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Impacts of fertilization management strategies on improved sorghums varieties in smallholder farming systems in Mali: Productivity and profitability differences

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A B S T R A C T

Sorghum is an important cereal crop cultivated by smallholder farmers of Mali, contributing significantly to their food demand and security. The study evaluated different fertilization strategies that combined organic and inorganic fertilizer applications with three sorghum varieties. The experiments were conducted over three cropping seasons (2017–2019) in three sites (Bamako, Bougouni, and Koutiala respectively) within the Sudanian region of Mali. Our results showed a significant effect of season, variety, and fertilization strategies on grain and stalk yields. Grain yield increased by 8–40% in Koutiala, 11–53% in Bougouni, and 44–110% in Bamako while the average stalk yield was above 5000 kg ha^{-1} with fertilized treatment compared to unfertilized treatment in the three sites. Fadda performed the best variety, mean grain yield was 23% and 42% higher than that of Soumba and Tieble, respectively. Similarly, there was a progressive increase in grain yield with an increasing level of poultry manure (PM) from 0 to 150 g/hill and cattle manure (CM) from 0 to 100 g/hill. However, the application of 100 g/hill of CM and PM plus 3 g/hill of Di-ammonium Phosphate (DAP) increased yield by 8% and 12% respectively compared to only CM or PM treatments. The results further revealed higher yield gain by 51% (Bamako), 57% (Koutiala), and 42% (Bougouni) for T_{10}-[PM (100 g/hill) + Micro-D_DAP (3 g/hill)] equivalent to 73 $kgNha^{-1}$ than others (T_2-T_9), but not proportionate to the highest value-cost ratio (VCR). Radar charts used to visualize sustainable intensification (SI) performance in the three domains (productivity, profitability, and environment) showed that the environmental variable has a direct influence on productivity, meanwhile profitability across the strategies ranged from low to moderate value across sites and different fertilizer strategies. Our study, therefore, recommends the use of multiple-choice fertilizer strategies includingT_2-CM (50 g/hill)+PM(50 g/hill), T_5-DAP-Micro-D (3 g/hill), T_6-DAP41:46:00 and T_9-PM(50 g/hill) alongside with improved sorghum varieties tested, for higher productivity and profitability across the region.

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1. Introduction

Sorghum in the semi-arid region of Mali is primarily produced between 500 and 1200 mm rainfall isohyets [1,2] and is a basic staple food for large portions of the population. In recent times, farmers are evermore integrated into a cash-based economy, and sorghum is increasingly grown not only for food but also for cash income and animal fodder. There has been a strong demand for sorghum grain from both rural and fast-growing urban populations and processing companies [3]. Thus, improving crop yield and food self-sufficiency under increasing population growth is a primary goal for attaining food security in a smallholder farming system in Mali [4,5]. When compared with maize production, multiple studies conducted under medium to severe water stress conditions demonstrated that sorghum yield can be higher and more profitable than maize yield [6,7]. Sorghum's tolerance to variable weather patterns was also observed in a recent assessment of growth response to decadal variations in temperature and rainfall in Mali, which indicated that sorghum yield variation was not correlated to weather patterns, while maize yield was positively correlated with rainfall variations [8]. The majority of smallholder farmers in Mali are characterized as less dependent on external inputs, and hence production is often limited to satisfy the food needs of the family and livelihood improvements. Sorghum, therefore, is produced primarily to meet the food needs of the family [9].

Despite its importance to food needs, the aggregate sorghum yield has stagnated, occasionally making it to 1 t/ha in good rainfall years but often remaining around 0.75 t/ha [10,11]. Low adoption of improved agricultural technologies could be explained among others by the fact that the technology development process fails to incorporate the traits valued by farmers [12]. The overall major causes of low sorghum yield in the region include lack of access to improved seed, inappropriate sowing dates with risk of water stress, low nitrogen (N) and phosphorus (P) use, and poor crop management with few external inputs [13,14], among those limiting factors. N and water are of major relevance. On the other hand, declining soil fertility has proven a dominant constraint toward achieving improved yield in the region [15,16]. The constraints on cereal production especially sorghum escalated in Mali where cotton production is responsible for the largest share of foreign exchange earnings from agriculture [17]. The production of cotton gives farmers access to chemical fertilizer and other inputs that are provided on credit by the cotton company [8]. Many farmers in the region are unable to access inorganic fertilizer due to a lack of credit facilities, fertilizer's high cost, and lack of policy and institutional support for fertilizer use [18]. Thus, maize and other cereals, grown in rotation with cotton, benefit only from the residual effects of the fertilizer used on cotton [19]. The limited access to inorganic fertilizer and inadequate use of manure amendments is compounded by continuous cropping leading to soilnutrient mining and a decline in soil organic matter contents [19]. Recent studies suggested that inorganic fertilizer use has increased in recent years [20,21], but low yield to fertilizer response rates caused by low soil fertility remains a challenge [11,22]. Typical crop management practice that addresses soil fertility, pests, and water management is further complicated by climate variability and change. A recent meta-analysis of sorghum response to soil fertility options in Africa reported 47–98% yield increases with N and P chemical fertilizers and 43–87% yield increases with the use of organic fertilizer sources across 29 studies in Africa [23] The same study further estimated that net returns from N + P applications were higher than those from N alone, but the net returns with both mineral fertilizer treatments were considerably lower than those with sorghum–cowpea (*Vigna unguiculata*) rotations. When little or no nutrients are added to the soil as is the case with many sorghum-based cropping systems, it leads to a continuous decline in soil nitrogen which frequently results in low yields. The combination of organic resources and mineral fertilizer as inputs formed the technical backbone of the integrated soil fertility management (ISFM) approach. This is important for higher and sustained land productivity, increased efficiency of nutrient use, reduced environmental stress, and adaptation of input application rates to within-farm soil fertility gradients where these are important [24].

Traditionally, farmers broadcast manure and mineral fertilizers to supply nutrients to crops. The method of application of fertilizers to crops is found to be inefficient for increased productivity, owing to inappropriate quantities applied and the high cost of inputs in many locations in dryland areas. Micro-dosing technology consists of applying small doses of nutrient sources in the planting hills or close to seedlings immediately after emergence [25]. The techniques vary depending on soil and climatic conditions. For instance, in southern Africa, farmers use fertilizer measured out in an empty soft drink or beer bottle cap, while in the West Africa region, the farmers measure fertilizer with a three-finger pinch (ICRISAT, 2009). Farmers in the Sahelian part of West Africa use a soda bottle cap to allocate fertilizer, hence fertilizer micro-dosing is popularly known as the Coca-Cola technique [26]. This technology has also been strategically combined with other practices such as seed priming [27], water harvesting, or application of manure, crop residues, and compost prepared from household and garden wastes [28]. Organic and inorganic inputs combined render longer-lasting effects on nutrients and physical properties of the soil than those either source used alone. Farmers choose technologies that have a higher benefit/cost ratio and net positive gains with low risk. The profitability of technologies in areas with favourable conditions such as rainfall does not present a major challenge, their profitability in the semi-arid region, with multiple constraints to production, is uncertain.

