Grain yield under GAP ranged from 5.41 to 5.89 t ha^{-1}, as against 4.15 to 4.84 t ha^{-1} under FP, where GAP had 21 – 42% higher yield than FP. Also, the 1000-grain weight recorded under GAP was generally significantly higher than under FP. Also, despite non-significance, the total aboveground

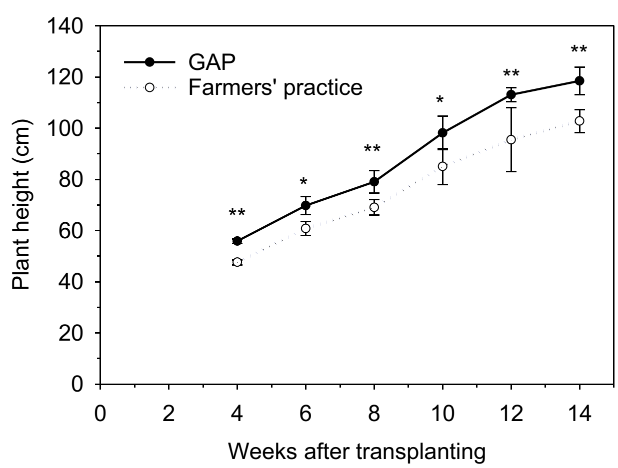

Figure 2. Effects of crop management practices on plant height in the 2019 dry season. Horizontal bars represent standard error. GAP = good agricultural practices, * significant at $p = 0.05$, and ** significant at $p = 0.001$.

Table 4. Effect of crop management practices on yield and yield parameters of rice for three cropping seasons in Biem No. 1, Ghana.

	Management practice		
	Farmers' practice (FP)	Good agricultural practice (GAP)	Paired t-test (p at < 0.05)
2019 dry season			
Aboveground dry biomass (t ha^{-1})	14.64 ± 3.25	15.71 ± 2.31	0.460^{ns}
Number of tillers m^{-2}	269.19 ± 42.11	222.88 ± 23.95	0.017*
1000 grain weight (g)	23.41 ± 1.60	27.90 ± 2.93	0.002*
Grain yield (t ha^{-1})	4.84 ± 0.35	5.87 ± 0.97	0.019*
2020 wet season			
Aboveground dry biomass (t ha^{-1})	9.44 ± 0.49	10.98 ± 1.89	0.057^{ns}
Number of tillers m^{-2}	172.58 ± 25.89	180.4 ± 27.23	0.619^{ns}
1000 grain weight (g)	25.94 ± 1.73	27.75 ± 1.61	0.067^{ns}
Grain yield (t ha^{-1})	4.42 ± 0.57	5.41 ± 0.94	0.043*
2020 dry season			
Aboveground dry biomass (t ha^{-1})	10.42 ± 2.15	11.82 ± 2.74	0.29^{ns}
Number of tillers m^{-2}	149.14 ± 34.36	177.52 ± 35.23	<0.001*
1000 grain weight (g)	24.82 ± 1.91	25.87 ± 1.39	0.005*
Grain yield (t ha^{-1})	4.15 ± 0.86	5.89 ± 1.15	<0.001*

Values presented are means ± standard deviation, GAP good agricultural practices; * represents statistical significance at 5% level of probability; ns: not significant at $p > 0.05$.

biomass was higher (by 1.33 t ha^{-1}; 7–16%) under GAP compared to FP. In the 2019 and 2020 dry seasons, the tiller number was significantly higher under GAP than the FP. However, no significant difference in the tiller number per m^2 was reported between GAP and FP in the 2020 wet season.

