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# Microdosing of Compost for Sustainable Production of Improved Sorghum in Southern Mali

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**Abstract:** The depletion of soil organic matter is one of the major challenges constraining agricultural production in the southern zone of Mali. This study evaluated the effects of compost types, methods, and dose applications on the productivity and sustainability of sorghum. Two types of compost (farmer practice and cotton stems) were applied to sorghum at two rates (microdosing at 2.5 t ha$^{-1}$ and broadcasting at 5 t ha$^{-1}$) and evaluated on 30 farmer fields in 2019 and 2020. The treatments used included CPA (cotton stem compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), CPA (cotton stem compost at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), CP (farmer compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), CP (famer compost at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), control (100 kg ha$^{-1}$ DAP), and control. The results showed that regardless of the compost type, applying a microdose of 2.5 t ha$^{-1}$ improved the growth rate, plant height, grain yield, and biomass yield by 15%, 18%, 47%, and 27%, respectively, when compared to the control. No statistical difference was observed in the yield of 2061 kg ha$^{-1}$ between applying compost by microdosing at 2.5 t ha$^{-1}$ and broadcasting at 5 t ha$^{-1}$. It can be inferred that the application of compost by microdosing makes it possible to achieve a 100% fertilized surface compared to broadcasting, with a nitrogen use efficiency of more than 55%. The application of compost by microdosing at 2.5 t ha$^{-1}$ resulted in an economic gain of 334,800 XOF ha$^{-1}$, which was 27% higher than that obtained with the application of compost by broadcasting at 5 t ha$^{-1}$. Conversely, the contribution to the improvement of soil nitrogen stock varied from 12–20% with a microdose of 2.5 t ha$^{-1}$ compared to 100% for broadcasting compost at 5 t ha$^{-1}$ per application. Therefore, the availability of cotton stems in the southern zone of Mali presents an opportunity for farmers to implement compost microdose technology to double the fertilized area and improve sorghum productivity.

**Keywords:** organic manure; broadcasting; yield; fertilizer; Sahel

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## 1. Introduction

One of the main constraints of agriculture in Mali remains the depletion of soil organic matter [1]. This situation is aggravated by the practice of continuous land cultivation without sufficient nutrient additions due to low access to mineral fertilizers that are costly [2] but also demographic pressures on land [3] that lead to low crop yields [4]. The bi-annual recommendation of 5 t ha$^{-1}$ of manure [5] is not available to all farmers to cover farm needs [6]. About 68% of Malian farmers are poor smallholders who lack the financial resources to purchase mineral fertilizers [7]. Thus, composting using cereal residues in combination with cattle dung was developed to fill the nutrient gaps and ensure sustainable agricultural production [8]. This practice contributed to the development of cotton sectors in Mali and the Sahel countries [5,9].

Unfortunately, composting is being limited by several factors. For instance, cereal biomass is becoming increasingly insufficient to be used for both animal feed and compost production following increases in human populations that demand plant and animal-based food [10,11].

The southern zone of Mali is characterized by a cotton-based cropping system that occupies 32–41% of cropland [6]. With an average annual production of about 760,000 t of seed cotton [12], there is a significant amount of biomass produced, which remains an opportunity for compost production.

The farmer practice of manure use in the southern zone of Mali is characterized by targeted application, taking into account soil fertility status, access to manure, and the rotation system. Manure is usually applied to poor fields in order to restore fertility lost by crop exports. Thus, the quantities contributed per hectare vary according to the crop and soil types [1]. Faced with the need to remain on the same fields, farmers who are resource-endowed prefer to fertilize cotton and maize and hope that the millet and sorghum crops that follow will benefit from the residual effects of fertilization [11].

