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Response of different soybean varieties to phosphorus fertilizer microdosing and rhizobium inoculation in the sub-humid zone of Northern Benin

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ABSTRACT

Soybean cultivation has expanded among farmers in Benin, yet yields remain below potential, mainly due to declining soil fertility and poor seed quality. This study evaluated the effects of organo-mineral microdose fertilization and rhizobium inoculation on the agronomic performance of three soybean varieties in the sub-humid zone of Northern Benin over two consecutive growing seasons. A split-plot design with three replications was used. The main factor was soybean variety, consisting of one traditional variety and two improved varieties (TGX1910-14F and TGX1830-20E). The sub-factor was fertilization, with nine treatments: i) control (no fertilizer, manure or inoculum), ii) phosphorus microdosing (MD; 10 kg P/ha), iii) recommended phosphorus rate (RR; 33 kg P/ha), iv) rhizobium inoculation (I), v) MD+I, vi) farmyard manure (F; 3 t/ha), vii) MD+F, viii) F+I, and ix) MD+I+F. The results showed that variety, fertilization and their interaction significantly affected soybean yield parameters. The improved variety TGX1910-14F produced the highest grain yield (2492 kg/ha), outperforming both the traditional variety and TGX1830-20E. The RR, MD+I+F and MD+F treatments resulted in the greatest yield improvements, with increases of approximately 95%, 100% and 103% compared to the control, respectively. Economic analysis indicated that these same treatments also generated the highest gross margins, with increases of 140%, 142% and 149% compared to the unfertilized control. Overall, the combined application of microdose phosphorus with inoculum, manure or both, particularly when applied to the TGX1910-14F variety, appears to be an effective strategy for improving soybean productivity and farmer income in Northern Benin.

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INTRODUCTION

Soybean is one of the world's most important crops. As a major source of protein and vegetable oil for both human and animal consumption (Couto *et al.*, 2011), it holds a strong position in global markets (Abbasi *et al.*, 2010). Beyond its nutritional value, soybean contributes significantly to sustainable agriculture through its ability to fix atmospheric nitrogen, thereby restoring soil fertility and enhancing crop productivity (Smaling *et al.*, 2008).

Despite these advantages, soybean production in sub-Saharan Africa remains generally low compared with global averages. Yields are constrained by poor soil fertility, suboptimal crop management, and limited access to high-performing varieties (Ronner *et al.*, 2016; van Heerwaarden *et al.*, 2018). Low biological nitrogen fixation (BNF) efficiency, common in smallholder fields, further limits productivity due to its sensitivity to soil nutrient status, rhizobial effectiveness, and genotype × environment interactions (Ferguson *et al.*, 2019). These constraints highlight the need for integrated and context-specific agronomic innovations capable of addressing multiple yield-limiting factors simultaneously.

In Benin, average soybean yields rarely exceed 0.5 t ha^{-1} (MAEP, 2014), far below the potential yield of approximately 3 t ha^{-1} (Agnoro, 2008). Yield gaps persist due to factors such as soil degradation from poor land management, climatic variability including delayed rainfall, declining soil fertility, and limited farmer education (Adimi *et al.*, 2017). To meet growing food and income needs, there is an urgent need to promote low-cost, environmentally sound technologies that encourage the use of external inputs in soybean production.

Several technologies for soybean intensification already exist. These include improved varieties with higher productivity and resistance to pests and diseases (Okogun *et al.*, 2005; Buruchara *et al.*, 2011), seed inoculation with effective rhizobial strains (McInnes and Haq, 2007; Houngnandan *et al.*, 2009; Afzal *et al.*, 2010; Hussain *et al.*, 2011; Tairo and Ndakidemi, 2014), and rational or integrated fertilizer use (Buerkert *et al.*, 2001; Muehlig-Versen *et al.*, 2003).

Microdose fertilization has recently emerged as a promising option for improving nutrient-use efficiency in smallholder systems, offering a cost-effective means of enhancing productivity on nutrient-depleted soils (Hayashi *et al.*, 2008; Twomlow *et al.*, 2011). Likewise, rhizobium inoculation has been shown to improve nodulation, nitrogen fixation, and grain yield when effective strains are used under suitable soil conditions (Ulzen *et al.*, 2016). However, the combined effects of microdose fertilization, inoculation, and varietal performance in sub-humid environments remain insufficiently explored—particularly in West Africa, where soil fertility gradients and heterogeneous management practices strongly influence technology performance.