With these considerations in mind that the rural communities in Mali benefit from research-driven results of improved technologies and practices for their agricultural productivity and household income. We established a multi-locations experiment using contrasting sorghum varieties, to quantify the effect of the various strategic fertilization management for improving yields in a farming system where little or no inputs are applied for sorghum crop alongside the economic feasibility of each treatment management over a growing period (2017–2019). The objective of this study was therefore to determine yield, total water use agronomic efficiency, and net return of sorghum under different strategic fertilization for sustainable sorghum production in Mali and West Africa region.

2. Material and methods

2.1. Study area, climatic condition, and soils

The experiment was established during three consecutive growing seasons (2017–2019) at the three sites. The sites were chosen along the rainfall gradient of Mali within the Sudan and Guinea savanna agroecological zones of Mali. The first site was ICRISAT experimental station (12.521°N, −8.07°W, 352 m a.s.l; Sudan savanna), Bamako. The second site was Africa RISING technology park (12.67°N,-5.72°W 306 m a.s.l; Sudan savanna) located at M'pessoba village in Koutiala region; The third site was Africa RISING technology park (11.42°N,-7.48°W 344ma.s.l; Guniea Savanna), located at Madina village, Bougouni region; These sites have a mono-modal rainfall pattern with a distinct rainy season (May–October). The experiment established at Africa RISING technology parks was used as part of innovative experiments to disseminate improved agronomic practices for increased productivity towards promoting the better livelihood of the smallholder farmers in the region. The sites have a hot tropical climate with a mean annual, maximal (minimal) daily temperature of 34.3 °C (21.5 °C) at Bamako, 33.5 °C (22.6 °C) at Koutiala and 32.3 °C (21.9 °C) at Bougouni with peaks of up to 36 °C. The composite soil samples at 0–20 cm depth were analyzed in each site for soil texture, organic carbon, N, P, K, and pH respectively. Table 1a revealed that the soil of the experimental sites is typically sandy loam and slightly acid with a pH of 5.2, 6.0, and 4.8 respectively. The organic C content in Koutiala (1.2 g kg^{-1}) and Bamako (2.3 g kg^{-1}) are slightly below the average value (3–5 g kg^{-1}) for both Sudan savannah and Sudano-Sahelian region [29]. Also, available P is below the critical level of 8 mg kg^{-1} that was established for cereal crops in the region [30]. Organic manure from both ruminants and non-ruminants has been proven as complementary organic fertilizer using micro-dosing technology [25], however, due to crop-livestock farming systems are being practiced by most smallholder farmers across the sites/region, indicates the availability of both poultry and cow manure in the regions The poultry and cow manure used during the experiment were sourced from one target farm, and each season samples of both poultry and cow manure were subjected to laboratory analysis (Table 1b), to quantify the N, P, and K content respectively in percentage.

2.2. Experimental design

The experiment had a split-plot design with four (4) replications. The main plots were three sorghum varieties [Soumba, Fadda, Tieble (CSM335)]. The sub-plots were ten (10) different fertilization strategies which consisted of inorganic fertilizer (DAP 18:46:00), cattle manure, poultry manure, and the combination of cattle manure and poultry manure, and control (Table 2). The sorghum varieties are used to represent a wide diversity of varieties cultivated by farmers in Mali. They are composed of both landraces and improved varieties. The gross size of each plot was 15 m^2 which consisted of four ridges 5 m long, spaced 75 cm apart. Sowing was done at 30 cm between plants giving a total plant population of 44,440 hills ha^{-1}. The land was harrowed and ridged with the tractor at Bamako and ridged with work bulls in Koutiala and Bougouni. The ridges were made 75 cm apart; the plots were then laid out as per treatments. In the three seasons (2017, 2018, and 2019), the experiment was established on the 17th June and 10th of July at Koutiala, the 8th of July, 11th & 10th of July at Bougouni, and 14th June 7th & 10th July at Bamako region respectively. The sowing date aligned with the optimum planting window for sorghum in the region [31]. Sowing was done at 5–7 seeds per hole at a depth of 3–5 cm and thinned to 2 plants per hill between 2 and 3 weeks after planting (WAP). In season 1 (2017) experimental plots were used to cultivate legume crops in the following season across the sites, meanwhile, the same field site was maintained for cropping seasons 2018 and 2019. Additionally, the fields were not protected from livestock grazing during the dry season, the crop residues are removed each season in order to mimic farmer practices in the study area, thus, the carry-over effect of organic residues in form of root biomass could not be noticed and was not considered in our analysis.

2.3. Data observation and analysis

Agronomic data were collected during cropping seasons including growth and yield parameters. Days to 50% flowering was observed for each treatment as the total number of days from the day after sowing to the stage when 50% of the plant stand in each

Table 1a
Physical and chemical properties of the soil (0–20 cm depth) at the three sites (Koutiala, Bougouni and Bamako).

Soil parameters	Bamako	Koutiala	Bougouni
Sand (%)	67.8	55	66.9
Silt (%)	22.8	20	18
Clay (%)	9.3	25	15
Soil texture	SandyLoam	SandyLoam	SandyLoam
pH(H20)	4.8	5.2	6.0
OC, gkg-1	2.3	1.2	5.7
Total N, gkg-1	0.2	0.1	0.5
Available P, mgkg-1	0.1	4.6	3.6
Ca, mg/kg	1.4	2.4	1.6
Mg,mg/kg	1.0	0.4	0.4
K, mg/kg	0.1	0.0	0.1
Na, mg/kg	0.1	0.1	0.1

NB: OC- organic carbon, *N*- Nitrogen, *P*- phosphorus, K-Potassium, Ca- Calcium, MgMagnesium; Na-Sodium.

Table 1b
Chemical properties of cattle dung and poultry manure samples used from 2017 to 2019.

Source	Cattle dung manure			Poultry manure		
Season	2017	2018	2019	2017	2018	2019
pH	8.37	6.19	8.32	9.35	9.81	8.20
EC (dS/m)	3.18	2.82	4.81	0.91	0.85	2.97
O·C (%)	47.88	70.97	26.45	2.59	3.78	4.38
N (%)	0.57	0.50	0.71	1.41	1.19	1.47
P (mg/kg)	12,971	12,466	23,995	6570	4885	4965
K (mg/kg)	12,099	11,729	797	1026	1099	779
Ca (mg/kg)	98.3	133.8	221.1	69.2	102.9	50.3
Mg (mg/kg)	92.5	54.8	59.4	101.7	66.6	111.8

NB: **EC**- electrical conductivity, ***OC***- *organic carbon,* ***N***- *Nitrogen,* ***P***- *phosphorus,* ***K****Potassium,* ***Ca***- *Calcium,* ***Mg****Magnesium.*

Table 2
Fertilization strategy and total N applied (kgha^{-1}) per treatment.

