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Agronomic and economic assessment of input bundle of soybean in moderately acidic Savanna soils of Ghana

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Abstract

Integrated input for crop productivity can increase food security among smallholder farming systems. The study evaluated agronomic and economic response of four input bundle treatments on five soybean [*Glycine max* (L.) Merr.] cultivars conducted under rain-fed conditions over a 4-yr period in Ghana. Experiments were a randomized complete block in factorial arrangement with four replications. Input bundles were NoduMax inoculant (I), phosphorus application (P), inoculated seed followed by phosphorus application (I+P), and certified seed as control treatment. Cultivars were Afayak, Jenguma, Quarshie, Songda, and Suong-Pungun. Soils were moderately acidic (5.7 pH) with macro- and micronutrient deficiencies. Grain yield, mean gross margin (MGM), and benefit–cost ratio (BCR) for input bundles were in descending order I+P bundle > P bundle > I bundle > control. Yield was greater in I+P bundle over I bundle, P bundle, and control by 27, 16, and 65%, respectively. Grain yield, MGM, and BCR in descending cultivar order were Afayak > Jenguma > Suong–Pungun > Quarshie > Songda. Grain yield was greater in Afayak over Jenguma, Suong-Pungun, Quarshie, and Songda by 3, 11, 13, and 21%, respectively. Cultivar yield differences may be genetically driven. This study suggests smallholders can benefit from increased returns from inoculation + phosphorus synergy. The results indicate that low soybean yields in smallholder farms are not the result of high input cost or low prices but rather are due to the inability of farmers to shift from low input productivity to innovative production technologies. Integrating soybean as a commercial crop within staple crops of smallholder farmers can provide additional income and nutrition for households.

1 | INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is an important agronomic and economic crop for smallholder cropping systems for food and feed and as a source of soil

Abbreviations: BCR, benefit–cost ratio; MGM, mean gross margin.

fertility improvement. The crop is cultivated worldwide for its high content of protein (35–52%) and oil (14–24%) (Hartman, West, & Herman, 2011; Vollmann, 2016); for human nutrition, poultry feed, livestock, and aquaculture industries; as a biofuel (Masuda & Goldsmith, 2009); and as a nutraceutical (Hartman et al., 2011; Tikde, Ramakrishna, Kiran, Kosturkova, & Ravishankar, 2015). Soybean is native to northeast Asia, but the United States, Brazil, and Argentina dominate world production of soybean. In sub-Saharan Africa, the crop is cultivated largely in the savanna belt under rainfed systems (Khojely, Ibrahim, Sapey, & Han, 2018). South Africa is the lead producer, with an average yield of 2,290 kg ha^{-1}, followed by Zambia (1,940 kg ha^{-1}), Nigeria (960 kg ha^{-1}), and Uganda (600 kg ha^{-1}) (Khojely et al., 2018). Other countries with considerable production include Zimbabwe, Malawi, Ghana, Sudan, and Ethiopia. Over the past four decades, soybean production in sub-Saharan Africa increased in area and yield from 20,000 ha at 13,000 tons (0.65 Mg ha^{-1}) in 1970 to 1.5 million ha at 2.3 million tons (1.53 Mg ha^{-1}) in 2016 (Khojely et al., 2018). However, average yields are low in smallholder farms (<1.0 t ha^{-1}) (Khojely et al., 2018) compared with the world average yield of 2.8 Mg ha^{-1} (Purdy & Langemeier, 2018). This is largely a result of low soil fertility, limited high-yielding cultivars, and low input use (Pagano & Miransari, 2015). In Ghana, over 80% of the nation's soybean crop is produced in the northern savanna, with average yield of less than 0.8 Mg ha^{-1} in smallholder farms (Aidoo, Mensah, Opoku, & Abaidoo, 2014; Amanor-Boadu et al., 2015) compared with Ghana's national yield average of 1.65 Mg ha^{-1} (SRID-MOFA, 2016; World Bank, 2017). Despite significant progress made in achieving high-yielding soybean cultivars (Tefera, 2011), soybean yields remain relatively low due to low-input farming practices (Tamimie, 2017), a lack of knowledge about agronomic management, and declining soil fertility; these factors limit successful and sustainable soybean production in smallholder farming systems (Khojely et al., 2018). In subsistence farming, legumes are cultivated without external inputs (Goldsmith, 2017; Tamimie, 2017) but require large amounts of N to produce high yields (Miransari, 2015b; Smil, 2002). Miransari (2015b) observed that soybeans require 220 kg ha^{-1} N to produce 2,737 kg ha^{-1} of seed. Fortunately, the crop is capable of hosting *Bradyrhizobia* bacteria in root nodules to meet the large amounts of N required for growth and development through biological N fixation. It is reported that soybeans can fix 360–450 kg ha^{-1} of N in tropical cropping systems (Miransari, 2015b), and inoculation with rhizobia bacteria in the soils can supply 50–60% of soybean N requirements (Miransari, 2015a). Thus, artificial inoculation of soybean with *rhizobia* bacteria is an efficient mechanism to increase soybean yield.

Core Ideas

- Soils were moderate acidic with low to very low macro- and micronutrient deficiencies.
- Agronomic and economic benefits increased with inoculum plus phosphorus application.
- High-yielding cultivars can maximize net return with input use and proper agronomics.
- Integrated nutrient and crop management practices are key to smallholder farmers.
- Soybeans can provide smallholder farmers additional household income and nutrition.

Phosphorus, an important constituent of biological N fixation, is required in large amounts for plant growth and is essential for energy transfer during the process of symbiotic N fixation, which requires large amounts of energy for nitrogenase activity (Vance, Graham, & Allan, 2000). Cassman, Whitney, and Fox (1981) observed that soybean nodules are a stronger sink for P than roots and shoots. Therefore, P application plays an important role in the establishment, growth, and development of soybeans as well as in the growth of rhizobial strains (Beck & Munns, 1984). Symbiotic N fixation in legumes depends on the environment, management practices, rhizobia strains, and type of legume (Woomer, Baijukya, & Turner, 2012). Somasegaran and Hoben (1985) observed a wide range of specificity between legume–*rhizobium* symbiosis and noted that use of specific *Bradyrhizobial* strains on promiscuous legume genotype, the environment, and management practices are key factors to increasing grain yield. However, differences in effectiveness of *Bradyrhizobial* strains on different soybean cultivars have been noted (Jaiswal, Anand, & Vaishampayan, 2017; Okereke, Onechie, Onunkwo, & Onyeaba, 2001). Thus, selecting appropriate soybean cultivars and inoculants is important to increase N fixation and grain yield.