3.4. *Effect of crop management practices on nutrient use efficiency of rice*

Results of the effect of crop management practices on NUEs (NUE, PUE, and KUE) of rice are presented in Table 5. It was observed that apart from the 2020 minor season, crop management practices did not significantly ($p > 0.05$) influence the NUEs of rice. In this study, the NUE, PUE, and KUE under FPs ranged from 58 ± 7 to 69 ± 48 kg grain kg^{-1} N, 298 ± 104 to 332 ± 191 kg grain kg^{-1} P, and 158 ± 55 to 176 ± 101 kg grain kg^{-1} K, respectively, while that of the GAP ranged from 59 ± 10 to 65 ± 13 kg grain kg^{-1} N, 205 ± 36 to 223 ± 43 kg grain kg^{-1} P and 109 ± 19 to 118 ± 23 kg grain kg^{-1} K, respectively.

3.5. *Effect of different water management regimes on rice grain yield*

Two water management regimes viz. alternate wet-dry (AWD) irrigation and continuous flooding (CF) with GAP were compared on lowland rice production. Results showed that the yield under CF-GAP was higher (6.08 t ha^{-1}) than AWD-GAP (5.51 t ha^{-1}), with the lowest yield under farmers' method (4.88 t ha^{-1}) of water and crop management (Figure 3). Rice produced under CF using GAP produced 25% higher grain yield than the FP, with the expense of more than double amount of irrigation water (amount of water used for irrigation not measured). Also, rice yield under AWD-GAP was higher by 13% than under FP.

Table 5. Effect of crop management practices on nutrient use efficiency of rice for three cropping seasons.

	Management practices		
	Farmers' practice (FP)	Good agricultural practice (GAP)	Paired t-test (p at < 0.05)
2019 dry season			
Nitrogen use efficiency (kg grain kg^{-1} N)	57.64 ± 7.03	64.55 ± 10.61	0.271^{ns}
Phosphorus use efficiency (kg grain kg^{-1} P)	304.60 ± 108.40	222.50 ± 36.58	0.228^{ns}
Potassium use efficiency (kg grain kg^{-1} K)	161.50 ± 57.46	117.90 ± 19.39	0.228^{ns}
2020 wet season			
Nitrogen use efficiency (kg grain kg^{-1} N)	58.09 ± 28.41	59.48 ± 10.38	0.921^{ns}
Phosphorus use efficiency (kg grain kg^{-1} P)	297.70 ± 103.73	205.00 ± 35.78	0.117^{ns}
Potassium use efficiency (kg grain kg^{-1} K)	157.80 ± 54.99	108.70 ± 18.97	0.117^{ns}
2020 dry season			
Nitrogen use efficiency (kg grain kg^{-1} N)	68.62 ± 48.42	64.76 ± 12.60	0.644^{ns}
Phosphorus use efficiency (kg grain kg^{-1} P)	331.80 ± 191.20	223.20 ± 43.40	0.002*
Potassium use efficiency (kg grain kg^{-1} K)	175.90 ± 101.35	118.30 ± 23.03	0.002*

Values presented are means ± standard deviation; * represents statistical significance at 5% level of probability; ns: not significant at $p > 0.05$.

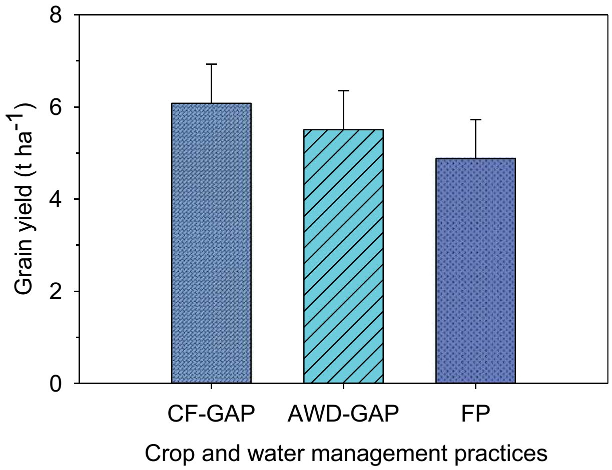

Figure 3. Grain yield of rice under three water and crop management practices in 2019 dry season. Error bars denote standard error. CF-GAP = continuous flood irrigation with good agricultural practices; AWD-GAP = alternate wet and dry irrigation with good agricultural practices; FP = farmers' practice of irrigation and crop management.