Owing to the low availability of manure and limited access to agricultural inputs, including mineral fertilizers, resulting in low crop yield [13], fertilization technology by microdosing or localized plant-hole fertilization with low doses of fertilizer has been developed as an alternative [14,15]. This technology has been shown to improve the productivity of different soils and crops [15]. However, most research on microdosing has largely focused on the application of mineral fertilizers [16]. A previous study conducted in Burkina Faso showed that applying cotton stem compost at a dose of 6 t ha$^{-1}$ combined with mineral fertilizers significantly improves maize yields [8].

In this study, we hypothesized that cotton stem compost applied in microdoses at a rate of 2.5 t ha$^{-1}$ can achieve significantly greater agronomic performance compared to the commonly used broadcasting of 5 t ha$^{-1}$. Compost application in microdoses can also promote the sustainability of the sorghum production system. Therefore, the objective of this study was to evaluate the effectiveness of compost combined with mineral fertilizer applied in microdoses to sorghum crop. Specifically, the study aimed to evaluate the effectiveness of the half-dose (2.5 t ha$^{-1}$) of compost by microdosing in comparison with the recommended dose of 5 t ha$^{-1}$ by the broadcasting application method and assess the effects on the indicators of sustainable intensification.

## 2. Materials and Methods

### *2.1. Study Sites*

The study was carried out in the region of Koutiala (Figure 1) and specifically in the villages of N'Golonianasso (12°43′07″ N 5°69′42″ W), Sirakélé (12°30′50″ N 5°28′40″ W), and Zansoni (12°36′33″ N 5°34′3″ W), which are all located in the most long-standing cotton production area in southern Mali (Figure 1). Cotton is grown on around 30% of the land. The study was carried out during the 2019 and 2020 growing seasons. The highest rainfall amounts were recorded between July and September. From the beginning of July to the second half of September, the rainfall rarely stopped for more than five days. The annual cumulative rainfall recorded in 2019 was 808 mm in N'golonianasso compared to 650 mm in Sirakélé and 831 mm in Zansoni, while in 2020, it was 1019 mm in N'Golonianasso, 890 mm in Sirakélé, and 960 mm in Zansoni. Comparatively, 2020 was the wettest year.

The temperatures ranged from 22 °C to 35 °C. Agricultural production is mainly focused on cotton, maize, sorghum, and small millet cultivation. Plains and rocky highlands dominate the study area. The soils are of the tropical ferruginous type with sandy-loam to sandy-loamy textures, high acidity (pH < 5.6), and low organic matter content.