Farmers are motivated by good returns on investment for their productive efforts but increasing crop yields requires investment in productivity to yield profit and to afford farmers the opportunity to save and reinvest in other viable activities. Osmani, Isman, Ghosh, and Hossain (2014) noted that producing soybean as a marketable or commercial crop is markedly different from subsistence production that depends on traditional production practices. Input integration in soybean production provides an opportunity for higher grain yield and positive investment returns to smallholder farmers. The objective of this study was to determine the most efficient input bundle treatments of artificial seed inoculation (I) with

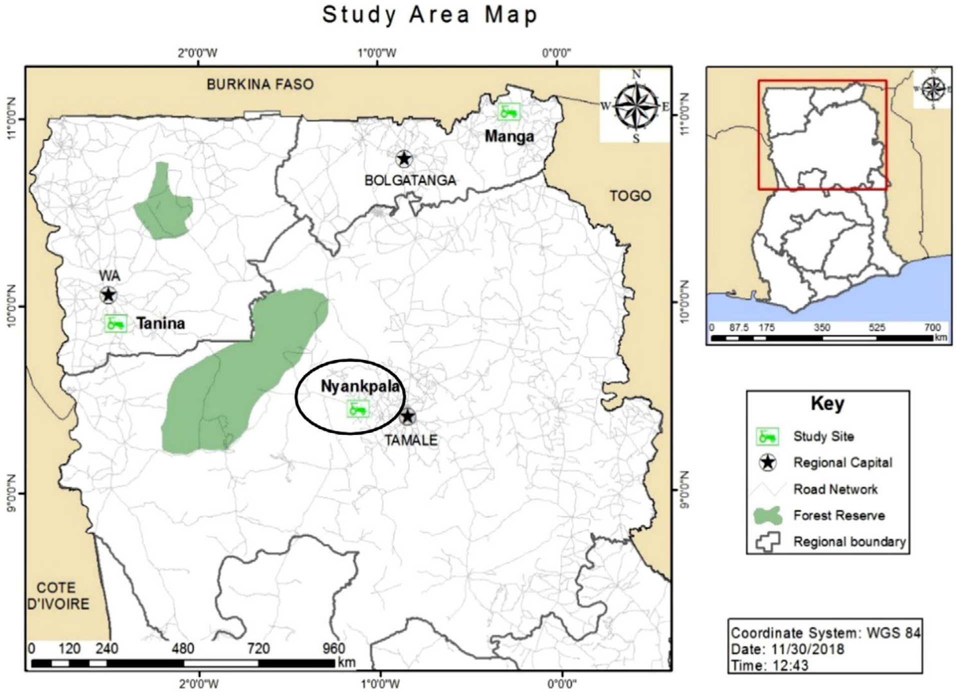

FIGURE 1 Study location at Nyankpala, Ghana

Bradyrhizobium japonicum, P application, inoculation followed by phosphorus application (I+P), and certified seed only (control) on five soybean cultivars that would provide positive investment returns to smallholder farmers in northern Ghana.

2 | MATERIALS AND METHODS

2.1 | Experimental site and climatic and soil characteristics

Field experiments were conducted during the 2014–2017 crop seasons at CSIR-Savanna Agricultural Research Institute in Nyankpala (9°23′54.08″ N; 0°58′58.57″ W, 102 m asl), northern Ghana (Figure 1). Northern Ghana is largely Guinea Savanna with unimodal rainfall from May to October (Figure 2). Climatic data of the study area were obtained from http://en-climatedata.org/africa/ghana/northern-region/nyankpala (Figure 2). Mean monthly minimum and maximum temperatures were highest in March (31 °C) and lowest in August (26 °C). Average annual rainfall was 1,092 mm; rainfall amounts were lowest in January (2 mm) and highest in September (225 mm) (Figure 2).

The soils are Nyankpala series classified under Savanna Ochrosols, Plinthic Luvisols (Adjei-Gyapong & Asiamah, 2002; FAO-UNESCO, 1988; Serno & Van de Weg, 1985). Serno and Van de Weg (1985) described the soils as well drained, with shallow to very shallow profiles, dark brown to pale grayish, brown loamy fine sand, combined with soft ironstone underlain by iron-pan exposures at the surface.

2.2 | Soil sampling and experimental design

Fifteen soil core samples were extracted each year (except 2015) from experimental fields with 2.5 × 36.6 cm soil probe (AMS Inc.). Core samples were extracted to 15 cm depth, air dried, processed, and shipped through international soil shipment protocol to Waypoint Analytical Laboratories Inc. for physico-chemical analysis.

The experiment was a split plot with cultivar as the main plot factor and input bundle as a subplot factor in 5 × 4 factorial arrangement with a randomized complete block in four replications. The main plot factor was five soybean cultivars: Afayak, Jenguma, Quarshie, Songda, and Suong-Pungun (Table 1).

The subplot factor was an input bundle in four treatment levels; inoculated certified seed only (I bundle), phosphorus application only (P bundle), seed inoculation followed by P application (I+P bundle), and certified seed only (control). Treatment plots were six rows that measured 5 × 4.5 m (22.5 m^2), with 1-m alleys between replications.