3.6. Economic analysis

3.6.1. Cost of production inputs

The application of the production inputs (except irrigation as it was not measured), machine and labour, was higher under GAP (2777 USD ha^{-1}) than under FP (2497 USD ha^{-1}) by 279 USD ha^{-1} (11%) (Figure 4A). The lower cost under FP was mainly due to lower cost incurred in land preparation, lower cost for harvesting and threshing and low rate of NPK fertilizer application. In both methods, the highest production cost was mainly attributed to the excessively higher cost of land preparation and labour (Figure 4B, C).

3.6.2. Total cost of production, net profit, and benefit: cost ratio

Table 6 shows that about 28% higher total average revenue was accrued from milled rice per hectare harvested from the GAP practices (USD 4693) compared to FP (USD 3667). Taking into account the average total variable production cost, practicing GAP resulted in an average gross margin (net profit) of USD 1916 ha^{-1}, which was 64% higher than what was obtained under FP (USD 1170 ha^{-1}) (Table 6). Despite higher production costs, the B:C ratio is higher in GAP than under FP by 47%.

3.7. Trade-off between input use and performance indicators under two crop management practices

A summary of the production inputs used for the three-season study showed that FP has the lowest cost of land preparation, irrigation water, shelling/threshing, and NPK fertilizer (Figure 5). Regarding the five indicators compared, GAP had the highest grain yield, net profit, and NUE. The lower PUE and KUE in GAP were due to the lower amount of P and K fertilizer application in FP.

4. Discussion

4.1. Effect of crop management practices on growth parameters

The significantly higher ($p \leq 0.05$) plant height under GAP than under FP shows the crop was not under water and fertilizer stress. The adoption of recommended mineral fertilizer application rates and timely application in GAP produced taller plants. Mineral fertilizers are major contributors to crop growth and total dry matter production (Essel et al., 2020; Fageria et al., 2014). Application of recommended rate of mineral fertilizers provided adequate nutrients for optimum crop growth resulting in taller plants. This finding is consistent with Fashina et al. (2002) that the availability of adequate nutrients from mineral fertilizers results in improved cell activities, enhanced cell multiplication, and enlargement and luxuriant plant growth.

4.2. Effect of crop management practices on rice yield and yield attributes

Grain yield under FP was significantly ($p \leq 0.05$) lower than under GAP but was higher than the national average yield (2.9 t ha^{-1}) (FAOSTAT, 2023) and the reported yield in previous studies in sub-Saharan Africa (SSA), for example, 3.9 t ha^{-1} in Mauritania (Haefele et al., 2001) and 4.8 t ha^{-1} in Benin (Tanaka et al., 2013). Also, the