Although many previous studies have examined these management options individually or in pairs, few have investigated their integrated or sequential effects. Given the persistent yield gap and the need for environmentally sustainable intensification pathways, combining improved varieties with optimized nutrient management and rhizobial inoculation may offer a viable strategy for improving soybean productivity in Northern Benin. Understanding how these components interact is therefore essential for developing agronomically effective and economically feasible recommendations for smallholder farmers. This study aims to evaluate the response of selected soybean varieties to microdose fertilization and rhizobium inoculation under the sub-humid conditions of Northern Benin.

MATERIALS AND METHODS

Study sites and farm characteristics

The experiment was conducted at the Agricultural Research Station of Northern Benin (CRA-Nord) in Ina village (Ina district, Bembèrèkè municipality; 9°57′N, 2°42′E; 365 m a.s.l.), located 70 km northeast of Parakou. Ina lies within agro-ecological region III of Benin, which receives 900–1200 mm of annual rainfall. The climate is characterized by a single rainy season from May to October. The soils are ferruginous tropical soils with low inherent fertility, classified as Acrisols or Lixisols according to the World Reference Base, and corresponding to the French soil classification system (Youssouf and Lawani, 2002).

Trial installation and management

The experiment was conducted over two consecutive years (2019 and 2020) using a split-plot factorial design (3 × 9) with three replicates. The main plots consisted of nine fertilizer/inoculation treatments: (i) control without fertilizer, manure, or inoculum; (ii) phosphorus microdosing (MD, 10 kg P ha^{-1}); (iii) recommended rate of phosphorus (RR, 33 kg P ha^{-1}); (iv) rhizobium inoculation (I); (v) MD+I; (vi) farmyard manure at 3 t ha^{-1} (F); (vii) MD+F; (viii) F+I; and (ix) MD+I+F. The sub-plots consisted of three soybean varieties: two improved varieties (TGX1910-14F and TGX1830-20E) and one traditional variety.

Farmyard manure was applied in hills one week before sowing to enhance its efficiency (Ibrahim *et al.,* 2015; Tovihoudji *et al.,* 2017, 2018). For microdose P applications, small planting hills were dug at each sowing point, with P fertilizer applied and the holes closed afterward. In the RR treatment, P fertilizer was spot-broadcasted approximately 10 cm from each planting hole without incorporation, following local farmers' practices.

Soil preparation was performed uniformly across all plots in early June, using flat ploughing to a depth of 0.2 m. Individual plots measured 5 m × 4 m (20 m^2) with nine rows per plot. Blocks were separated by 2 m and plots within blocks by 1 m. The improved varieties were obtained from the Agricultural Research Center of Northern Benin (CRA-Nord), while the traditional variety was sourced from local soybean producers. Sowing was carried out on 25 June in 2019 and 26 June in 2020 after three successive days of rainfall of at least 10 mm. Five seeds were sown per plot at a spacing of 0.5 m x 0.2 m and then thinned at 03 plants per plot at 14 days after sowing, giving a density of 300,000 plants per hectare (currently recommended density). Weed control was done manually on 20 and 45 days after sowing.

Measurements and calculations

Baseline soil and amendment analyses

Before sowing, soil samples were collected at a depth of 20 cm from each experimental block using an auger. The samples were combined to form a composite sample for the experimental site, air-dried, and sieved for laboratory analysis. Soil properties measured included particle size distribution (Gee and Or, 2002), pH (van Reeuwijk, 2002), organic carbon (Walkley and Black, 1934), total nitrogen, and available and exchangeable phosphorus following van Reeuwijk (2002). Chemical analyses were conducted at the Soil and Plant Analysis Laboratory of INRAB (CRA, Agonkanmè). The soil was acidic (pH < 7) with a sandy-loam texture in the topsoil.

Nutrient levels were low for nitrogen (<750 mg kg^{-1}) and phosphorus (<18 mg kg^{-1}), while exchangeable potassium was medium (>0.10 cmol kg^{-1}). Organic matter and cation exchange capacity were 5.8 g kg^{-1} and 6.4 cmol^{+} kg^{-1}, respectively, and bulk density was 1.6 g cm^{-3} (Table 1).