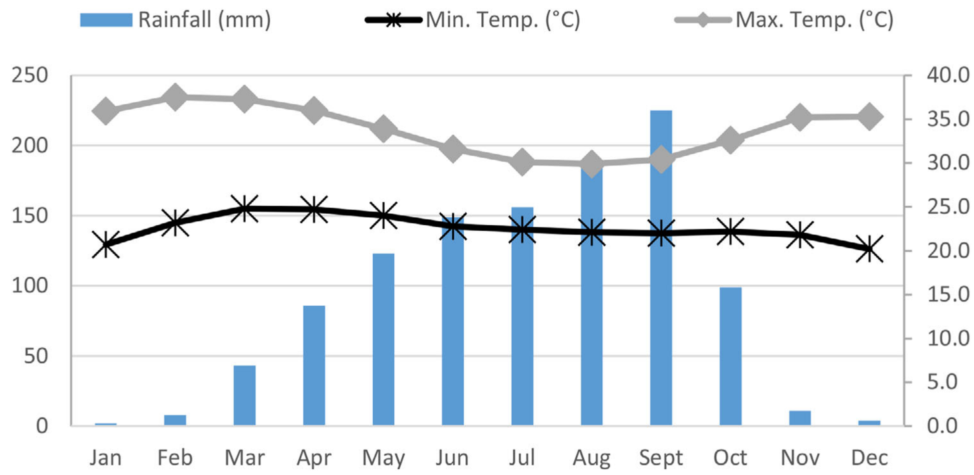

FIGURE 2 Monthly average maximum and minimum temperatures and average monthly cumulative rainfall at Nyankpala averaged over 4-yr (2014–2017)
Data source: https//:en.climate-data.org.

TABLE 1 Soybean cultivars and characteristics used in the 4-yr (2014–2017) experiment at Nyankpala, northern Ghana

Name		Maturity		Year of	Special characteristics
Local	**Accession**	**group**	**d**	**release**	**of cultivar**
Jenguma	TGx 1448-2E	medium	110–117	2003	drought tolerant, shatter <3%
Quarshie	TGx 1445-2E	medium	110–115	2003	drought tolerant, shatter <10%
Afayak	TGx 1834-5E	medium	110–115	2012	trap crop, shatter <8%
Songda	TGX 1445-3E	medium	110–115	2012	trap crop, shatter ≈20%
Suoug-pungun	TGx 1799-8F	early	85–110	2012	earliness for late planting

Note. Source: Denwar and Wohor (2013); Modernghana (2003).

2.3 | Planting and crop management

Fields were plowed, disc harrowed, and ridged to 75 cm with a four-row disc bedder. Planting was done within the first week of July in each year. Soybean cultivars were tested for germination percentage prior to planting (Napoleon, Sylvester, & Riseman, 2018; Seefeldt, 2012). Seeding density was set at 40 kg ha^{-1} but was adjusted appropriately based on cultivar germination percentage and thinned at second leaf stage to 27 plants m^{-2} (75 × 5 cm). Seeds were inoculated with NoduMax at 10 g kg^{-1} seed of a 100-g pack, peat-based inoculant, *Bradyrhizobium japonicum*, strain USDA 110 (2×10^9 viable cells g^{-1}) with gum Arabic carrier (IITA-Business Incubation Platform). Seed inoculation followed the procedure directed by the Business Incubation Platform: seeds were manually drill-seeded at 2- to 3-cm soil depth and covered with soil to ensure proper seed–soil contact. Phosphorus (46% triple super phosphate) was applied after thinning at 60 kg P_2O_5 ha^{-1} in band placement along a drill 5 cm away and below the plant root zone and covered with soil.

2.4 | Pest management

GlyKing 480 SL (glyphosate; Rainbow Agro-Sciences Ltd, Accra) and alligator 400 EC (pendimethalin; Louis Dreyfus Commodities Ltd.) were mixed at the recommended rates of 0.84 kg a.e. ha^{-1} and 1.5 kg a.i. ha^{-1}, respectively. Spraying was done immediately after planting with a 15-L knapsack sprayer fitted with flat fan nozzle that delivered a spray volume of 200 L ha^{-1}.

Hand weeding followed between the V5 and V6 stages (Fehr & Carviness, 1977; Petersen, 2009). Lambda Super 2.5 EC (lambda-cyhalothrin; Kumark) was applied at a rate of 0.025 kg a.i. ha^{-1} in a spray volume of 150 L ha^{-1} at reproductive stage to manage flower- and pod-feeding insects. Routine monitoring and pest surveillance were

TABLE 2 Estimated cost for each bundle treatment average across years at Nyankpala, northern Ghana

Item	Certified seed	I bundle	P bundle	I+P bundle
	$ ha^{-1}			
Land preparation	30.48	30.48	30.48	30.48
Seed	40.63	40.63	40.63	40.63
Planting	40.63	40.63	40.63	40.63
Weeding	27.09	27.09	27.09	27.09
Fertilizer (46% triple super phosphate)	–	–	34.48	34.48
NoduMax inoculum	–	13.54	–	13.54
Pesticides	15.35	15.35	15.35	15.35
Harvest/collect	43.34	43.34	43.34	43.34
Thresh/winnow	48.76	48.76	48.76	48.76
Materials	14.45	14.45	14.45	14.45
Services	27.09	27.09	27.09	27.09
Total variable cost, US$	287.82	301.36	322.30	335.84
Output (soybean price kg^{-1}) = 0.5079 US$				

Note. Conversion rate at 1 US$ = 4.43 (May–Nov. 2017 average; Oanda.com). Data from Soybean Management with Appropriate Research and Technology Farm. I, inoculant; P, phosphorus application; I+P, inoculated seed followed by phosphorus application.

followed until harvest. Grain yield (Mg ha^{-1}) was determined from a 7.5-m^2 net plot (two center rows) from each treatment plot.

2.5 | Economic analysis

Several methods are used to assessment economic efficiency in agricultural productivity, but the most commonly used method is the benefit–cost ratio (BCR), which is defined as the amount of additional output from a unit increase in nutrient input (FAO, 2005; Houssou, Andam, & Asante-Addo, 2017; Rao & Reddy, 2010). Any technologies that propose increased use of inputs must be implemented only when such nutrient inputs are efficient and provide benefits that outweigh cost in a ratio greater than 1 (Morris, Kelly, Kopicki, & Byerlee, 2007; Rao & Reddy, 2010). The variable costs in this study were actual market prices from Soybean Management with Appropriate Research and Technology experimental farm purchases averaged across a 4-yr production period (Table 2).

Grain yield (kg ha^{-1}) was multiplied by soybean prevailing price at harvest to determine gross returns for each treatment and cultivar. Stover yield was not part of economic output. Soybean price was quoted as farm gate price at harvest from Esoko-Ghana (November 2017) commodity market prices (Esoko, 2019). All prices were recorded in local currency (Ghana cedi [GHS]) and converted to US dollars (US$) at an average of US$ 1 = GHS 4.43 currency exchange rate (May–November 2017; Oanda.com).