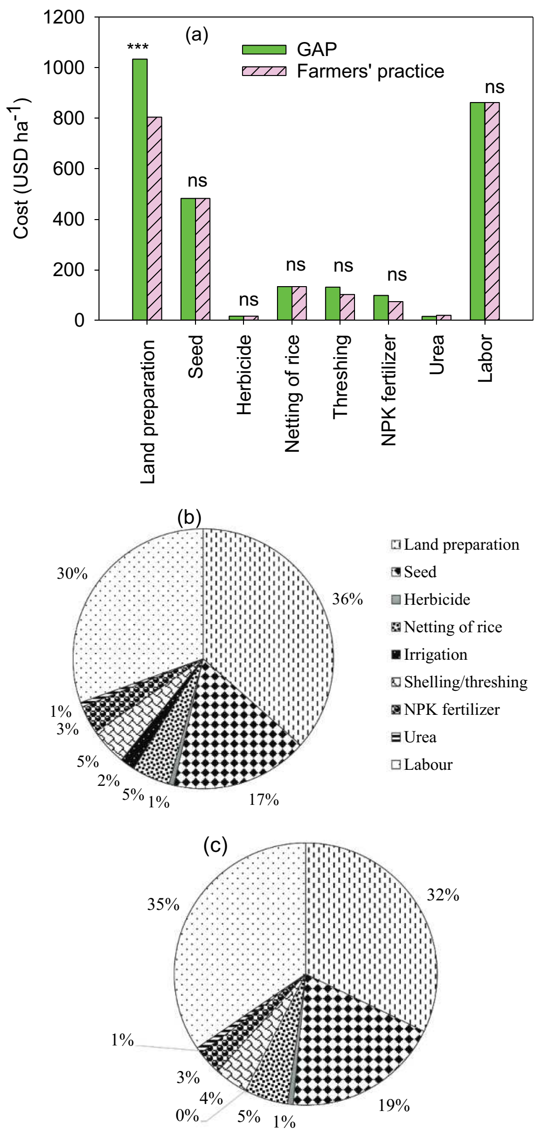

Figure 4. Cost of rice production for individual operations (USD ha^{-1}) for GAP and farmers' practices (A), percentage share of production cost in GAP (B), and percentage share of production cost among different input items in farmers practice (C) at Biemso No.1.

grain yields recorded in this study are within the 1.1–5.2 t ha^{-1} and 1.1–5.2 t ha^{-1} range for irrigated lowland and rainfed lowland rice, respectively, reported by Senthilkumar (2022). From the survey of 255 households in lowlands and irrigated upland in various villages of Ghana, Arouna et al. (2021b) reported an average yield of 1.38 t ha^{-1} with top 10th farmers yield of 3.2 t ha^{-1}. The relatively higher grain yields recorded under FP in our study could be attributed to the partial GAP practiced by farmers (e.g. partial bunding (i.e. short irregular bunds, which easily break down when there are heavy rains) to control water, ploughing, and use of improved seed) and adequate rainfall received by the crop during the cropping period. According to Nakamura et al (2012, 2013, 2016), low inherent soil fertility, particularly in the lowlands, has been identified as a major factor limiting rice yields in SSA; a similar situation observed in this study where the initial soil physicochemical properties (Table 2) were below the critical levels of nutrients required for rice production. The problem is even compounded as resource-poor farmers are not able to purchase and apply fertilizers at the recommended rate due to very limited accessibility and relatively high cost (Vlek et al., 2017). This is evidenced by the fact that even though 100% of the farmers at the study site applied fertilizers to their rice crop (Table 3), the quantity applied