Table 1. Initial state of soil fertility before the installation of the trial

Depth	0-20 cm
Soil texture	
Sand (%)	83
Silt (%)	12
Clay (%)	6
Texture	Sandy-loam
Soil chemical properties	
pH-$_{H2O}$	6.0
Organic C (g kg^{-1})	5.8
Total N (mg kg^{-1})	458
P Bray-1 (mg kg^{-1})	7.6
Exch. K (cmol$_{+}$ kg^{-1})	0.21
CEC (cmol$_{+}$ kg^{-1})	6.4
Bulk density (g cm^{-3})	1.6

Each year, a representative sample of farmyard manure (FYM) was oven-dried at 40 °C, ground through a 1 mm sieve, and analyzed for organic carbon, total nitrogen, phosphorus, and potassium. On average, the FYM contained 14.8 ± 5.6% C, 1.4 ± 0.5% N, 0.3 ± 0.2% P, and 0.9 ± 0.4% K.

Yields and yield components

Harvest was conducted on 16 October 2019 and 12 November 2020 on the three inner rows of each plot (4 m^2) to determine yield. Neighboring plants in each row were left as a buffer to minimize edge and neighbor effects. Grain and haulm were weighed in the field. Grain moisture content was determined for each replicate after oven-drying at 70 °C to constant weight, following an initial drying at 105 °C for 30 minutes. Haulm subsamples were further oven-dried at 70 °C to constant weight for moisture correction. The number of plants and pods per plant was recorded, and the 100-grain weight was determined using three replicates per plot. The harvest index (HI) was calculated as the ratio of grain dry weight to total aboveground dry biomass. Soybean grain and haulm yields were then expressed on a dry weight basis as kg ha^{-1}.

Calculations

Yield increases were calculated using the following equation:

Response = 100 * (Yt – Yc)/Yc, where Yt = yield of treatment t (kg ha-1) and Yc = yield of the control (kg ha^{-1}).

The agronomic efficiency of P was calculated as a proxy of P use efficiency as follows: AE-P = (Yt –Yc) / Pt, where Yt and Yc are the yields per hectare of the treatment considered and of the control, respectively; Pt the quantity of P provided per hectare for this treatment.

Also, the rainwater use efficiency (RUE) was determined by the ratio between the grain yield and the total amount of rainfall during the experiment.

Economic analysis

The economic profitability of the different treatments was assessed using gross margin (GM), gross return, benefit–cost ratio (BCR), and value–cost ratio (VCR). Fixed costs included the cost of seeds and major labor activities (land preparation, seeding, weeding, ridging, harvesting, and threshing), while variable costs comprised the cost of fertilizers and their application. Input and output prices were based on the average market prices over the two cropping seasons (2019–2020; Table 2). Government-fixed prices were used for seeds and fertilizers. Labor costs for land preparation, planting, manure/fertilizer application, weeding, and harvesting were recorded during the experiments. Costs associated with digging planting holes and the labor required for hill application of amendments were summed and included in labor costs (Table 2).

Table 2. Input and output prices used in the economic analysis

	Unit	Values
Inputs		
Manure	FCFA per 50 kg bag	200
Inoculum	FCFA per bag	2.500
Phosphorus	FCFA per 50 kg bag	14.000
Labor for soybean cultivation		
Tillage	FCFA ha^{-1}	30.000
Seeds	FCFA kg^{-1}	1000
Seeding	FCFA ha^{-1}	12.000
Weeding	FCFA ha^{-1}	30.000
Harvesting	FCFA kg^{-1}	15.000
Threshing	FCFA 100 kg^{-1}	1.000
Winnowing	FCFA 100 kg^{-1}	1.000
Output		
Soybean grain	FCFA kg^{-1}	240

The soybean grain price was based on the official average over the past five years, with a maximum of 175 FCFA kg^{-1}, a minimum of 125 FCFA kg^{-1}, and an average of 150 FCFA kg^{-1} (1 US$ = 570 FCFA; https://www.gouv.bj/actualite/974/la-campagne-2020-2021-commercialisation-soja-benin-lancee).

Total revenue was calculated by multiplying grain yield by the average grain unit price. Gross margin was calculated by subtracting variable costs from total revenue, and gross return was calculated by subtracting the sum of fixed and variable costs from total revenue. The BCR was calculated as the ratio of gross return to total cultivation costs (fixed + variable).

The VCR was computed as the difference in grain yield between fertilized plots and the control, multiplied by the unit market price of grain, and divided by the cost of applied fertilizer. According to FAO (2005), VCR interpretation follows general guidelines: VCR < 1 indicates negative returns on investment, VCR = 1 indicates positive returns but not economically viable, and VCR ≥ 2 indicates positive returns that are economically viable.