3 | DATA COLLECTION AND STATISTICAL ANALYSIS

Plant data collected were nodule and shoot development plant^{-1} at pod setting (R3), plant height and days to 50% flowering (R1) and physiological maturity (R7), grain yield, and related attributes. Average dry shoot biomass (g) and nodule weight (mg) per plant were determined by oven-dried fresh shoots and nodules that had been stored in brown paper bags at 65 °C for 48 h. Grain yield (kg ha^{-1}) was assessed from net plots of 7.5 m^2 and extrapolated to kg ha^{-1} at 12% adjusted moisture.

$$\text{Yield}\left(\text{kg ha}^{-1}\right) = \left[(\text{Net plot yield (g)}/1{,}000\text{g}) \times \left(\text{Area (ha)}\frac{10{,}000\text{m}^2}{\text{Net plot area, m}^2} \times \frac{100-\text{MC}}{88}\right)\right]$$

where MC is moisture content (%). Harvest index was calculated as the ratio of grain yield to biological yield. Biological yield was the total plant yield aboveground.

$$\text{Harvestindex (\%)} = \frac{\text{Grain yield (seed yield)}}{\text{Biological yield (seed yield + stover)}}$$

A two-way ANOVA was performed using PROC MIXED model for SAS version 9.4 (SAS, 2016) for the effects of cultivar (C), input bundle (IB), and their interactions (C × IB). The effects of C, IB, and C × IB interaction were fixed,

TABLE 3 Physico-chemical soil properties (0- to 15-cm depth) of series Nyankpala (Savanna Ochrosols, Plinthic Luvisols) at Nyankpala in northern Ghana

Soil properties	Soil test values	Interpretation
Physical		
Soil texture, %		
Sand	59.4	–
Silt	30.9	–
Clay	9.7	–
Classification	–	sandy loam
Chemical		
Mean pH	5.7	moderately acidic
Buffer pH	6.86	–
P, mg kg^{-1}	14.5	low
K, mg kg^{-1}	49.5	low
Ca, mg kg^{-1}	449.7	medium
Mg, mg kg^{-1}	75.7	very high
S, mg kg^{-1}	9.5	low
B, mg kg^{-1}	0.1	very low
Cu, mg kg^{-1}	0.2	very low
Fe, mg kg^{-1}	79.7	medium
Mn, mg kg^{-1}	113.5	medium
Zn, mg kg^{-1}	4.4	medium
Na, mg kg^{-1}	14.7	very low
Soluble salts, dS m^{-1}	0.12	very low
OM, %	1.3 ENR 71	very low
NO_3–N, mg kg^{-1}	7.5	–
Al, mg kg^{-1}	436.8	–
CEC, meq/100 g	3.02	–

Note. CEC, cation exchange capacity; OM, organic matter. Soil analysis by Waypoint Analytical Inc.

and the effects of year and replication (block) were random (Moore & Dixon, 2015). Factor means were separated at $P < .05$ with the Fisher's protected LSD with DIFFS option on LSMEANS statement for letter grouping (Saxton, 1998). Economic analysis was performed on effects of input bundle and cultivar, ignoring any existing interactions. Economic analysis was calculated using the BCR: $\mathrm{BCR} = \frac{\mathrm{MGR}-\mathrm{MVC}}{\mathrm{MVC}}$ where MVC is the mean variable cost, and GNM is the gross net margin (MGR – MVC).

4 | RESULTS

4.1 | Soil fertility status and recommendation

The soils were sandy loam, with 59.4% sand, 30.9% silt, and 9.7% clay (Table 3), with moderate soil acidity (pH 5.7) and buffer pH 6.86 (Table 3). The major nutrients P (14.5 mg kg^{-1}), K (49.5 mg kg^{-1}), and S (9.5 mg kg^{-1}) were rated low when averaged across years (Table 3). Calcium (449.9 mg kg^{-1}) and Mg (75.7 mg kg^{-1}) were rated medium and very high, respectively. Micronutrients B, Cu, and Na were rated very low (0.1, 0.2, and 14.7 g kg^{-1}, respectively), whereas Fe, Mn, and Zn were rated medium (79.7, 113.5, and 4.4 g kg^{-1}, respectively). Soluble salts (0.12 dS m^{-1}) and organic matter (1.3% ENR 71) were very low, with mean values of NO_3–N at 7.5 mg kg^{-1} and Al at 436.8 mg kg^{-1}. Effective cation exchange capacity was 3.0 meq/100 g (Table 3). Guidelines for soil fertility amendments for a yield target of 3,350 kg ha^{-1} (50 bushels) included lime rate of 0.6 Mg $acre^{-1}$ (1.5 kg ha^{-1}) and P and K at 90.2 kg P_2O_5 ha^{-1} and 111.6 kg K_2O ha^{-1}, respectively (Table 4). Nitrogen was not recommended, but other elements in trace amounts included Mg and S at 15.2 and 17.7 kg ha^{-1}, respectively, and B and Cu, each at 1.12 kg ha^{-1}.

TABLE 4 Soil fertility guidelines for soybean crop for Nyankpala sites in northern Ghana Waypoint Analytical Inc., Memphis, TN

Nutrient	Form	Rate recommended
Lime, Mg ha^{-1}	CaO_3	1.5
N, kg ha^{-1}	N	0
P, kg ha^{-1}	P_2O_5	90.2
P, kg ha^{-1}	K_2O	111.6
Mg, kg ha^{-1}	Mg	5.1
S, kg ha^{-1}	S	17.7
B, kg ha^{-1}	B	1.12
Cu, kg ha^{-1}	Cu	0.75
Mn, kg ha^{-1}	Mn	0
Zn, kg ha^{-1}	Zn	1.0

Note. Guidelines proposed by Waypoint Analytical Inc.

4.2 | Agronomic response of soybean cultivars to input bundle treatments

There was no significant effect of input bundle × cultivar for all agronomic variables evaluated (Tables 5 and 6), suggesting that cultivars responded similarly to input bundle treatments over the 4-yr period. The main effects of input bundle and cultivar significantly influenced agronomic performance of soybean over the 4-yr production period at Nyankpala (Tables 5 and 6).