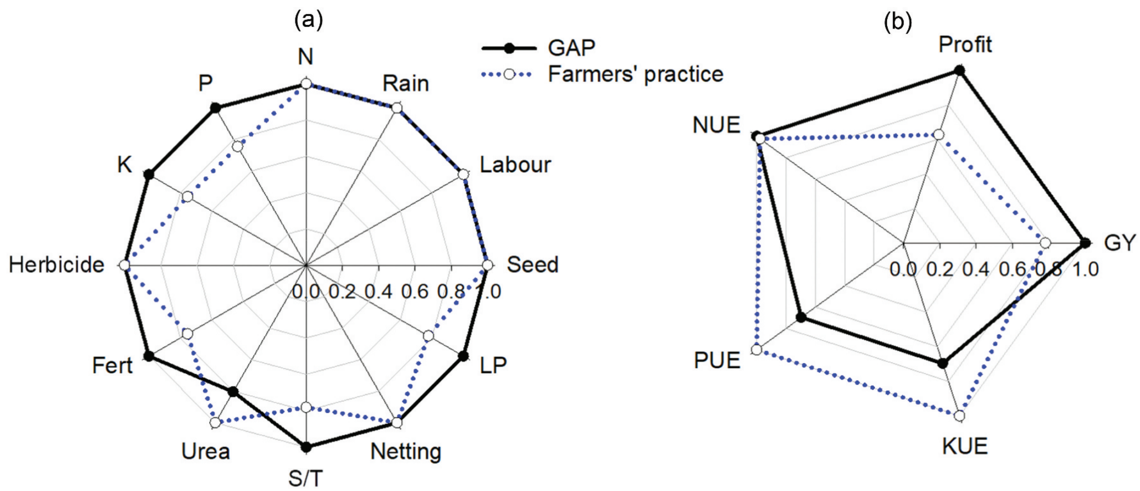

Figure 5. Comparison of production inputs (a) and sustainable rice production indicators (b) for rice production under packages of integrated good agricultural practice (GAP) and farmers practice (FP) in Biemso No. 1. Data averaged across three cropping seasons. The symbols and units used are: Seed = cost of seed input per ha (USD); labour = labour input cost for harvesting, threshing, winnowing, milling, bagging, and fertilizer and herbicide application (USD ha^{-1}); rain = rainfall water (mm $season^{-1}$); N = nitrogen fertilizer input (elemental N, kg ha^{-1}); P = phosphorus fertilizer input (elemental P, kg ha^{-1}); K = potassium fertilizer input (elemental K, kg ha^{-1}); herbicide = input cost of herbicide per ha (USD); Fert = input cost of NPK fertilizer per ha (USD); urea = input cost of urea per ha (USD); S/T = input cost of shelling/threshing rice (USD); netting = input cost of netting rice per ha (USD); LP = input cost of land preparation per ha for bunding, ploughing and levelling (USD); GY = grain yield (kg ha^{-1}); profit = net profit from rice (USD ha^{-1}); NUE = nitrogen use efficiency (kg grain kg^{-1} fertilizer N); PUE = phosphorus use efficiency (kg grain kg^{-1} fertilizer P); KUE = potassium use efficiency (kg grain kg^{-1} fertilizer K). NB: The 0–1 scale used in the figure is normalized values. For example, in Figure 5(B), the higher the value, the greater the sustainability indicator between GAP and FP. Thus, on average, GAP recorded higher grain yield and profit with normalized values of 1.0 and 1.0, respectively, compared with FP which had normalized values of 0.8 and 0.6 for grain yield and profit, respectively.

Table 6. Total revenue, production cost, net benefit, and benefit: cost ratio of rice production under two crop management practices at Biemso No.1.

	Cost of management practices (USD)	
	Good agricultural practice (GAP)	Farmers' practice (FP)
Revenue from milled rice per hectare	4693	3667
Total revenue	4693	3667
Total production cost (TPC)	2777	2497
Net profit	1916	1170
Net benefit: cost ratio (B:C ratio)	0.69	0.46

Average grain yield of rice for the three seasons at the experimental sites from GAP plots = 5.72 t ha^{-1} and farmer practice = plots = 4.47 t ha^{-1}; Quantity of milled rice = 70% of un-milled rice; Price of 100 kg of milled rice = USD 117.20

wasinadequate but fertilizer was applied at times it was obtained irrespective of crop demand and growth stage. The impact of fertilizer use in crop production is large in regions of low soil fertility, particularly characterized by very low levels of nitrogen (N), phosphorus (P) nutrients, and organic matter. Among SSA countries, mineral fertilizer application in Ghana is among the lowest (Buri et al., 2010; Nakamura et al., 2016). The adoption of recommended mineral fertilizer rates and timely application is a very essential component of GAP. However, the application of fertilizers in SSA including Ghana by resource-poor farmers is only one-sixth of that in Asia (Nakamura et al., 2016).