Statistical analysis

All data were analyzed using R software version 4.0.5. Prior to analysis, data were checked for normality and homogeneity of variance. A linear mixed-effects model ANOVA was then performed, and means were compared using Tukey's honestly significant difference (HSD) test at $p < 0.05$. Fixed effects in the model included treatment, variety, and year, while cropping year and replicates were treated as random effects. When a significant treatment × variety × year interaction was detected, separate models were fitted for each year (2019 and 2020), with treatment, variety, and their interaction as fixed effects and replicates as random effects.

RESULTS

Rainfall during experiment

Fig. 1 presents the distribution of daily and cumulative rainfall during the trial period in 2019 and 2020. During the trial period, the cumulative rainfall in 2019 and 2020 was 775.3 mm and 879.9 mm respectively. Total rainfall received from vegetative to flowering stage (0 to 48 DAS) accounted for 39.5% and 41.8% in 2019 and 2020 respectively compared to 47,9% and 41.7% from flowering to maturity stage (48 to 90 DAS). The minimum cumulative rainfall in 2019 and 2020 (28.2 mm and 35.3 mm, respectively) was observed in the month of June against 263.3 mm and 332.3 mm as the maximum rainfall obtained in the month of August and July respectively.

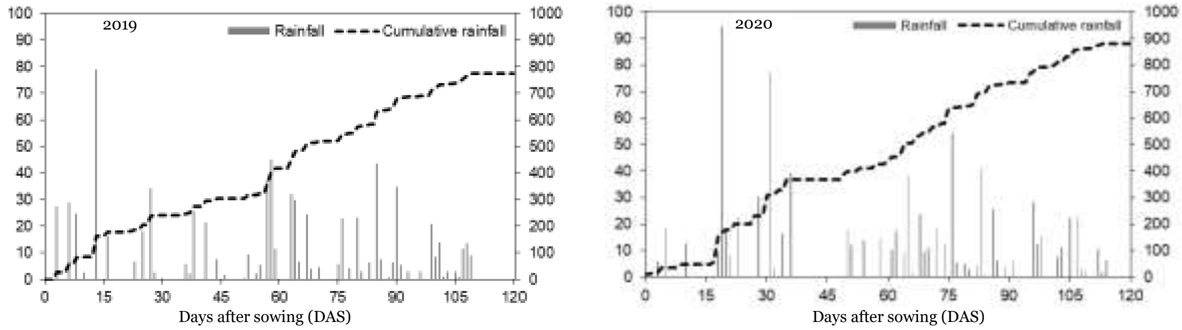

Fig. 1. Rainfall distribution from sowing to harvest in 2019 and 2020

Soybean grain and haulm yield

Grain yield was affected by year, variety and treatment (Fig. 2A, $p < 0.001$). The year 2019 gave a highest grain yield (2490.5 kg ha^{-1}) than 2020 (2180.6 kg ha^{-1}). TGX1910-14F variety gave a highest grain yield (2492.1 kg ha^{-1}) compared to the other. The treatments RR, MD+I+F and MD+F are allowed to increases grain yield respectively to 95, 100 and 103 % compared to control. There was an interaction between variety and treatment (Fig. 2, $p < 0.001$). In fact, at the level of TGX1910-14F, all treatments resulted the highest grain yield unlike the two others.

Like grain yield, year, variety and treatment significantly affected soybean haulm yield (Fig. 2B, $p < 0.001$). The year 2019 also gave a highest haulm yield (1846.5 kg ha^{-1}) than 2020 (1616.3 kg ha^{-1}). TGX1910-14F variety gave a highest haulm yield (1982.8 kg ha^{-1}) compared to the two other varieties. MD+F and MD+I+F treatments increased haulm yield by 175 and 177%, respectively, compared to control. Any interaction between different factors was observed.

Yield components

The harvest index (HI) was significantly affected by year, variety, and treatment ($p < 0.001$; Table 3). Mineral fertilization treatments, either alone or combined with inoculation, produced a higher HI compared to the unfertilized/no-inoculum control. There was also a significant interaction between variety and treatment ($p < 0.01$; Table 3). Specifically, for TGX1910-14F, all treatments resulted in a higher HI, unlike the other two varieties.

The 100-grain weight varied significantly between years and varieties ($p < 0.001$; Table 3), with the highest values recorded in TGX1910-14F (16 g) and TGX1830-20E (13.8 g). Mineral fertilization also had a significant effect on 100-grain weight ($p < 0.001$; Table 3). All treatments, whether applied alone or combined with inoculation, produced higher 100-grain weights compared to the control (7 g). A significant variety × treatment interaction was also observed ($p < 0.001$; Table 3). All treatments resulted in higher 100-grain weight in TGX1910-14F, a pattern not observed in the other two varieties.