4.3 | Nodule and shoot development

Input bundle differed significantly for nodule number, fresh nodule weight, and dry nodule weight plant^{-1} (Table 7). The synergy of the I+P bundle consistently recorded the highest nodule number (n = 39), fresh nodule weight (904.6 mg plant^{-1}), and dry nodule weight (257.4 mg plant^{-1}). The increases in nodule number, fresh nodule weight, and dry nodule weight plant^{-1} of I+P bundle over I bundle were 22, 26, and 32%; P bundle by 44, 30, 36%; and control by 160, 106, and 102%.

Cultivar differed significantly in nodule number, fresh nodule weight, and dry nodule weight plant^{-1}. Afayak and Suong-Pungun had the highest mean number of nodules plant^{-1} (n = 33 and 32, respectively). The lowest mean number of nodules (n = 21) was on Quarshie (Table 7). Songda (878.7 mg) had the highest fresh nodule weight plant^{-1} but did not differ from Suong-Pungun (800.9 mg) compared with Afayak (692.0 mg) and Jenguma (584.1 mg). Fresh nodule weight plant^{-1} was lowest in Quarshie (495.9 mg). Afayak (221.0), Songda (221.9), and Suong-Pungun (220.7 mg) did not differ in dry nodule weight plant^{-1} but differed from Jenguma (158.8) and Quarshie (138.6 mg).

Shoot yield plant^{-1} differed significantly among input bundle treatments (Table 7). The combined effect of I+P bundle had the highest fresh (38.5 g) and dry (11.1 g) shoot weight plant^{-1} and the lowest fresh (22.2 g) and dry (6.9 g) shoot weight plant^{-1} control treatment (Table 7). Cultivar differences significantly influenced dry shoot yield plant^{-1} but were not significant for fresh shoot yield plant^{-1}. Jenguma (9.4 mg) had the highest dry shoot yield plant^{-1} but did not differ from Afayak (9.2 mg). Suong-Pungun had the lowest dry shoot yield plant^{-1} (8.1 g), but it did not differ from Quarshie (8.8 g) and Songda (8.3 g).

4.4 | Plant height and development days

There was a significant impact of input bundle on plant height at 50% flowering and at physiological maturity (Table 8). The combined effect of I+P bundle improved average height plant^{-1} at flowering (44.5 cm) and physiological maturity (54.8 cm) by 6–8% over the control treatment, I bundle, and P bundle (Table 8). The effect of cultivar differed significantly in mean height plant^{-1}

TABLE 5 Probability of *F* values for nodules per plant, shoots per plant, and plant height of five soybean cultivars to input bundle treatments in a 4-yr experiment at Nyankpala in northern Ghana

Effects	df	Nodules per plant			Shoots per plant		Plant height	
		Nodules	Fresh wt.	Dry wt.	Fresh wt.	Dry wt.	50% flower	50% maturity
		no.	mg		g		cm	
Input bundle, IB	3	<.0001	<.0001	<.0001	<.0001	<.0001	.0126	.004
Cultivar, C	4	.0002	<.0001	<.0001	.2285	.0328	.004	.1385
IB × C	12	.97	.5332	.8627	.6371	.6824	.2581	.1715
LSD (0.05)								
IB		4.9	114.4	27.9	4.4	.87	2.23	2.42
C		5.5	127.9	31.1	3.8	.97	2.49	2.70
IB × C		11.0	255.8	62.3	7.6	1.94	4.99	5.41

TABLE 6 Probability of *F* values for development days, yield attributes, grain yield, and harvest index of five soybean cultivars to input bundle treatments in a 4-yr experiment at Nyankpala in northern Ghana

Effects	df	Development days		Yield attributes				
		50% flower	50% maturity	Pods per plant		Seeds per plant	Grain yield	Harvest index
		d		no.		g	Mg ha^{-1}	no.
Input bundle, IB	3	.398	.464	.0011	.0021	<.0001	<.0001	.4085
Cultivar, C	4	.0216	<.0001	.0002	.0063	<.0001	<.0001	.7936
IB × C	12	.8177	.9999	.6553	.7619	.2321	.9654	.8841
LSD (0.05)								
IB		1.09	1.07	4.0	8.5	.24	118.7	.026
C		1.22	1.20	4.5	9.5	.27	132.7	.030
IB × C		2.44	2.40	9.0	18.9	.54	265.4	.059

TABLE 7 Four-year average of the main effects of input bundle and cultivar on nodule and shoot yield per plant in soybean at Nyankpala, northern Ghana

Factors	Nodule yield per plant			Shoot yield per plant	
	no.	Fresh wt.	Dry wt.	Fresh wt.	Dry wt.
		mg		g	
Input bundle					
I + P bundle	39a	904.6a	257.4a	38.5a	11.1a
I bundle only	32b	719.5b	194.5b	27.3b	8.2b
P bundle only	27c	697.5b	189.6b	29.3b	8.9b
Certified seed	15d	439.7c	127.3c	22.2c	6.9c
SEM (±)	6.2	137.9	38.9	5.8	1.3
$P \leq .05$	***	***	***	***	***
Cultivar					
Afayak	33a	692.0b	221.0a	30.3a	9.2ab
Jenguma	27b	584.1cd	158.8b	31.1a	9.4a
Quarshie	21c	495.9d	138.6b	30.1a	8.8abc
Songda	28b	878.7a	221.9a	27.9a	8.3bc
Suong-Pungun	32a	800.9ab	220.7a	27.4a	8.1c
SEM (±)	6.3	139.5	39.2	5.9	1.3
$P \leq .05$	***	***	***	ns	*

Note. Means within a category and in the same column with the same letter case group are not significantly different (α = .05). ns, nonsignificant.
*Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

at flowering but not at physiological maturity. Afayak (45 cm) recorded the highest mean plant height but was not different from Suong-Pungun (44 cm) at flowering. Songda and Quarshie were the shortest cultivars, with mean heights of 41 and 40 cm, respectively, but did not differ from Jenguma (42 cm) (Table 8).

Developmental days to flowering and physiological maturity did not differ significantly among input bundle treatments (Table 8). Cultivar effect differed significantly in development days to flowering and physiological maturity (Table 8). The longest days to flowering (47 d) and physiological maturity (115 d) were observed on Jenguma and Songda, which differed significantly from Suong-Pungun, with mean flowering at 45 d and physiological maturity at 100 d.