Notation	Treatment/Unit	DAP/Urea	Dried Cattle Manure	Dried Poultry Manure	Total N applied
		kgha^{-1}			
T_1	Control	–	–	–	–
T_2	CM (100 g/hill)		4450	–	22
T_3	CM(100 g/hill)+DAP (3 g/hill)	133	4450	–	46
T_4	CM(50 g/hill)+PM (50 g/hill)		2220	2220	36
T_5	DAP Micro_D (3 g/hill)	133	–	–	24
T_6	DAP41:46:00	228	–	–	41
T_7	PM (100 g/hill)	–	–	4450	49
T_8	PM (150 g/hill)	–	–	6670	73
T_9	PM (50 g/hill)	–	–	2220	25
T_{10}	PM(100 g/hill)+DAP (3 g/hill)	133	–	4450	73

NB DAP- Di-ammonium phosphate; CM-Cattle Manure, PM-Poultry manure.

replicate plot (approx. 7.5 m^2) had flowered. Also, grain and stalk yields were measured from harvested two rows at the center of each plot [7.5 m^2 area (5 m × 1.5 m)]. The panicle and stalk were sun-dried for 2 weeks before threshing. Grain and stalk yields (kg ha^{-1}) were determined. Data were subjected to analysis of variance (ANOVA) using GEN STAT analytical tool (19th edition). Year, fertilization strategy, and variety were taken as factors to determine the level of significance at 5% probability. Fisher's least-significant difference (LSD) test was computed where the *F* values were significant at the $P = .05$ level of probability [32]. Type III analysis of variance and graphical illustration in "R" by Kenward-Roger's method was further used to explore the effect of different levels of poultry and cattle manure applied on the measured grain and stalk yield across years and sites [33]. Additionally, we defined sustainable intensification (SI) as increasing crop yield while reducing negative environmental impacts and at the same time enhancing positive ones [34]. Thus [35], have developed a sustainable intensification assessment framework (SIAF) incorporating five domains to define and assess sustainable intensification which include productivity, economic, environmental, human, and social domains. In this study, the analysis of three out of five SI indicators were applied including productivity (Grain + stalk yield), profitability (net-income), and environment (calculated as TWU) by converting into absolute value (range from 0 to 1) using radar charts diagram. This helps to assess promising fertilization strategies for each site and sorghums used through the interaction of the SI indicators.

Total water use (TWU), water use efficiency (WUE), agronomic efficiency (AE), Gross margin for N applied, and value cost ratio (VCR).

The estimation of total water use (TWU) by sorghum varieties during growing seasons across the fertilization strategies was calculated using reference crop evapotranspiration (ET_o) by recommended crop coefficient (K_c) for sorghum [36]. The Penman-Monteith equation was used to calculate reference evapotranspiration (ET_o). The variables of this equation were described in FAO Irrigation and Drainage Paper No.56 [37] as described below.

$$TWU = K_c\, ET_o \tag{1}$$

$$ET_o \frac{0.408\Delta(R_n - G) + Y\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + Y(1 + 0.34u_2)} \tag{2}$$

where.

ET_o: reference evapotranspiration [mm day^{-1}]; R_n: net radiation at the crop surface [MJ m^{-2} day^{-1}]; G: soil heat flux density [MJ m^{-2} day^{-1}]; T: mean daily air temperature at 2 m height [°C]; $u_{2:}$ wind speed at 2 m height [m s^{-1}]; e_s saturation vapour pressure [kPa]; $e_{a:}$ actual vapour pressure [kPa]; e_s - e_a:saturation vapour pressure deficit [kPa]; D: slope vapour pressure curve [kPa °C^{-1}]; ɣ: psychrometric constant [kPa °C^{-1}].

In the context of integrated soil fertility management (ISFM), we computed agronomic efficiency (AE) across different fertilizer sources tested. AE is a measure of the amount of additional grain yield obtained per kilogram of nutrient applied [38]. AE is used for making a rough evaluation of the efficiency of N fertilizer use but does not provide information on economic incentives.

AE is defined as the incremental return to applied inputs, or

$$\mathrm{AE} - \mathrm{X}(\text{kg grain / kg nutrient } \mathrm{X}) = \frac{(\mathrm{Y_f} - \mathrm{Y_c})}{\mathrm{X_{appl}}} \tag{3}$$

where.

Y_f and Y_c refer to yields (kg/ha) where nutrients have been applied (Y_f) and in the control plot (Y_c); X_{appl} is the amount of nutrient X applied (kg nutrient/ha) from either fertilizer or organic inputs.

Furthermore, the gross margin for *N*-applied was calculated as the extra grains produced resulting from the differences between fertilized and unfertilized treatment multiplied by the local price of grain at the time of harvest. Here, the cost of inputs and the labour related to micro-dosing applications were not considered. Also, the value cost ratio (VCR) was calculated to make an assessment of the economics of the fertilizer application by comparing the value of additional yield with the cost of the inputs required to achieve the yield increase [39].

$$\mathrm{VCR} = \frac{\text{Extra grain produced(kg) x value of the produce (FCFA/kg)}}{\text{Inputs applied (kg) x cost of inputs (FCFA/kg)}} \tag{4}$$

The analysis was carried out based on the prevailing market price including the cost of sorghum grain each year, and poultry or cow manure per bag in the study areas, to assess promising fertilization technologies for each location and site under a sorghum-based cropping system. Also, the grain yield threshold of 2000 kg ha^{-1} was determined as a break-even yield that farmers can produce