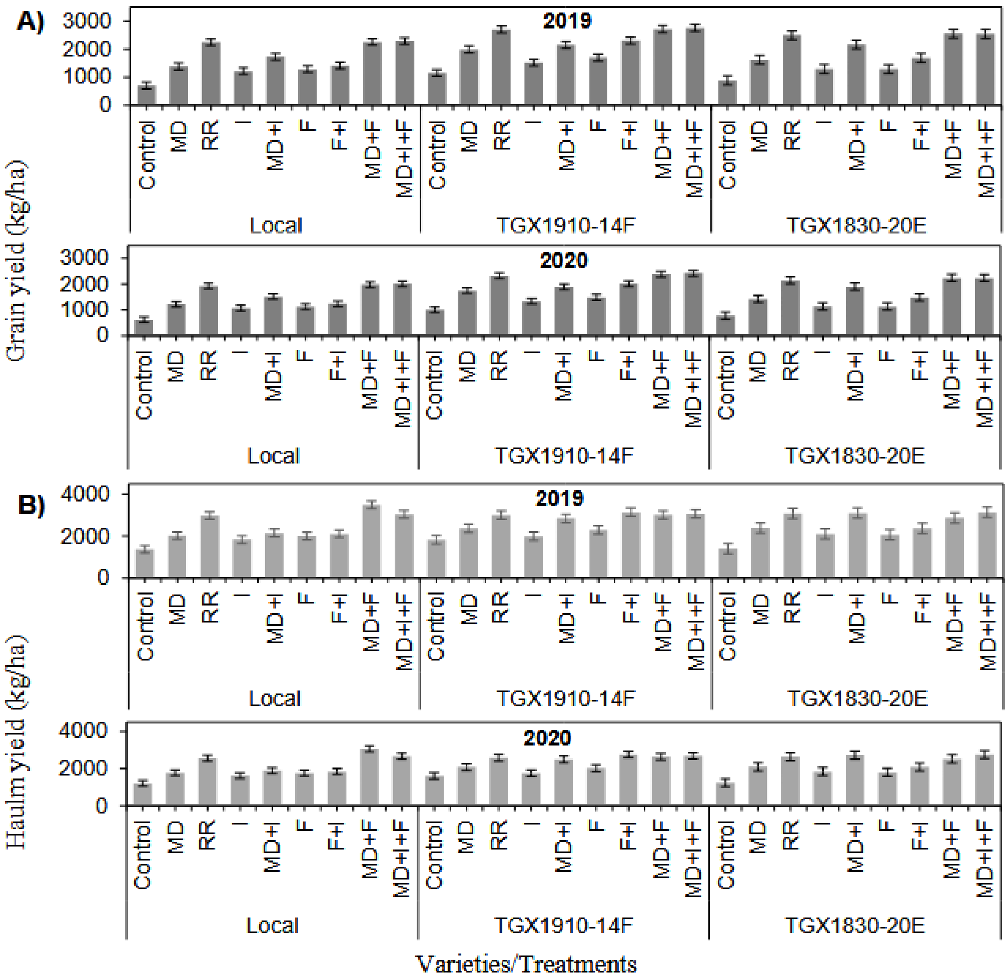

Fig. 2. Effect of years, treatments and varieties on soybean grain (A) and haulm (B) yields

MD: Microdose, RR: Recommended Rate, I: Inoculation, MD+I: Microdose +Inoculation, F: Manure, F+I: Manure+Inoculation, MD+F: Microdose + Manure, MD+I+F: Microdose+Inoculation+Manure.

The number of pods at harvest varied significantly among years and varieties ($p<0.001$; Table 3). Treatments also have a significant effect ($p<0.001$; Table 3) on the number of pods at harvest with an average increase of 213, 204, and 188% over the control (38 pods/plant) for treatments MD+I+F, RR and MD+F respectively (Table 3). There was an interaction between variety and treatment ($p<0.001$; Table 3) for the number of pods at harvest. Indeed, the RR and MD+I+F treatments gave the highest number of pods per plant at harvest in the Local variety, in contrast to the other two varieties where they are the second-best treatments after the MD+F treatment (Table 3).