4.5 | Yield and attributes

Pod and seed number plant^{-1}, 100-seed weight, and grain yield were significantly influenced by input bundle treatments (Table 9). The synergy of the I+P bundle increased pod number, seed number plant^{-1}, 100-seed weight, and grain yield over the I bundle only by 13, 15, 6, and 27%;

TABLE 8 Four-year average of input bundle, cultivar, and interactions on plant height and development days in soybean at Nyankpala northern Ghana

Effects	Plant height		Development	
	50% flower	50% maturity	50% flower	50% maturity
	cm		d	
Input bundle				
I + P bundle	44.5a	54.8a	46a	112a
I bundle only	42.1b	51.5b	47a	111a
P bundle only	41.3b	51.8b	46a	111a
Certified seed only	41.2b	50.6b	46a	111a
SEM (±)	3.8	4.6	.45	.44
$P \leq .05$	*	**	ns	ns
Cultivar				
Afayak	44.5a	54.1a	46b	114c
Jenguma	41.5bc	51.6a	47a	115a
Quarshie	40.4c	50.6a	46b	114b
Songda	41.1c	52.1a	47a	115a
Suong-Pungun	43.7ab	52.4a	45c	100c
SEM (±)	3.8	4.6	.49	.48
$P \leq .05$	**	ns	*	***

Note. Means within a category and in the same column with the same letter case group are not significantly different (α = .05). ns, nonsignificant.
*Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

TABLE 9 Four-year average of input bundle, cultivar, and interaction effects on yield and attributes in soybean at Nyankpala, northern Ghana

Effects	Yield and attributes				
	Pods per plant	Seeds per plant	Seed size	Yield	Harvest index
	no.		g 100^{-1}	Mg ha^{-1}	no.
Input bundle					
I + P bundle	43a	84a	11.9a	2.08a	0.45a
I bundle only	38bc	73bc	11.2c	1.64c	0.46a
P bundle only	40ab	77ab	11.6b	1.79b	0.47a
Certified seed only	35c	66c	11.1c	1.26d	0.44a
SEM (±)	7.9	15.1	.28	146.3	0.03
$P \leq .05$	**	*	***	***	ns
Cultivar					
Afayak	40b	77ab	12.2a	1.85a	0.46a
Jenguma	40b	79ab	11.9ab	1.79ab	0.45a
Quarshie	45a	83a	11.2c	1.63cd	0.46a
Songda	37bc	70b	10.5d	1.53d	0.45a
Suong-Pungun	34c	68c	11.6b	1.66bc	0.46a
SEM (±)	7.9	15.2	.29	147.9	0.04
$P \leq .05$	**	*	***	***	ns

Note. Means within a category and in the same column with the same letter case group are not significantly different (α = .05). ns, nonsignificant.
*Significant at the .05 probability level. **Significant at the .01 probability level. ***Significant at the .001 probability level.

TABLE 10 Four-year average of economic production analysis on input bundles on five soybean cultivars at Nyankpala, northern Ghana

Effects[a]	Mean yield	Price	MGR	MVC	MGM	BCR no.
	Mg ha^{-1}	US$ kg^{-1}				
Input bundle						
I + P bundle	2.08	0.5079	1,056.53	335.84	720.70	2.2
I bundle only	1.64	0.5079	832.91	301.35	531.56	1.8
P bundle only	1.79	0.5079	910.31	322.29	588.02	1.8
Certified seed only	1.26	0.5079	638.79	287.81	350.98	1.2
Cultivar						
Afayak	1.85	0.5079	939.57	335.84	603.73	1.8
Jenguma	1.79	0.5079	910.16	335.84	574.32	1.7
Quarshie	1.63	0.5079	829.05	335.84	493.21	1.5
Songda	1.53	0.5079	774.85	335.84	439.01	1.3
Suong-Pungun	1.66	0.5079	884.59	335.84	508.75	1.5

Note. BCR, benefit–cost ratio; MGM, mean gross margin; MGR, mean gross revenue; MVC, mean variable cost.
[a]Control, certified seed only. I, inoculum; P, phosphorus.

over the P bundle only by 8, 9, 3, and 16%; and over control by 23, 28, 7, and 65%, respectively (Table 9). Yield and its attributes were lowest in the control treatment. Cultivars differed significantly in pod and seed number plant^{-1}, 100-seed weight, and grain yield (Table 9). The number of pods plant^{-1} was improved in Quarshie (45 pods plant^{-1}) by 13% over Jenguma and Afayak (40 pods plant^{-1}) and by 22 and 32% over Suong-Pungun (34 pods plants^{-1}) and Songda (37 pods plant^{-1}), respectively. Similarly, the number of seeds plant^{-1} was greatest for Quarshie (83 seeds plant^{-1}) but did not differ significantly from Afayak (77 seeds plant^{-1}) and Jenguma (79 seeds plant^{-1}) but increased significantly by 19 and 22% over Songda and Suong-Pungun, respectively.

Seeds weight per 100 seeds was increased in Afayak over Jenguma, Quarshie, Songda, and Suong-Pungun by 3, 9, 16, and 5%, respectively (Table 9). Grain yield followed a similar pattern, with increases of 3, 13, 21, and 11% for Afayak over Jenguma, Quarshie, Songda and Suong-Pungun, respectively (Table 9). Although Suong-Pungun had the lowest number of pods and seeds plant^{-1}, grain yield was lowest for Songda (1.53 Mg ha^{-1}), probably due to low seed size (10.5 g/100-seed weight). Harvest index did not differ significantly with cultivars and input bundle treatments (Table 9).

4.6 | Economics analysis

The analysis of production economics resulted in the synergy of I+P with the highest mean gross margin (MGM) of US$ 720.70 ha^{-1}, representing a 105% increase over control (US$350.98 ha^{-1}) (Table 10). Similarly, the MGM for I bundle only (US$531.56 ha^{-1}) and P bundle only (US$588.02 ha^{-1}) indicated increases of 52 and 68% over the control, respectively. Application of the I+P bundle had the highest BCR of 2.2 compared with 1.8, 1.8 and 1.2 for I bundle only, P bundle only, and control, respectively. Economic production analysis on cultivars differed on economic returns, with Afayak having the highest MGM (US $ 603.73 ha^{-1}) and BCR (1.8). The lowest returns were observed in Songda, with MGM and BCR of US$ 351.03 ha^{-1} and 1.3, respectively. In descending magnitude, cultivar MGM and BCR were Afayak > Jenguma > Suong-Pungun > Quarshie > Songda, with corresponding values of US$ 603.73 ha^{-1} and 1.8 > US $ 477.72 ha^{-1} and 1.7 > US$ 416.81 ha^{-1} and 1.5 > US$ 402.37 ha^{-1} and 1.5 > US$ 352.03 ha^{-1} and 1.3, respectively (Table 9).