Higher yield by 21–42% under GAP compared to FPs was mainly attributed to the integrated bundled practices of land preparation, which involved puddling and levelling; precision line transplanting; optimal fertilizer application, and good weed control. In a similar study, Becker and Johnson (2001) reported a significant yield increase of 40% in Cote d'Ivoire due to bunding, concluding that this practice is noted for weed control. Obalum et al. (2012) reported that apart from assisting in weed control and facilitating transplanting operations, the major agronomic benefits of puddling include reduction in water infiltration and percolation rates in a paddy field, thus increasing yield. Furthermore, puddling aims at modifying the soil structure under a saturated field condition, thereby reducing the soil's hydraulic conductivity to enhance water retention. Normally, macropores are reduced, but the total porosity of puddled soils is either enhanced or unaffected, or slightly decreased due to an increase in micropores (Obalum et al., 2012). It was generally observed that the 1000-grain weight of rice recorded in this study (23.41–27.90 g) is higher than that earlier reported by Buri et al. (2015). Grain filling is strongly linked to improved crop nutrition (fertilizer applied in correct quantities and at the correct times) under adequate soil moisture supply.

The number of tillers per m^2 was smaller under FP than under GAP in the 2020 wet and dry cropping seasons. According to Buri and Issaka (2019), the number of effective tillers produced is a good indicator and a major determinant of yield in rice. Though the average number of tillers per m^2 for rice cultivated under FP (269.19 ± 42.11) was greater than the tiller number under GAP (222.88 ± 23.95) in the 2019 minor season, this did not reflect in higher grain yield under FP. Consistent with this finding, Hasanuzzaman et al. (2009) reported that closer spacing reduced the number of effective tillers and increased tiller mortality, thus lowering the number of panicles and hence lower grain yield.

4.3. Effect of crop management practices on nutrient use efficiency of rice

Nutrient use efficiencies are widely used in crop production systems to measure the ability of a crop plant to acquire and utilize nutrients for their physiological processes and grain yields. Mosier et al. (2004) stated two significant reasons for the efficient use of nutrients: to enhance food production with the same or lower nutrient input and to reduce nutrient outflows into the environment. This study observed that apart from the 2020 minor season, the type of crop management practices did not significantly ($p > 0.05$) influence the nutrient use efficiency of rice. However, generally, NUE, PUE, and KUE recorded under FP were greater than that recorded under GAP. Amgain et al. (2021) reported a similar trend where the SRP performance indicators, NUE, PUE, and KUE recorded higher values under FPs relative to GAP, where adequate nutrients were applied. This is because the yield increases associated with the increase in the fertilizer rates under the recommended fertilizer application may not have increased to the extent where it outweighs the nutrient use efficiency of the farmers' practice. The NUEs are mostly greater when the yield response to nutrients is higher. Also, NUEs are high at low yield levels, as in the case of the farmers' practice, because any small amount of nutrient applied resulted in a large yield response, as reported by Roberts (2008). Furthermore, this suggests that most of the farmers are likely 'mining' the soil of its nutrients due to the lower mineral fertilizer application rates under FP. From the survey results of this study, farmers applied 90-45-45 N-P_2O_5-K_2O kg ha^{-1} relative to the recommended fertilizer application rate of 90-60-60 N-P_2O_5-K_2O kg ha^{-1}, corroborating the findings by Dobermann (2000) that very high NUEs are often associated with soil nutrient mining, where the optimal NUE, PUE, and KUE are 68, 385, and 69 kg grain kg^{-1} elemental N, P, and K, respectively.

4.4. Effect of different water management regimes on rice grain yield

Unlike the adoption of all four components of GAP, different water management regimes did not significantly influence rice grain yield. Grain yield under GAP was higher than the FP, irrespective of the irrigation method (i.e. continuous flooding versus alternate AWD). Similar findings have been reported by Chapagain et al. (2011) where AWD did not cause a significant reduction in rice grain yields compared to those produced under continuous flooding in an experiment conducted in Chiba, Japan, and Devkota (2011) in Khorezm region of Uzbekistan.