Table 3. Combined effect of inoculum, manure and phosphorus fertilizer microdosing on yield components in 2019 and 2020

Varieties (V)	Treatment (T)	Harvest index (-)		100-grains weight (g)		Pod number (#)	
		2019	2020	2019	2020	2019	2020
Traditional	Control	0.34	0.34	5.5	5.1	33.5	24.3
	MD	0.41	0.41	9.1	8.2	85.7	76.5
	RR	0.42	0.43	11.1	9.5	148.0	136.2
	F	0.39	0.39	8.3	7.5	111.6	102.4
	MD+F	0.39	0.39	11.2	9.8	111.7	102.5
	SE	0.017	0.017	0.613	0.540	6.746	6.736
TGX 1910-14F	Control	0.39	0.39	9.5	8.4	43.8	34.6
	MD	0.45	0.45	16.0	14.1	101.9	92.7
	RR	0.47	0.47	21.7	18.7	118.3	107.1
	F	0.42	0.42	13.7	12.0	63.6	54.3
	MD+F	0.47	0.47	21.6	19.0	125.4	116.2
	SE	0.018	0.018	1.044	0.916	8.042	8.015
TGX 1830-20E	Control	0.38	0.38	7.3	6.4	49.7	40.5
	MD	0.40	0.40	13.2	11.6	69.1	59.9
	RR	0.44	0.45	20.2	17.3	94.7	83.9
	F	0.39	0.39	10.4	9.1	56.9	47.7
	MD+F	0.47	0.47	20.3	17.8	102.1	92.9
	SE	0.016	0.016	1.292	1.131	4.142	4.140
p-values							
Y		0.838		<0.001		<0.001	
V		<0.001		<0.001		<0.001	
T		<0.001		<0.001		<0.001	
Y*V		0.999		0.159		0.999	
Y*T		0.999		0.917		0.999	
V*T		0.005		<0.001		<0.001	
Y*V*T		1.000		0.999		1.000	

MD: Microdose, RR: Recommended Rate, I: Inoculation, MD+I: Microdose +Inoculation, F: Manure, F+I: Manure+Inoculation, MD+F: Microdose + Manure, MD+I+F: Microdose+Inoculation+Manure.

Agronomic and rainwater use efficiency

Phosphorus use efficiency (AE-P) was influenced by year and treatments (Table 4). The year 2019 recorded the highest AE-P value, reaching 90.3 kg grain kg^{-1} P. Mineral fertilization treatments, alone or in combination with inoculation, produced the highest AE-P values, ranging from 43.9 to 149.6 kg grain kg^{-1} P (Table 4). No significant interactions between variety, treatment, and year were observed (Table 4).

Rainwater use efficiency (RUE) was significantly higher in 2020 than in 2019, reflecting the large difference in rainfall amounts between the two years ($p < 0.001$; Table 4). RUE was also significantly affected by variety and treatment ($p < 0.001$; Table 4). The improved varieties showed the highest RUE values, ranging from 2.1 to 2.4 kg grain ha^{-1} mm^{-1} (Table 4).

Among fertilizer/inoculation treatments, MD+F and MD+I+F produced the highest RUE (2.9 kg grain ha^{-1} mm^{-1}), followed by RR (2.8 kg grain ha^{-1} mm^{-1}), all of which outperformed the control (1.0 kg grain ha^{-1} mm^{-1}). Similar to AE-P, no significant interactions were detected (Table 4).

Economic performance indicators

The economic analysis based on average input and output costs (Table 4) showed a substantially greater benefit for the improved varieties compared to the traditional variety. Overall, net income (NI), gross margin (GM), value–cost ratio (VCR), and benefit–cost ratio (BCR) were all significantly higher in the improved varieties. Across both years, the variety TGX1910-14F increased NI and GM by 488 USD (58%) and 760 USD (35%), respectively, compared with the traditional variety. Its BCR was also 55% higher than that of the traditional variety.

Table 4. Combined effect of inoculum, manure and phosphorus fertilizer microdosing on resource use efficiency and economic indicators in 2019 and 2020