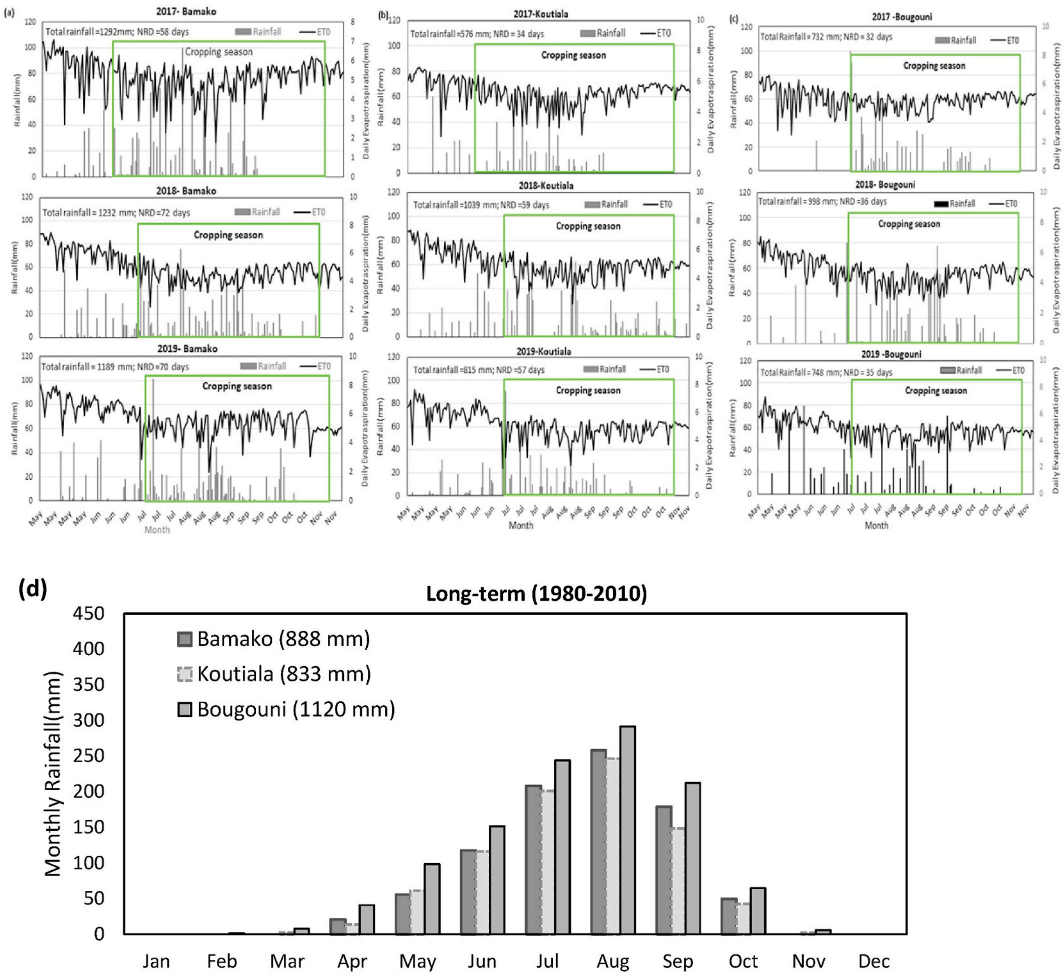

Fig. 1. (a–c): Daily rainfall, number of rainy days (NRD), and daily evapotranspiration during 2017–2019 growing seasons at the experimental sites in Bamako, Koutiala, and Bougouni respectively. (d): Average monthly rainfall (1980–2010) at the experimental sites in Bamako, Koutiala and Bougouni respectively. [in-comparison with the seasons of experiment].

for marginal economic benefit as earlier reported by Ref. [31].

3. Results

3.1. Rainfall distribution during cropping seasons in the study area

Daily rainfall was recorded at each site with the aid of an automatic rain gauge in Bamako and manual rain gauge installation in Koutiala and Bougouni. During the experiment (2017–2019), average annual rainfall over the 3-year cropping seasons was 1237, 810, and 826 mm for Bamako, Koutiala, and Bougouni respectively (Fig. 1). The growing season daily rainfall at Koutiala and Bougouni indicate low to high rainfall variations with low daily rainfall intensity compared to Bamako indicated high rainfall intensity within the season resulted to higher cumulative rainfall. There was high variability in the total number of rainy days (NRD) ranging from 32 to72 days across the sites. Comparatively, the GSR over the three years period (2017–2019) was higher than the average rainfall (1980–2010) of 888 mm in Bamako (Fig. 1a and d); below the average of 833 mm observed in Koutiala except for the year 2018 (Fig. 1b); below the average of 1120 mm in Bougouni (Fig. 1c). As shown in Fig. 1a and c, the cumulative rainfall received in the month of July and August constitutes about 44–72% (Bamako and Bougouni) and Fig. 1b shows 52–65% of average growing season rainfall (GSR) over Koutiala. The results indicate more rainfall was received at Bamako and Koutiala (except in the year 2017) than in Bougouni over the three cropping seasons. However dry spells observed in Koutiala and Bougouni regions during the growing season occurred between May and mid-July that coincides with the early vegetative growth stage of the sorghum. Evapotranspiration (ET) is a key component of water balance and is used to determine the appropriate sowing period for sorghum to avoid crop failure. During the experiment, the daily evapotranspiration was progressively lower throughout the cropping season (May–Oct) with the lowest value in the month of August which coincides with peak rainfall across the sites. The daily average evapotranspiration over the cropping season (3-year mean) ranged from 2.2 to 6.2 mm in Bamako, 2.7–5.5 mm in Koutiala, and 2.3–5.8 in Bougouni.

Table 3
Effect of season, fertilizer strategy, and variety on days to 50% flowering, grain and stalk yields for Bamako, Koutiala and Bougouni respectively (average of 2017–2019 experiments).

Site	Bamako			Koutiala			Bougouni		
Treatment/ Unit	50% Flowering Days	Grain yield kgha^{-1}	Stalk yield	50% Flowering Days	Grain yield	Stalk yield kgha^{-1}	50% Flowering Days	Grain yield kgha^{-1}	Stalk yield
Season (S)									
2017	95	1935	6021	96.02	1944	12,681	78	2715	11,847
2018	81	2045	6336	76.07	2748	10,500	75	1682	7612
2019	84	2260	7014	82.41	2143	8614	65	1809	6418
p level	***	***	***	***	***	***	***	***	***
LSD (0.05)	0.73	131	495	0.642	113.6	820	1.21	129	653
Fertilization Strategy(FS)									
T_1	90	1132	4030	84.84	1684	10,910	73	1365	7049
T_2	87	1930	6189	85.42	2313	10,239	73	1793	7632
T_3	86	2136	7296	83.42	2156	10,157	73	2218	9501
T_4	88	2059	6631	84.78	2359	11,725	73	2119	8998
T_5	88	1921	5408	85.36	2147	9476	74	2036	8580
T_6	87	1965	5375	84.72	2300	10,669	72	2142	9184
T_7	86	2237	6583	84.92	2316	10,607	73	2266	9691
T_8	86	2155	7416	85.64	2262	10,228	73	1993	7989
T_9	86	2080	6015	86.56	2150	10,746	72	1805	6868
T_{10}	86	2467	7200	82.72	2502	11,537	74	2248	9188
p level	***	***	***	**	*	ns	ns	**	***
LSD (0.05)	1.19	274	981	1.44	220	1776	2.07	265	1311
Variety (V)									
Fadda	89	2720	7023	88.56	2591	12,325	72	2488	9913
Soumba	80	1976	5646	76.72	2045	10,052	71	2054	8526
Tieble	91	1543	6702	89.23	2199	9417	75	1664	7437
p level	***	***	***	***	***	***	***	***	***
LSD (0.05)	0.65	150	537	0.79	121	9723	1.10	145	718
Mean	87	2080	6457	84.84	2278	10,598	72.9	2069	8626
CV%	3.3	24.6	18.1	3.1	19.6	20.6	6.5	15.8	18.7
Interaction									
FS*V	*	ns	ns	ns	ns	ns	ns	ns	ns
S*FS*V	ns	ns	ns	ns	ns	ns	ns	ns	ns