The observed grain yields were found to be in the upper range of those reported by García-Bolaños et al. (2011) in Mauritania (0.6–5.7 t ha^{-1}) and by Poussin et al. (2015) in the Upper Volta basin (0.7–7.5 t ha^{-1}). The highest average grain yield recorded under the GAP plots with continuous flooding was largely due to the good agricultural practice employed during the growing period. This attests to an earlier farmer survey by Senthilkumar et al. (2018), who reported that farmers appreciated the practice of GAP involving land clearing, tillage, bunding, the use of certified seeds, adopting a uniform plant spacing, thinning and gap filling, and application of mineral fertilizers, as according to the farmers, most of these practices were easy to carry out; however, 39% of the farmers surveyed pointed out that levelling was a difficult practice, with 20% highlighting that tilling, bunding, row planting, and adopting a uniform plant spacing was difficult to implement. The use of healthy seeds and seedlings coupled with row transplanting under good land preparation (bunding, puddling, levelling), and the adoption of recommended mineral fertilizer rates and timely application, good weed management, and effective water management are critical for effective crop growth and yields.

4.5. Profitability analysis

Higher profitability is achieved under GAP than under FP (Anwar et al., 2021; Devkota et al., 2021; Stuart et al., 2017, 2018). Good agricultural practices in rice are known to offer transformative gains in yields and profitability (Devkota et al., 2021; Stuart et al., 2017, 2018), and the high profitability often attributed to the use of high-yielding improved and short-duration hybrid rice varieties (Anwar et al., 2021), and adoption of integrated bundled agricultural solutions (Devkota et al., 2019, 2021).

The higher profitability under GAP could be attributed to the average higher rice yield of 5.72 t ha^{-1} for the three-season study, confirming the findings of Devkota et al. (2021), who observed higher profitability after yields exceeded 2.1 t ha^{-1}. This further agrees with Barbieri and Santos (2020) that closing yield gap is a major entry point for increasing profitability and is significantly correlated with yield. It is worth mentioning that, in a similar study by Stuart et al. (2018), the adoption of GAP by rice farmers in the Can Tho province of Vietnam increased profitability by 90% than the conventional farmers' practice. Profitability in rice production can thus be achieved through the adoption of GAP, which encompasses the use of high-yielding varieties, healthy seeds and seedlings, coupled with row transplanting, good land preparation options comprising bunding, puddling, and levelling, use of recommended mineral fertilizer application rates and timely application, as well as effective water and weed management, which improve the sustainability of rice production (Devkota et al., 2021).

4.6. Comparison of sustainability indicator gaps between GAP and farmers' practice

The study results showed a high yield gap (1.25 t ha^{-1}) and a profitability gap of USD 694.35. For Ghana to be self-sufficient in rice production with sustainability, it is important to consider sustainable rice performance indicators. In this study, the economic indicators considered were total variable cost of production, grain yield, and gross margin (net profit), whereas the environmental indicators were NUE, PUE, and KUE. Closing the yield gap could increase productivity (Barbieri & Santos, 2020; Devkota et al., 2020), profitability, and sustainability.

5. Conclusions

Results of this study show that there is a high potential of increasing lowland rice yields (by 1.25 t ha^{-1}) and profits (by 694 USD ha^{-1}) by adopting bundled agricultural solutions or integrated good agricultural practices. Major yield gap determinants for lowland rice production in Biem watershed of Ghana include proper land preparation (i.e. bunding, puddling, and levelling), the use of healthy seed and seedlings coupled with row transplanting, adoption of recommended mineral fertilizer rates and timely application, good weed management, and alternate wet-and-dry irrigation method. Lowland rice cultivation is currently the major rice production system in the country, and the adoption of these improved technologies (as a bundle) is very critical and timely, as they will contribute to increased lowland rice yields, enhanced local production, reduced import, and boost self-sufficiency. We, therefore, recommend that researchers, extensionists, and farmers' training and capacity building on the adoption of GAP as a package and not in bits and pieces be intensified under the Ministry of Food and Agriculture (MoFA) and the various Departments of Agriculture under the District/Municipal/Metropolitan Assemblies of the Ministry of Local government. Further farmer capacity development will lead to a better understanding and appreciation of GAP to achieve self-sufficiency in rice production.

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Disclosure statement

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