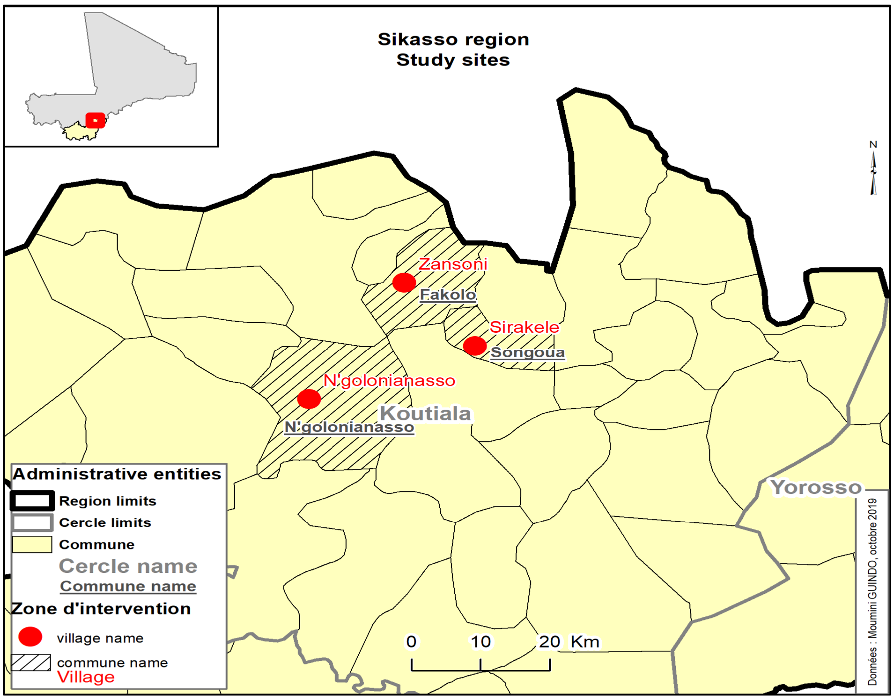


**Figure 1.** Study sites.

To determine the soil fertility status, composite soil samples were collected prior to the implementation of the trials. The soil samples were packaged and sent to the soil laboratory of Sadoré (ICRISAT-Niamey) for physico-chemical analyses. In each treatment, soil sampling was carried out diagonally towards both ends and in the middle, i.e., at 5 sampling points and a depth of 0–20 cm. The parameters analyzed included soil pH [17], % P (Bray-I) [18], total % nitrogen, and % soil organic carbon (SOC) [19]. The soil % K was extracted with 1 M NH4OACc solution [20] and determined by flame photometry, while the soil granulometry was determined by the sedimentation method. Soil physico-chemical properties are shown in Table 1.

**Table 1.** Soil physico-chemical properties of the study sites.

| Soil Characteristics | Study Sites | | |
|---|---|---|---|
| | **Sirakélé** | **N'golonianasso** | **Zansoni** |
| pH | 4.53 ± 1.04 | 4.55 ± 0.87 | 4.33 ± 1.00 |
| Total nitrogen (% N) | 0.19 ± 0.03 | 0.28 ± 0.04 | 0.18 ± 0.03 |
| Assimilable P. (mg/kg) | 10.09 ± 3.87 | 6.84 ± 7.82 | 13.71 ± 15.86 |
| Exchangeable K. (Cmol+/kg) | 0.14 ± 0.05 | 0.12 ± 0.02 | 0.18 ± 0.04 |
| Organic matter (% OM) | 0.35 ± 0.06 | 0.61 ± 0.15 | 0.34 ± 0.06 |
| Clay (% <0.002 mm) | 13 ± 7.65 | 11.83 ± 5.49 | 7.60 ± 3.65 |
| Fine silt (% 0.05–0.002 mm) | 13.40 ± 5.98 | 41.17 ± 10.19 | 21.40 ± 12.58 |
| Sand (% >0.05 mm) | 73.60 ± 9.13 | 47.00 ± 13.04 | 71.00 ± 12.45 |

The soils used in this investigation had low pH with values ranging from 4.33–4.55, indicating high acidity (Table 1). The organic matter content (% OM) of these soils was also low (<1.5%), as was the total nitrogen content (0.18–0.28% N). The phosphorus content of soils was low (<15 mg $kg^{-1}$), as was exchangeable potassium (<0.2 Cmol+/$kg^{-1}$). The texture of the soils varied from one village to another and ranged from sandy-silty to loamy-sandy.

### 2.2. Compost Production

The material used for composting consisted of cotton stems, cattle manure, wood ash, millet glumes/glumelles, and dead leaves of *Pennesetum pediselatum.* In the study area, this grass is known as "*N'Golo*" in the Bambara language. For the compost microdose experiment, the plant material was sorghum (*Sorghum bicolor* [L.] Moench) with the improved variety "Soubatimi" [21]. This variety is dual-purpose with high yield potential ranging from 2.5–3 t ha$^{-1}$ for grain and 10 t ha$^{-1}$ for fodder.

A total of 30 farmers from the three study villages were trained in composting techniques using cotton stems. Each farmer made a compost pile consisting of 500 kg of cotton stems combined with 100 kg of cattle manure and 25 kg each of millet glumes/glumelles, dead leaves of *Pennesetum pediselatum*, and wood ash. The dimensions of the piles were 2 m long, 2 m wide, and 1 m high, with 10 layers of 10 cm. The cotton stems were manually cut into small pieces of about 5–10 cm in length using a cutter. After constituting the compost, the piles were covered with black plastic and tarpaulin. A shed was erected to shelter the compost from the sun. Interventions after composting consisted of watering per week, i.e., 11 waterings in total, and turning of the compost pile on the 45th day. During the turning, large stems and the longer ones were further chopped. On the 90th day, which was the expected date of maturity, the compost was harvested and quantified in the fresh state before being dried in the shade.