5 | DISCUSSION

Declining soil fertility has been cited as one of the major challenges confronting agriculture in sub-Saharan Africa. This study confirms low and declining soil fertility previously cited as a major constraint to yield increase in smallholder agriculture (Khojely et al., 2018; Raimi, Adeleke, & Roopnarain, 2017; Snapp, 1998; Vanlauwe et al., 2017), resulting in the inability of smallholder farmers to increase crop yields to provide adequate food and household income for farm families. This study also confirms previous reports of moderate soil acidity and sandy loam of the study area (Adjei-Gyapong & Asiamah, 2002; FAO-UNESCO, 1988; Serno & Van de Weg, 1985). Sandy soils generally are low in organic matter, resulting in low buffering capacity and in high rates of water percolation, which render soils acidic (USDA-NRCS, 2014).

Although soil pH does not directly affect plant growth, it does influence soil nutrient availability, soil biological activity, and N fixation (McGrath, Wright, Mallarino, & Lensen, 2013). Soil pH refers to the acidity or alkalinity of the soil. Soil acidity and poor soil health have been associated with improper agronomic and production practices (Afari-Sefa et al., 2004; McGrath et al., 2013; Snapp, 1998). Monitoring soil pH is important because of the strong relationship between the availability of plant nutrients and soil pH (USDA-NRCS, 2014). Hence, soils with moderate acidity can limit potential crop yield (McGrath et al., 2013; Snapp, 1998). Due to wide range of macro- and micronutrient deficiencies, nutrient amendment guidelines of 1.5 Mg ha^{-1} lime, 90 kg ha^{-1} P_2O_5, 112 kg ha^{-1} K_2O, and 18 kg ha^{-1} S have been suggested. The application of 60 kg ha^{-1} P_2O_5 was probably inadequate to offset the low P availability in the study area. Snapp (1998) observed that most nutrient amendment recommendations in sub-Saharan Africa were subjective and made without due consideration to differences in soil types, smallholder farmer resource availability, or yield target. Soil fertility and lime recommendations should be based on site-specific soil test on land use history, soil texture, cultivar, and yield goal where possible.

Adoption of sustainable technologies that improve nutrient use efficiency aimed at increasing crop yield is an important step for smallholder farmers to increase income. Previous studies have reported increases in soybean yields with improved soybean cultivars (Buruchara et al., 2011), phosphate (P) fertilizer application (Kamanga et al., 2010; Kolawole, 2012), artificial seed inoculation with *Bradyrhizobia* (Alves, Zotarelli, Boddey, & Urquiaga, 2002; Thuita et al., 2012), or their combinations (Snapp, Aggarwal, & Chirwa, 1998). Phosphorus has long been recognized as a limiting element in acidic soils partly due to fixation with Fe and Al oxides (Adnan, Mavinic, & Koch, 2003; Ch'ng, Ahmed, & Majid, 2014). Phosphorus is essential for nitrogenase activity, nodule development (Reem, 2017), and increased energy required for N-fixation in soybean (Reem, 2017). Woomer et al. (2012) noted that soybean yields could increase over 60% with P application. Inoculation of soybean with *Bradyrhizobium japonicum* is reported to fix up to 300 kg ha^{-1} N (Khojely et al., 2018), providing 50–60% of the N requirement of soybean plants (Leggett et al., 2017; Miransari, 2015a). Application of the I bundle only, the P bundle only, and the I+P bundle increased soybean yields by 30, 43, and 65%, respectively, over certified seed only (control). The I+P bundle consistently improved nodule and shoot yield, plant height, yield, and its components over the other bundle treatments. Hence, the I+P bundle could be beneficial to smallholder farmers when used efficiently.

The lack of interactive effect of input bundle × cultivar suggests a parallel effect of cultivar on input bundle levels on the parameters evaluated. This means the differences among cultivars observed in this study were based on inherent cultivar differences or characteristics. Jaiswal et al. (2017) reported differences in cultivar specificity and attributed them to genetic differences among the genotypes. Soybean cultivars have been noted to vary in their ability to fix N (Sogut, 2006), resulting in differences in growth and development. Yield differences among soybean cultivars have also been attributed to differences in duration of seed-filling period (Patterson & Raper, 1985). The low yields observed in Songda and Quarshie relative to Afayak, Jenguma, and Suong-Pungun were probably due to differences in inherent plant characteristics. Although pod and seed yield in Songda and Quarshie were relatively higher, the two cultivars had the lowest seed size, suggesting the role of seed size in yield. Additionally, the two cultivars were observed to have smoother and softer leaf cuticles without visible trichomes. This probably had two potential impacts on the cultivars: rapid transpiration, and insect defoliation. Leaf cuticles help to facilitate plant development and regulate healthy crop growth. One primary purpose of the leaf cuticle is reduction of transpiration from the leaves, which is critical in the savanna, which has erratic rainfall and long drought periods. The two cultivars were observed to attract insect defoliators such as Chrysomelids (leaf feeding beetles), variegated grasshoppers, and other leaf feeding insects. Although yield reduction from insect defoliation depends on crop growth stage (Catchot, Cook, Gore, & Irby, 2013), the impact is greater when defoliators manifest throughout the crop growth stage. Research has shown that 100% defoliation of the upper half of the soybean plant had the same yield effect as 50% defoliation in the whole plant (Catchot et al., 2013). This is particularly important because Chrysomelids and variegated grasshoppers feed mostly at the upper half of the crop plant.

The profitability potential of any crop production depends on yield and output price. Existing data in Ghana indicate that agricultural input use is economically beneficial (Houssou et al., 2017). Recent research by Martey, Gatti, and Goldsmith (2020) show relatively strong regional prices across Ghana and a healthy integration with international markets. This implies that low crop profitability among Ghanaian producers results from low input use, which induces yields, and is not caused by low prices.