Factors	AE-P (grain kg⁻¹)	RUE (kg/ha/mm)	Net income (USD)	Gross margin (USD)	VCR (-)	BCR (-)
Year (Y)						
2019	90.3b	2.4b	440.8b	707.5b	5.7b	1.2b
2020	79.1a	1.8a	351.5a	610.1a	4.9a	1.0a
SE	2.750	0.030	9.323	10.170	0.229	0.025
Varieties (V)						
Traditional	80.2	1.8a	309.8a	564.5a	5.3	0.9a
TGX 1910-14F	88.2	2.4c	488.4c	759.5c	5.3	1.4c
TGX 1830-20E	85.6	2.1b	390.3b	652.4b	5.3	1.1b
SE	3.368	0.036	11.418	12.456	0.280	0.031
Treatment (T)						
Control	-	1.0a	128.8a	360.6a	-	0.5a
MD	70.6bc	1.9cd	334.6bc	591.2bc	4.5ab	1.0bcd
RR	43.9a	2.8f	590.8e	873.4e	6.3bcd	1.6fg
F	53.1ab	1.6bc	249.9b	498.5b	3.2a	0.8b
MD+F	149.6e	2.9f	614.9e	899.1e	6.9cd	1.6g
SE	5.144	0.063	19.777	21.575	0.458	0.053
p-values						
Y	0.005	<0.001	<0.001	<0.001	0.029	<0.001
V	0.244	<0.001	<0.001	<0.001	0.999	<0.001
T	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Y*V	0.993	0.369	0.765	0.765	1.000	0.890
Y*T	0.982	0.057	0.795	0.795	1.000	0.998
V*T	0.057	0.167	0.159	0.15	0.517	0.139
Y*V*T	1.000	1.000	1.000	1.000	1.000	1.000

MD: Microdose, RR: Recommended Rate, I: Inoculation, MD+I: Microdose +Inoculation, F: Manure, F+I: Manure+Inoculation, MD+F: Microdose + Manure, MD+I+F: Microdose+Inoculation+Manure.

Similar to the improved varieties, fertilizer/inoculation treatments—alone or combined with inoculation or manure—resulted in the highest economic performance. The MD+I+F, RR, and MD+F treatments increased NI by 580, 591, and 615 USD, respectively, compared with the control without fertilizer and inoculum. Likewise, GM increased by 140%, 142%, and 149% under the MD+I+F, RR, and MD+F treatments, respectively, relative to the unfertilized control.

The highest VCR and BCR values were obtained under treatments I and MD+F, respectively, while the lowest values were recorded under treatment F (VCR) and the control (BCR) ($p < 0.001$; Table 4). Treatments I and MD+F increased VCR and BCR by 141% and 220%, respectively, compared with treatment F and the control ($p < 0.001$; Table 4).

DISCUSSION

This study evaluated the response of two improved soybean varieties and one traditional variety to microdose fertilization and rhizobium inoculation in the sub-humid zone of northern Benin over two consecutive growing seasons (2019 and 2020). Grain and haulm yields were significantly higher in 2019 than in 2020, likely due to slightly higher and better-distributed rainfall during the reproductive period (372 mm in 2019 compared with 369 mm in 2020). This result aligns with the well-documented sensitivity of soybean to rainfall during flowering and pod-filling stages, as water stress during these critical periods can reduce pod set, induce seed abortion, and ultimately decrease grain yield (Wang *et al.*, 2025).

Among the varieties tested, the improved variety TGX1910-14F produced significantly higher grain and haulm yields than TGX1830-20E and the traditional variety. Such genotypic differences have been widely reported in the literature, with improved varieties generally outperforming traditional ones under favorable agronomic conditions. This superior performance is often attributed to a higher harvest index, enhanced nodulation efficiency, and improved nutrient-use efficiency (Aduloju *et al.*, 2009; Ikeogu *et al.*, 2013; Lyimo *et al.*, 2017).

Mineral fertilization and microdose treatments, particularly when combined with manure and/or rhizobial inoculation (RR, MD+I+F, and MD+F), significantly increased grain yield and yield components compared with the unfertilized and uninoculated control. These findings are consistent with studies conducted in West Africa, notably in Ghana and Nigeria, where combined applications of phosphorus fertilizer and rhizobial inoculation consistently resulted in higher soybean yields than single-input or unfertilized treatments (Ulzen *et al.*, 2018, 2020; Kabiru *et al.*, 2024). Long-term studies further indicate that the co-application of rhizobial inoculants with PK fertilizers enhances nodulation, improves soil nutrient availability, and substantially increases grain yield compared with mineral fertilization alone or unfertilized plots (Wei *et al.*, 2023). Similarly, Amidou *et al.* (2005) reported that the application of 5–11 t ha^{-1} of manure combined with a half-dose of mineral fertilizer resulted in yield gains of 250–350 kg ha^{-1} in cotton and 250 to over 1,000 kg ha^{-1} in maize. In addition, Zoundji *et al.* (2015) and Belete *et al.* (2019) demonstrated that the combined use of phosphorus fertilization and rhizobium inoculation significantly increased soybean grain yield, seed weight, and dry haulm yield.