### 2.3. Experimental Set-Up and Compost Application on Farmer Fields

The compost was applied in blocks of 4 treatments in each of the 30 farmer fields and 2 controls. Each farmer field was considered a repetition. The seeding density used was 0.30 m between plants and 0.75 m between rows. A total of 5 sorghum seeds were sown per hole, and 3 seedlings were left after thinning. The agronomic parameters measured included the plant growth rate, measured on the same plants throughout the cycle (seeding-spruce); the height of the plants at harvest; planting density; and grain and biomass yields.

The compost produced was used in the experiment as an organic microdose at a rate of 2.5 t ha$^{-1}$ by placing it at a depth of 7–10 cm, and top dressing by broadcasting was applied at a dose of 5 t ha$^{-1}$ for farmer practice (Table 2). The experiment was carried out in 2019 and 2020, and the carryover effect was evaluated in 2020 from the trial of the previous year.

**Table 2.** Nutrient application per treatment.

| Treatments | N (kg ha$^{-1}$) | P (kg ha$^{-1}$) | K (kg ha$^{-1}$) |
|---|---|---|---|
| Control | 0 | 0 | 0 |
| Control (DAP 100 kg ha$^{-1}$) | 18 | 46 | 0 |
| CP (farmer compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 55.5 | 53 | 29 |
| CP (farmer compost at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 36.75 | 49.5 | 145 |
| CPA (cotton stem compost at 2. 5 t ha$^{-1}$ +100 kg ha$^{-1}$ DAP) | 51.75 | 51.25 | 35 |
| CPA (cotton stem compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 85.5 | 56.5 | 70 |

DAP = Diammonium Phosphate (18-46-0).

### 2.4. Nitrogen Use Efficiency and Sustainable Intensification

To assess the increase in grain yield due to nitrogen application (kg grain/kg N), we calculated nitrogen use efficiency using the following formula [22]:

$$\text{NitrogenUseEfficiency} = \frac{\text{Yieldwithnitrogen}\left(\text{kgha}^{-1}\right) - \text{Yieldwithoutnitrogen}\left(\text{kgha}^{-1}\right)}{\text{Amountofnitrogenapplied}\left(\text{kgha}^{-1}\right)}$$

The performance of treatments in terms of system sustainability was assessed through the analysis of indicators covering 5 domains, namely, productivity, profitability, the environment, social, and human conditions [23]. Productivity was determined from grain sorghum yields, while the gross margin (XOF ha$^{-1}$) was assessed by the difference in loads (compost, DAP fertilizer, seed, and plowing) and products (grains and biomass). As for the environment, the assessment of the partial balance ($\sum$Inputs − $\sum$Outputs, kg ha$^{-1}$) made it possible to determine the level of nitrogen deficiency in the soil. With regard to dietary energy intake, the indicator chosen was the amount of protein generated per treatment in kilocalories per hectare. A survey of 30 households in the three villages determined the labor needs for the implementation of each treatment or even the need for collective action.

Compost samples were also taken and analyzed to determine the nitrogen composition, C/N ratio, moisture content, and organic matter (% OM). The compost samples were collected from the matured compost heaps at three levels (on the surface, in the middle, and at the bottom) to constitute a composite sample per heap. A total of 500 g of fresh compost for each pile was dried in the oven at 105 °C for 24 h before being submitted for analysis at the Sotuba Sol-Eau-Plante laboratory (Bamako). Organic matter was determined by the loss-on-ignition method, and nitrogen was measured by the Kjeldahl digestion method.