***, ** and * mean significant different at $p < .001$, $p \leq .01$, $p \leq .05$; ns: not significant; CV**%-** coefficient of variations; [T_1- Control; T_2- CM (100 g/hill); T_3 - CM (100 g/hill)+ DAP(3 g/hill) Micro-D; _T_4 –CM (50 g/hill) + PM (50 g/hill); T_5- DAP (3 g/hill) Micro-D; T_6- DAP41:46:00; T_7-PM (150 g/hill); T_8-PM(100 g/hill); T_9-PM (50 g/hill); T_{10}- PM (100 g/hill)+ DAP(3 g/hill) Micro-D].

3.2. Effect of fertilization strategy and treatments on days to 50% flowering

There was a significant effect of fertilization strategy, and sorghum variety at Bamako and Koutiala except for the Bougouni site (Table 3). The days to 50% flowering observed was generally longer in 2017 (95 days in Bamako; 96 days in Koutiala and 78 days in Bougouni) compared to that of the 2018 and 2019 seasons in the three sites. The higher value of observed days to 50% flowering in the 2017 season could be associated with the slight decline in NRD. In Bamako, the control without fertilizer (T_1) observed delayed flowering (average of 90 days) compared to other treatments (T_2-T_{10}) varied between 86 and 88 days. In Koutiala, 50% flowering was observed between 83 and 87 days across the treatments. Highly significant differences were observed among the sorghum varieties with Tieble (CSM335) having the highest observed mean of 91 days in Bamako; 90 days in Koutiala and 75 days in Bougouni followed by Fadda while the least observed mean was Soumba variety. Though all the sorghum varieties are characterized as medium-maturing sorghum, Soumba attained 50% flowering earlier, 10 days earlier than Fadda and Tieble.

3.3. Effect of fertilization strategy and treatment on grain and stalk yield

The average grain and stalk yields were significantly different among season, fertilization strategy, and sorghum varieties except for stalk yield in Koutiala (Table 3). In Bamako, grain and Stalk yields produced were significantly higher in the 2019 season (2260 and 7014 kg ha-1) than in the 2018 and 2017 cropping seasons. In Koutiala, the highest mean stalk yield (12,681 kg ha^{-1}) was produced in the 2017 season which was higher by 21 and 47% than the stalk yield produced in the 2018 and 2019 growing seasons. On average, there was a significant yield gained in 2018 which was 41 and 28% higher than that of 2017 and 2019 cropping seasons. At Bougouni, the average grain and stalk yields were significantly higher in the 2017 season (2715 and 11,847 kg ha^{-1}) than 2018 and 2019 seasons. Grain yield of T_2-T_{10} increased by 70–118% in Bamako; 28–49% in Koutiala, and 31–65% in Bougouni compared to control (T_1). At a mean grain yield threshold of $\geq$2000 kg ha^{-1}, T_3, T_4, T_7, T_8, T_9, and T_{10} produced higher than other treatments in the Bamako site. In Koutiala, T_2 – T_{10} was produced higher than other treatments meanwhile at the Bougouni site, T_3 –T_7 and T_{10} produced higher grain yield than other treatments. Over the 3-year cropping seasons, T_{10} - [Poultry manure (100 g/hill) + DAP (3 g/hill)] indicated *N*-rate of 73 kgha^{-1} produced the highest mean grain yield of 2467 kgha^{-1} (Bamako), 2502 kgha^{-1} (Koutiala) and 2248 kgha^{-1} (Bougouni) respectively suggesting an increase in grain yield with the increase in N rate applied.

There was a significant difference among the sorghum varieties (Table 3). Fadda produced the highest mean grain yield which was increased by 37 and 76% (at Bamako); 27 and 18% (at Koutiala); 20 and 50% (at Bougouni) for Soumba and Tieble. As shown in Fig. 2a-b, the analysis of different rates of poultry and cattle manure or combination against control treatment on grain yield, indicating a significant difference at $p < .002$ for sites, $p < .0001$ for fertilizer strategies, the interaction between sites and treatment at $p = .464$. Also, there was a progressive increase in grain yield with an increasing level of poultry manure (PM) from 0 to 150 g/hill and cattle manure (CM) from 0 to 100 g/hill. The application of 100 g/hill of either CM or PM plus DAP (3 g/hill), the grain yield increased by 8% and 12% respectively compared to only CM or PM treatments. The combined application of CM (50 g/hill) +PM (50 g/hill) produced above 2000 kg ha^{-1}. Fig. 3a and b reveals that both C and M and PM produced higher stalk yield than unfertilized treatment. The results showed mean significant differences at $p < .00001$ for sites and fertilizer strategies, and interaction between sites and treatment at $p < .003$. Stalk yield with increasing rate of poultry manure (PM) from 0 to 150 g/hill and also for cattle manure (CM) from 0 to 100 g/hill for grain yield. The addition of DAP 3 g/hill to 100 g/hill of either CM or PM produced the highest mean stalk yield.

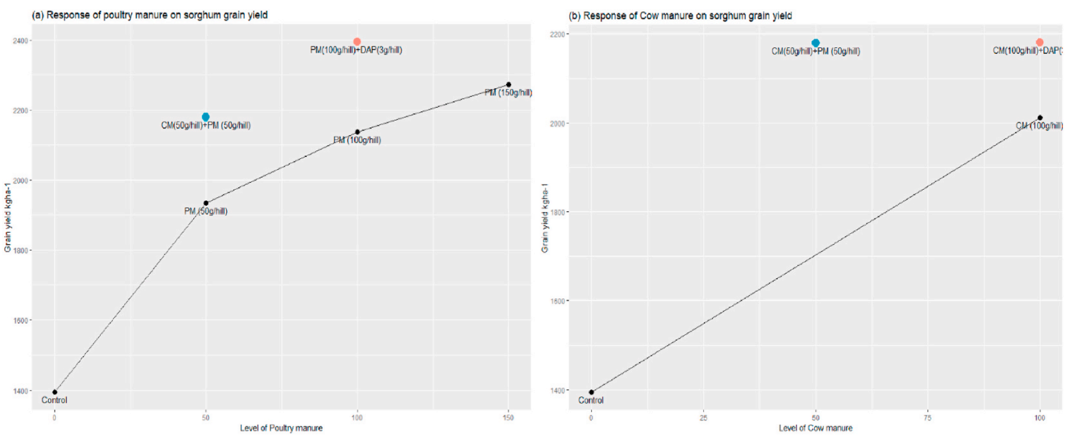

Fig. 2. a–b: Response of different level of poultry and cattle manure on grain yield across the three sites. *Type III analysis of variance by Kenward-Roger's method showed mean significant different at* $p < .002$ *for sites,* $p < .0001$ *for fertilization strategies, interaction between sites and treatment at* $p = .464$.