FAO (2005) used 2002 year input and crop prices in Ghana and reported BCRs of 2.9, 10.0, 4.9, and 3.6 for maize (*Zea mays* L.), rice (*Oryza sativa* L.), cassava (*Manihot esculenta* Crantz), and groundnuts (*Arachis hypagaea* L.), respectively, and concluded economic benefit for the cultivation of these crops in Ghana. Similarly, the World Bank (2012) reported a nutrient/output ratio for maize of 2.6, whereas Chapoto and Ragasa (2013) reported ratios of 4.9 and 3.6 on maize with and without a fertilizer subsidy program, respectively. However, Jayne et al. (2015) found BCRs on maize in Ghana was less than 2.0 between 2007 and 2011 but recorded a BCR of 3.0 when maize prices were relatively high in 2012 and 2013; this finding was attributed to high maize prices during the period. Rao and Reddy (2010) reported a minimum BCR ≥1 as profitable for input adoption in soybean. Soybean is a relatively new crop compared with maize, which is a staple in Ghana. This study showed that the synergy of the I+P bundle was the most attractive for farmer adoption with BCR of 2.2, representing a 76.2% increase over the control treatment.

The BCRs of the I bundle and the P bundle were 1.8, corresponding to 54.0 and 60.0% increases, respectively, over the control. Although cultivar BCRs were >1, higher returns were observed with Afayak, Jenguma, and Suong-Pungun. This study agrees with Asei, Ewusi-Mensah, and Abaidoo (2015), who reported higher investment returns with combined application of Teprosyn Mo and Legumefix of BCR > 2 in soybean, whereas returns with sole application of Legumefix inoculant or Teproyn Molybdenum were <2 in northern Ghana. In contrast, Ulzen, Abaidoo, Mensah, Masso, and Abdel Gadir (2016) reported higher BCR (2.0–4.7) with artificial soybean inoculation. These differences could be attributed to several factors, including spatial differences in soil types and fertility (Ulzen et al., 2016). Additionally, differences in components of production are important considerations in economic analysis. In this study, the components of production were 55% labor cost, 24% input cost, 15% fixed cost, and 6% miscellaneous (Goldsmith, 2017; Reynolds & Awuni, 2017), compared with 75% or more labor in typical smallholder production system with low input system (Dogbe et al., 2013; Tamimie, 2017).

The BCR values reported in this study reflect farm gate price at harvest time rather than peak price period. Peak prices of soybean generally occur 6–8 mo after harvest, often close to the next planting season, resulting in higher returns than at harvest price (Nziguheba et al., 2010). Nziguheba et al. (2010) reported BCRs > 2 at peak price for various crops in Ghana for all locations studied. The difficulty of smallholder farmers holding on to peak price period is storage, which requires significant capital investment. Smallholders, who lack storage, end up selling at harvest when prices are lowest but when their own cash needs are highest. The demand for soybean in Ghana by the livestock and food sectors exceeds domestic production by 60% (Marty & Goldsmith, 2020), which explains the relatively high prices for soybean in Ghana. For example, the most recent official data from 2013 show the food industry importing 167,000 Mg of food oil, or 63% of the nation's need (FAO, 2020). The large demand for soybean in Ghana resulting from the fast-growing poultry and food-processing sectors should lend confidence to farmers that greater productivity in terms of input adoption and higher yields will result in greater profitability, not a precipitous fall in soybean prices.

Expanding yield, and thus domestic supply, would have significant effects on the greater Ghanaian economy through multiplier effects. Recent research in Kenya (Nicholson, van de, Matyoko, Schmidt, & Goldsmith, 2020) shows the extent of the linkages from soybean production in the form of adding value and jobs, upstream to manufacturers and suppliers of inputs and downstream to processors, food and feed manufacturers, and poultry and aquaculture producers. Countries such as Ghana can limit hard currency exports and lower the costs of imported feeds, meals, and oils when local producers can productivity expand domestic output. For example, locally available soy flour presents school lunch operators in northern Ghana a source of protein at one-third the price of the traditional ingredients, such as ground beef and dried mackerel (Goldsmith et al., 2019).

Soybean yields within smallholder farmers in the region are generally low (average, <0.8 Mg ha^{-1}) (Aidoo et al., 2014; Goldsmith, 2017). The use of appropriate management practices could motivate farmers to attain higher soybean yields per unit area compared with yield obtained from subsistence farming practices. This study demonstrates that low yield can be the result of low acceptance of sustainable management technologies, low effort in productivity, and unsustainable agronomic practices resulting in low revenue rather than increased input costs.

6 | CONCLUSION

Healthy and fertile soils form the foundation for improved crop yields and knowledge in soil fertility recommendation require site-specific soil testing for soil nutrient amendment. This study indicated that in moderately acid tropical soils, the synergy of *rhizobium* inoculation + P application could increase soybean growth and development; increased crop growth, development, and yields were consistently indicated over all other input bundles in all the variables measured. Additionally, the combined effect of *rhizobium* inoculation + P application produced BCR far above any of the treatment bundles. This suggests that soybean cultivation can be a commercial crop within the context of smallholder farming system. However, this requires a shift from subsistence farming practices of low input use to integrated input and appropriate crop management practices, which requires the use of a high-yielding soybean variety, input integration, appropriate plant density, and pesticides that improve grain yields.

Smallholder farmers are highly skilled, and, given the necessary enabling environment and encouragement through input accessibility and affordability, soybean can be a fast-growing commercial crop among smallholder farmers. The low soybean yields obtained in smallholder farms are in part due to a low level of awareness regarding the potential benefits of improved agronomic production practices. Women dominate soybean production in smallholder systems in Ghana and as a vulnerable group require assistance from policy makers and from public and private sectors to access markets to optimize returns. Increased extension education, support with triple super phosphate fertilizer price adjustment, ensuring collective action through strengthening farmer-based organizations, AAATAAAA and out grower schemes to facilitate risk management could be beneficial to smallholder farmers. Collective action improves access to agricultural inputs and markets, which would be beneficial to the women who dominate the soybean production system.

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest in this research, authorship, and/or publication of this article.

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