Analysis of variance (ANOVA) was conducted to test the effect of the compost type and application method as fixed effects on the measured sorghum productivity indicators. The Student–Newman–Keuls test was used for means comparison when significant at 5% ($p$ < 0.05). Statistical analyses were conducted using Genstat software, 18th edition.

## 3. Results

### 3.1. Quantity and Characteristics of Compost

Compost quantities ranged from 595–623 kg across villages, with an average of 613.7 kg per farmer (Table 3). In terms of quality, the nitrogen composition was 1.3–1.5%, and that of organic matter varied from 39–48%.

**Table 3.** Quantity and characteristics of compost.

| Compost | Study Sites | | |
|---|---|---|---|
| | Sirakélé | N'golonianasso | Zansoni |
| Quantity (kg) | 616 ± 54 | 623 ± 27 | 595 ± 49 |
| Total nitrogen (% N) | 1.46 ± 0.18 | 1.30 ± 0.13 | 1.37 ± 0.04 |
| C/N ratio | 18.68 ± 6.16 | 20.40 ± 1.45 | 16.53 ± 0.99 |
| Organic matter (% OM) | 45.92 ± 9.75 | 47.83 ± 10.26 | 38.93 ± 3.34 |

### 3.2. Effect of Compost Application on Sorghum Growth Rate

In 2019, except for the control treatment at 60 days after planting, the sorghum growth rate was similar for all treatments (Figure 2), while in 2020 and in the carryover effect experiment, there was a significant difference between treatments. For instance, the treatment that received improved compost through microdose application (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) or by broadcasting (CPA_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) obtained similar daily growth rates of 0.69 cm and 0.96 cm, respectively, from 0–15 days after sowing (DAS) and 15–30 DAS. This growth rate was significantly increased by 8–10% compared to farmer compost treatments applied in microdoses (CP_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) or by broadcasting (CP_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) and more than 22% for the treatment with 100 kg ha$^{-1}$ DAP and the control.

A daily growth rate of 1.55 cm was obtained between 30–45 DAS for all compost treatments (improved or farmer practice) and application methods (microdosing or broadcasting), while treatment with 100 kg ha$^{-1}$ DAP and the control showed the lowest daily growth rates, which were less than 12% and 20%, respectively. This trend was similar to that observed for the period between 60–75 DAS, with daily growth rates of 3.72 cm and 2.71 cm for the period between 75–90 DAS. The growth rates for the DAP treatment (100 kg ha$^{-1}$) and control were less than 13% and 33%, respectively, during 60–75 DAS and less than 11% and 27% for the period of 75–90 DAS. A general decrease in the growth rate was observed from 75 DAS for all treatments.