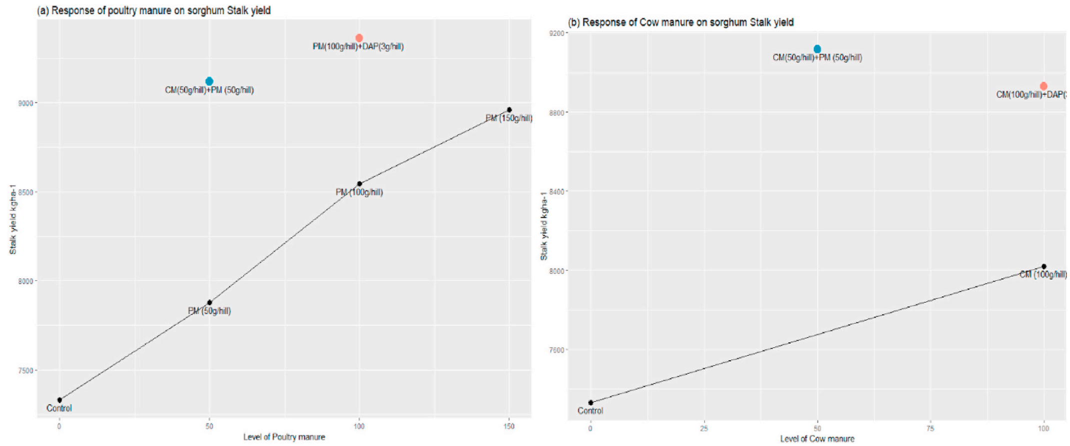

Fig. 3. a–b: Response of different level of poultry and cattle manure on stalk yield across the three sites. *Type III analysis of variance by Kenward-Roger's method showed mean significant different at p < .00001 for location and fertilization strategies, interaction between sites and treatment at p < .003.*

3.4. Agronomic efficiency, profitability, and SI indicators

The agronomic efficiency (AE) was highly significant and differed among the season, fertilizer strategies (T_2-T_{10}), and sorghum varieties across the sites (Table 4). The results revealed higher AE value in the 2018 cropping season than that of 2017 and 2019 cropping seasons in Bamako and Koutiala, while at the Bougouni site, the 2017 season was higher by 38 and 43% than that of the 2018 and 2019 seasons respectively. Similarly, AE values across the fertilizer strategies (T_2-T_{10}) were higher in Bamako than Bougouni and

Table 4
Effect of year, fertilizer strategy and variety on agronomy efficiency (AE), Gross margin for N used, and value: cost ratio (VCR) in Bamako, Koutiala and Bougouni respectively.

Site	Bamako			Koutiala			Bougouni		
Treatment/ Unit	AE kg/ kgN	Gross Margin for N used FCFA ha^{-1}	VCR	AE kg/ kgN	Gross Margin for N used FCFA ha^{-1}	VCR	AE kg/ kgN	Gross Margin for N used FCFA ha^{-1}	VCR
Season(S)									
2017	16.0	90,135	1.0	14.3	70,189	0.7	24.6	119,005	1.3
2018	36.1	211,643	2.2	21.0	97,199	1.1	15.2	73,442	0.8
2019	22.3	127,237	1.3	12.0	57,158	0.6	13.9	71,595	0.7
p level	***	***	***	***	***	***	***	***	***
LSD (0.05)	4.63	22,883	0.3	3.27	14,825	0.19	4.09	18,508	0.23
Fertilization Strategy (FS)									
T_2	35.8	119,607	1.2	14.0	80,820	0.6	19.3	53,543	0.5
T_3	21.8	150,625	1.1	20.2	56,179	0.6	18.5	106,631	0.8
T_4	26.1	138,969	1.3	19.0	84,321	1.0	21.2	94,221	1.1
T_5	20.5	126,315	1.8	11.3	57,879	1.1	28.1	83,909	2.0
T_6	34.8	124,893	2.2	25.7	76,912	1.9	19	97,184	1.4
T_7	22.6	165,676	1.3	8.6	78,933	0.4	12.1	110,378	0.7
T_8	14.0	153,446	0.8	11.8	72,253	0.6	12.8	78,582	0.6
T_9	29.3	107,260	1.7	19.0	58,188	1.3	18	54,973	1.0
T_{10}	18.3	200,256	1.2	11.9	108,156	0.7	12.3	112,705	0.6
p level	***	**	***	***	**	***	***	**	***
LSD (0.05)	7.681	43,636	0.53	5.75	27,456	0.3	6.9	33,229	0.34
Variety (V)									
Fadda	38.1	219,309	2.3	18.7	89,414	1.0	21.8	110,365	1.1
Soumba	20.3	114,614	1.2	14.1	64,174	0.7	15.4	75,242	1.0
Tieble	15.9	95,093	1.0	14.4	70,959	0.7	16.6	78,435	1.0
p level	***	***	***	**	**	**	**	***	**
LSD (0.05)	4.2	23,900	0.29	3.2	15,038	0.16	3.76	18,200	0.19
Mean	24.8	143,005	1.5	15.7	74,849	0.8	17.91	88,014	0.93
CV (%)	38.1	37.6	43.9	45	45.2	46.3	47.1	46.5	45.1
Interaction									
FS*V	ns	ns	ns	ns	ns	ns	ns	ns	ns

***, ** and * mean significant different at p < .001, p ≤ .01, p ≤ .05; ns: not significant; CV%- coefficient of variations; [T_1- Control; T_2- CM (100 g/hill); T_3 - CM (100 g/hill)+ DAP(3 g/hill) Micro-D; _T_4 –CM (50 g/hill) + PM (50 g/hill); T_5- DAP (3 g/hill) Micro-D; T_6- DAP41:46:00; T_7-PM (150 g/hill); T_8-PM(100 g/hill); T_9-PM (50 g/hill); T_{10}- PM (100 g/hill)+ DAP(3 g/hill) Micro-D], FCFA =West African CFA franc.