Agronomic efficiency of phosphorus (AE-P) and rainwater use efficiency (RUE) were significantly affected by year, variety, and fertilization treatment. The highest AE-P was recorded in 2019, whereas RUE was greater in 2020, reflecting differences in total rainfall and its temporal distribution between the two seasons. Improved soybean varieties exhibited higher AE-P and RUE than the traditional variety, indicating a superior physiological capacity to convert both applied nutrients and available water into biomass and grain yield. Similarly, mineral fertilization treatments, either applied alone or in combination with rhizobial inoculation or manure (MD+F, MD+I+F, MD+I, F+I, and RR), resulted in significantly higher AE-P and RUE values compared with the unfertilized and uninoculated control. These results are consistent with previous studies demonstrating that improved soil fertility enhances root growth, water uptake, and transpiration efficiency, thereby increasing crop water productivity (Zwart qnd Bastiaanssen, 2004; Liu *et al.*, 2020). Further support is provided by a long-term (40-year) study in a soybean–maize rotation system, which showed that the combined application of mineral fertilizers and manure significantly increased water use efficiency, partial factor productivity of nitrogen fertilizer, and nitrogen physiological efficiency in both crops. This management practice also improved soil water conservation—particularly in the 40–60 cm soil layer—and enhanced soil nitrogen retention within the upper 60 cm, thereby reducing the risk of nitrogen leaching. The most pronounced benefits were observed with the application of 13.5 t ha^{-1} of manure (Liu *et al.*, 2024).

Economic performance closely reflected yield responses across varieties, seasons, and fertilization treatments. The improved variety TGX1910-14F and the 2019 cropping season generated higher net income (NI) and gross margin (GM) than the other varieties and the 2020 season. Compared with the traditional variety, TGX1910-14F increased NI and GM by 58% and 35%, respectively. Similarly, the RR, MD+I+F, and MD+F treatments substantially enhanced economic returns, increasing NI by 359%, 350%, and 377%, respectively, and GM by 142%, 140%, and 149%, respectively, relative to the unfertilized and uninoculated control. These results reinforce broader evidence that integrated soil fertility management (ISFM)—which combines organic amendments, mineral fertilizers, and biological inputs—can simultaneously improve crop productivity and farm profitability for smallholder soybean producers (Bambani *et al.*, 2024). Consistent with this, Ahiabor *et al.* (2014) reported significantly higher profit margins for inoculated soybean receiving 45 kg P ha^{-1} compared with non-inoculated plots supplied with the same phosphorus rate.

Overall, the positive response of soybean to the combined application of phosphorus microdose, manure, and rhizobial inoculation underscores the critical role of phosphorus availability and effective nodulation as major limiting factors in the phosphorus-deficient soils of tropical savanna agroecosystems. Phosphorus fertilization stimulates nodule initiation and development and enhances biological nitrogen fixation, while rhizobial inoculation ensures an efficient and functional symbiosis. Together, these complementary inputs improve plant nitrogen nutrition and grain yield, a response that has been consistently observed across a wide range of environmental conditions (Wei *et al.*, 2023).

CONCLUSION

This study evaluated the effects of organo-mineral microdose fertilization and rhizobium inoculation on the agronomic and economic performance of three soybean varieties in the sub-humid zone of Northern Benin. Soybean productivity varied between years, with higher yields observed under more favorable climatic conditions. Among the varieties tested, the improved TGX1910-14F consistently outperformed the traditional and other improved varieties, confirming its superior adaptability and yield potential under the study conditions. Fertilization and inoculation practices significantly influenced soybean performance. Plots receiving mineral fertilizer, microdose phosphorus, or combinations with manure and rhizobial inoculation produced higher yields than unfertilized plots. Integrated treatments combining mineral nutrients, organic inputs, and inoculation provided the greatest agronomic advantage, highlighting the importance of enhancing both soil fertility and biological nitrogen fixation. Economic analysis mirrored these results, with the highest profitability observed in treatments combining microdose fertilization with manure and/or inoculation, as well as in plots receiving recommended mineral fertilization. Overall, the findings demonstrate that integrating microdose phosphorus, manure, and rhizobium inoculation is a promising strategy to improve both soybean productivity and profitability in the low-fertility soils of Northern Benin, especially when coupled with high-performing varieties such as TGX1910-14F.

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