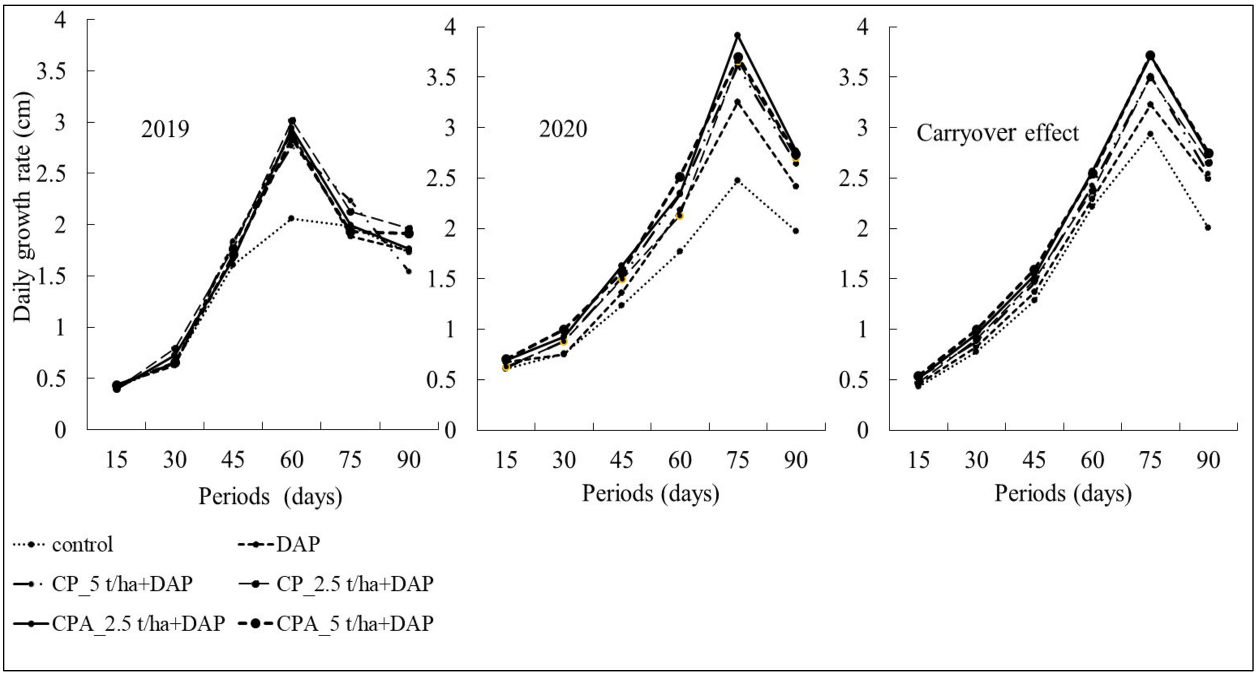


**Figure 2.** Growth rate for sorghum plant per treatment.

### *3.3. Effects of Compost on Plant Height, Planting Density, Grain, and Biomass*

#### 3.3.1. Direct Effect of Compost Application

The analysis of variance showed highly significant differences ($p < 0.001$) between treatments for plant height, grain yield, and biomass yield (Table 4). Except for the control, all treatments obtained an average height of 245.4 cm at harvest, with an average biomass yield of 11,168 kg ha$^{-1}$. The control treatment had the shortest plants with a height of less than 16% compared to the tallest plants and also produced the lowest biomass of less than 24% compared to other treatments.

**Table 4.** Effect of compost application on agronomic parameters of sorghum.

| Treatment Effect (Mean of 2019 and 2020) | Height (cm) | Planting Density | Grain Yield (kg ha$^{-1}$) | Biomass Yield (kg ha$^{-1}$) |
|---|---|---|---|---|
| Control | 205.2 | 80,346 | 1160 | 8509 |
| DAP 100 kg ha$^{-1}$ | 233.7 | 84,769 | 1716 | 10,408 |
| CP (farmer compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 239.1 | 87,860 | 1916 | 11,069 |
| CP (farmer compost at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 250.7 | 87,287 | 2043 | 11,787 |
| CPA (improved compost with cotton stems at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 248.8 | 90,168 | 2320 | 11,649 |
| CPA (improved compost with cotton stems at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 254.6 | 82,299 | 1963 | 10,926 |
| Mean | 238.7 | 85,453 | 1853 | 10,725 |
| *p*-value | <0.001 | 0.409 | <0.001 | <0.001 |
| S.E.D | 7.66 | 5167.9 | 169 | 628 |
| % CV | 14.5 | 27.4 | 41.3 | 26.5 |
| Year effect | | | | |
| 2019 | 242.5 | 87,087 | 1845 | 10,384 |
| 2020 | 226.9 | 80,389 | 1879 | 11,780 |
| Mean | 238.7 | 85,453 | 1853 | 10,725 |
| *p*-value | 0.006 | 0.054 | 0.783 | 0.002 |
| S.E.D | 5.58 | 3455.1 | 124.7 | 439.9 |
| % CV | 15.8 | 27.2 | 45.3 | 27.6 |

For planting density, no statistically significant differences were observed between treatments ($p = 0.409$). On average, there were 85,453 plants per hectare with a coefficient of variation of 27.4 (Table 4). The results on the grain yield showed significant differences ($p < 0.001$) between treatments. The highest yield of 2061 kg ha$^{-1}$ was obtained from improved compost treatments (improved or farmer practice) with a microdose application of 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP or with the broadcasting of 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP

(Table 4). The 100 kg ha$^{-1}$ DAP treatment yielded less than 17% compared to the highest yield. The lowest yield of 1160 kg ha$^{-1}$ was obtained with the control.