Koutiala sites, which implies that for every kilogram of nitrogen utilized, more kilogram of grain is produced. These results showed the addictive effects of manure (cattle and poultry) and inorganic fertilizer under low inherent soil fertility conditions in Bamako compared to Bougouni and Koutiala. Across the sites, AE value increase with decreased *N*- rate application. For example, at the Bamako site, the highest AE value was 36 kg grain/kg N at 22 kgNha^{-1} applied for T_2. Conversely, T_8 and T_{10} produced the lowest AE values, 14 and 18.3 kg grain/kg N respectively at 73 kg Nha^{-1} which was at a higher rate. The results showed that all the fertilizer strategies, T_2-T_{10} except for T_8 in Bamako; T_3, T_4, T_6, and T_9 respectively in Koutiala; T_2 - T_6, and T_9 in Bougouni were higher than the average threshold AE of 17 kg grain/kg N. Additionally, the estimated AE value was significantly higher for Fadda indicating 38.1 kg grain/kg N (Bamako), 18.7 kg grain/kg N (Koutiala), and 21.8 kg grain/kg N (Bougouni) compared to Soumba and Tieble.

Highly significant differences (Table 4) were seen among the year, fertilization strategies and sorghum varieties across the sites for gross margin for N applied and value: cost ratio (VCR). In the 2018 cropping season, the estimated gross margin for N applied and VCR was higher indicating 211,643 FCFAha^{-1} and 2.2 (Bamako), 97,199 FCFA ha^{-1} and 1.1 (Koutiala) than that of 2017 and 2019 cropping seasons while at Bougouni site, 2017 season was significantly higher than 2018 and 2019 season. Across the treatments, the estimated highest gross margin for N used did not equate to the highest VCR, due to variations in grain yields produced by the sorghum varieties. The mean highest gross margin by T_{10} in Bamako (200,256 FCFA ha^{-1}) and Koutiala (106,156 FCFA ha^{-1}) which was 51% and 57% compared to other fertilization strategies (T_2-T_9). At the Bougouni site, T_{10} had the highest gross margin of 42% (112,705 FCFA ha^{-1}) which was at par with T_7 (110,378 FCFA ha^{-1}) and higher than other treatments. Also, VCR varied among the fertilization strategy, ranging from 0.8 to 2.2 (Bamako); 0.6–1.9 (Koutiala), and 0.6–2.0 (Bougouni) with T_6 (DAP41:46:00) had the highest value

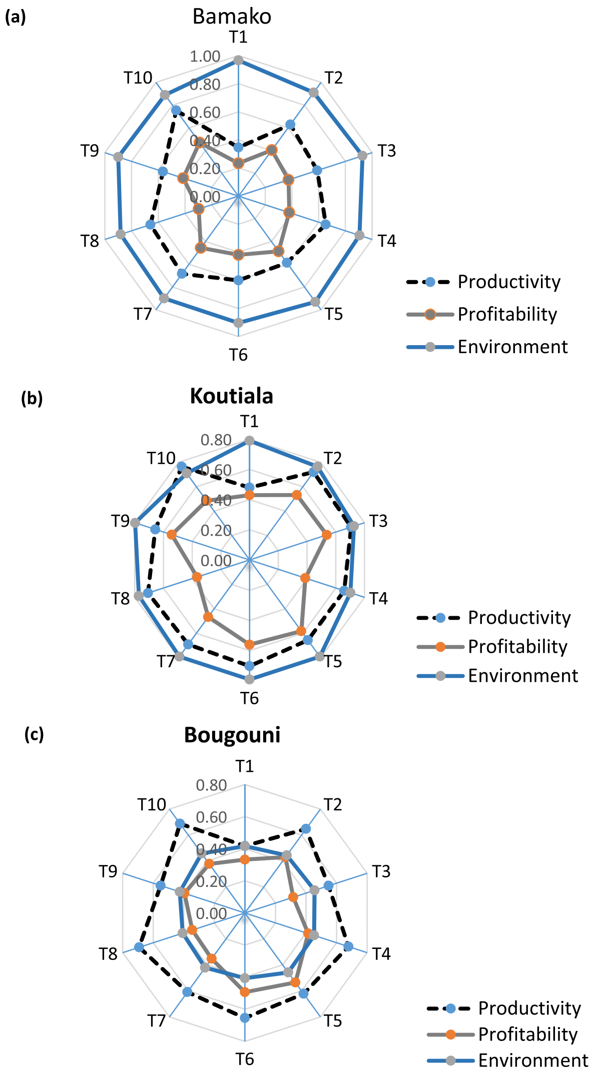

Fig. 4. Sorghum productivity and profitability trade-off with Environment (calculated as TWU) under different fertilization strategies in (a) Bamako; (b) Koutiala; and (c) Bougouni regions of Mali. *[T_1- Control; T_2- CM (100 g/hill); T_3 - CM (100 g/hill) + DAP(3 g/hill) Micro-D;_T_4 –CM (50 g/hill) + PM (50 g/hill); T_5- DAP (3 g/hill) Micro-D; T_6- DAP41:46:00; T_7-PM (150 g/hill); T_8-PM(100 g/hill);T_9-PM (50 g/hill);T_{10}- PM (100 g/hill) + DAP(3 g/hill) Micro-D].*

corresponding to 41 kg N ha^{-1}. Following the average threshold VCR of $\geq$1, farmers in Bamako have more profits for use of N either organic or inorganic fertilizer compared to the limited choices available for farmers in Koutiala and Bougouni. Also, the estimated gross margin for N used and VCR by Fadda variety was significantly higher than that of Soumba and Tieble varieties across the locations. However, the farmers may not break even (VCR <1) using Soumba and Tieble varieties in Koutiala.

On SI indicators performance, the results are presented using radar charts to facilitate comparisons of the different fertilizer strategies in the three domains [productivity, profitability, and environments (calculated TWU)] for all the sites (Fig. 4a–c), to further identify technology viable for adoption and implement across farms in Mali. At all sites, T_1-unfertilized sorghum productivity was very low below 0.5 and fertilized sorghum productivity was strongly responsive to the environment, where productivity was highest with T_{10}-PM(100 g/hill)+DAP (3 g/hill). Also, the profitability indicates very low to moderate values estimated across different fertilization strategies. In Fig. 4, Bamako, T_5, T_6, T_7 & T_{10} were higher and had a similar level of net returns compared to other treatments based on the average productivity. In Koutiala (Fig. 4b), T_2, T_3, T_5, T_6, T_9 & T_{10} had a similar level of profit at current average productivity compared to others while the highest net returns by T_6 (DAP41:46:00) followed by T_5 [DAP Micro-D (3 g/hill)]. Fig. 4c represents Bougouni shows T_2, T_5, T_6 & T_9 had similar levels of net returns which were higher compared to other treatment sources. There was a strong effect of environment on productivity across different fertilization strategies in Bamako and Koutiala than in Bougouni.

4. Discussion

Our study has demonstrated the fertilization strategy through the micro-dosing technique of organic sources and inorganic fertilizer (Di-ammonium phosphate, DAP) or the combination of both to sorghum plants offered improved productivity, increased agronomic efficiency, and high economic returns. The effect of fertilizer strategy on days to flowering suggests genotypic differences in phenological development between seasons due to available water content to the crop [40]. The results further showed that sorghum yields (grain and stalk) could be better under fertilized conditions compared to unfertilized conditions with respect to inherent soil fertility. The results were in agreement with the findings by Ref. [20] that sorghum yields increase with the increase in the amount of *N*-applied. Additionally, our results have shown that strategic hill fertilization otherwise called micro-dosing technology has great potential to improve sorghum productivity in a low-input farming system, as its identified as a climate-smart technology [41]. Similar findings were reported for pearl millet in Niger where the application of 6 g NPK fertilizer per hill double millet yields obtained from the farmer's traditional practice [42] and also positive economic benefits to the use of fertilizer [43,44]. There was a statistically significant effect of fertilization strategy on agronomy efficiency (AE) across the sites due to varying N applied. These results agreed closely with the findings reported by Ref. [38] that when applying very large amounts of nutrient inputs, AE is reduced and conversely lower amount of nutrient inputs will lead to an increase in AE. These strategies are also highly profitable as evidenced by their favourable gross margins and a high value–cost-ratio indicated multi-choice fertilizer strategies across the sites. Though a positive response to microdose fertilization was observed, generally, low VCR was estimated across the treatments and sites. These results were in agreement with the finding by Ref. [45] for millet production. On the contrary [46], showed to achieve higher VCR using lower quantities of fertilizer at a rate of 0.3 g NPK per planting hill. However, our results are found reproducible in a low inputs farming system because the experiment was managed to replicate typical farmers' practices.

4.1. Implications of fertilizer strategies under micro-dosing techniques for scaling and adoption in smallholder farming system

It is obvious that farmers in the two agroecological zones of Mali are facing low farm income due to low inherent soil fertility or inadequate use of required inputs resulting in low yields [28]. It has been shown that ISFM using micro-dosing technology has great potential to improve sorghum productivity and soil health in the region, though significant variability among the sorghum varieties relative to fertilization strategies across the three sites. This agreed with the statement of [47]; that ISFM is a holistic approach to declining soil fertility constraints that embraces the full range of driving factors and consequences of soil degradation. Furthermore, the use of both organic and inorganic fertilizers could further improve soil structure, increase soil organic matter, and enhance nutrient uptake by plants. The application of micro-dosing technology is strategic whereby a small amount of fertilizer either organic or inorganic with seeds of the target crop in the planting hole at sowing or a few weeks (3–4) after planting [25,44]. This technology is affordable to poor resource farmers and gives plants a quick start, avoiding end-of-season terminal drought resulting in an increase in yield. Poultry litter and cattle dung were readily available in most communities, and this has the potential to be an alternative source of nitrogen or complementary with mineral phosphorus fertilizer (DAP-Di-ammonium phosphate) for plant growth and increase sorghum productivity in smallholder farms when an appropriate quantity is applied. For instance, treatment fertilized with T_2-Cattle manure (100 g/hill), T_5-DAP (3 g/hill) and T_9-Poultry manure (50 g/hill) implies N application of 22, 24, and 25 kg ha^{-1} respectively. It showed a significant increase in grain yield by 70,74 and 84% in Bamako; 37, 27, and 28% in Koutiala; 31, 49, and 32% in Bougouni respectively compared to unfertilized treatment. Our results further revealed that cattle manure (100 g/hill) +DAP (3 g/hill) and poultry manure (100 g/hill) +DAP (3 g/hill) produced grain increase by 89 and 118% in Bamako, 28 and 49% in Koutiala while 62 and 65% increase was observed in Bougouni compared to unfertilized treatment. In addition, the VCR $\geq$1 portrays treatments not only for higher productivity but economically viable for farmers in the region to adopt.

Though, soil nutrient mining and labour-intensive challenges have raised concerns of some researchers and farmers [48]. In some instances, the lack of available household labor and resource (for example organic manure, and farm equipment for mechanization), and skills required to implement the recommendations could serve as limitations to the technology [49]. Nevertheless [50], have opinioned that fertilizer micro-dosing can contribute usefully to sustainable agricultural development and increasing crop yields, by judicious use of organic manures or in combination with little portions of inorganic sources for nutrient use efficiency. Hence, the principle that makes organic manure useful and important in soil fertility maintenance is its impact on soil fertility moisture-holding capacity, and structural characteristics [51]. The introduction of mechanization equipment by agricultural actors in the region is another important recommendation.

5. Conclusion

Our findings provide insight into appropriate agronomic and economic nutrient management practices that can help farmers profitably manage sorghum production under low soil fertility conditions. The study further demonstrated the benefit of integrated soil fertility management (ISFM) under a smallholder farming system for sustainable sorghum productivity and profitability using organic manure from both ruminants and non-ruminants as alternate or complementary organic fertilizer using micro-dosing technology. Also, the technology has great potential for increasing the nutrient use efficiency of crops and farmers' income as added benefits. The study confirmed the increased productivity of sorghum with the application of manure (either poultry or cattle) or combination with inorganic fertilizer to boost the inherent soil fertility and the water-holding capacity of the soil over time. Our study further revealed that the fertilization strategies with high-yielding potential did not necessarily result in high VCR due to variations in inputs cost and differences in variety-yielding potential. We, therefore, recommend.

- The use of high-yielding improved varieties along with multiple-choice fertilization strategies for higher productivity and profitability;
- Use of only Fadda and Soumba varieties in Koutiala and all the three sorghum varieties in Bougouni along with multiple choices of fertilization strategies [Cattle (50 g/hill) +Poultry (50 g/hill)], [DAP Micro-D (3 g/hill)], [DAP 41:46:00] and [Poultry manure (50 g/hill) for farmers in Koutiala for both high profitability.

Agricultural intensification in Mali and other Sahelian countries is difficult because of the insecurity prevailing in the region. The fertilizer strategies recommended in our study can therefore be considered the entry points for sustainable agricultural intensification in the drylands of West Africa because the technology will not unnecessarily expose the farmers to additional risk as the cash outlay is very low and with a low risk of crop failure and thus produced higher yields than the control (farmers' practice). We, therefore, further recommend that future research and development activities should focus on breaking the highlighted limitations by promoting the use of small-scale mechanization equipment among the smallholder farmers in the region.

Author contribution statement

Folorunso Mathew Akinseye: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Birhanu Zemadim Birhanu; Hakeem Ayinde A. Ajeigbe: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Madina Diancoumba: Performed the experiments; Wrote the paper.

Karamoko Sanogo: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Ramadjita Tabo: Conceived and designed the experiments.

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Data availability statement

Data associated with this study has been deposited at https://dataverse.harvard.edu/dataverse.xhtml?alias=AfricaRISING.

Declaration of interest's statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

No additional information is available for this paper.

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