Over the years, the tallest (242.5 cm) sorghum plants obtained in 2019 significantly decreased by 7% in 2020 ($p < 0.001$) (Table 4). The average grain yield of 1853 kg ha$^{-1}$ was not statistically different ($p = 0.783$) between the two years. However, the biomass yield of 10,384 kg ha$^{-1}$ in 2019 and 11,780 kg ha$^{-1}$ in 2020 differed significantly ($p < 0.001$).

#### 3.3.2. Carryover Effect of Compost Application

In the carryover effect experiment, the results showed significant differences ($p < 0.001$) between treatments regarding plant height at harvest, grain yield, and biomass yield. The application of improved compost by the microdose technique (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) or broadcasting (CPA_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) resulted in taller plants (238.5 cm) (Table 5). The plants were significantly higher (by 3%, 6%, and 9.5%, respectively) than those receiving farmer compost treatments in microdoses (CP_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), broadcasting (CP_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), and 100 kg ha$^{-1}$ DAP application. The highest grain yield of 2210 kg ha$^{-1}$ was obtained with the improved compost microdose application (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), which was 27% higher than that obtained by broadcasting (CPA_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP). The lowest yield of 1131 kg ha$^{-1}$ was obtained with the control treatment, corresponding to less than 49% compared to the highest yield with the microdose of the improved compost. The highest biomass amount of 12,415 kg ha$^{-1}$ was also obtained with the improved compost microdose (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), farmer compost (CP_2.5 t ha$^{-1}$ +100 kg ha$^{-1}$ DAP), and treatment with DAP (100 kg ha$^{-1}$). However, the application of these composts (improved or farmer practice) at a dose of 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP produced 8% less biomass than that of the microdose. The lowest biomass yield (10,227 kg ha$^{-1}$) was obtained with the control.

**Table 5.** Carryover effect of compost application on sorghum.

| Carryover Effect of Treatments in 2020 | Height (cm) | Planting Density | Grain Yield (kg ha$^{-1}$) | Biomass Yield (kg ha$^{-1}$) |
|---|---|---|---|---|
| Control | 198.62 | 73,259 | 1131 | 10,227 |
| DAP 100 kg ha$^{-1}$ | 215.7 | 74,074 | 1645 | 11,829 |
| CP (farmer compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | *225.07* | *72,926* | *1603* | 11,361 |
| CP (farmer compost at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 232.26 | *73,037* | 1941 | 12,510 |
| CPA (improved compost with cotton stems at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 239.85 | 74,593 | 2209 | 12,905 |
| CPA (improved compost with cotton stems at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) | 237.11 | 76,444 | 1640 | 11,506 |
| Mean | 224.77 | 74,056 | 1695 | 11,723 |
| *p*-value | <0.001 | 0.882 | <0.001 | <0.001 |
| S.E.D | 1.67 | 3196.40 | 199.7 | 519 |
| % CV | 2.9 | 16.7 | 23.7 | 17.1 |

### *3.4. Nitrogen Use Efficiency*

Under experimental conditions, sorghum cultivation without nitrogen application (control) resulted in a mean yield of 1160 kg ha$^{-1}$. Nitrogen use efficiency varied significantly ($p < 0.001$) depending on the treatment. The highest nitrogen use efficiency was obtained with treatment with DAP (18-46-0) at a dose of 100 kg ha$^{-1}$ and with the improved compost microdose (CPA 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) (Figure 3). One kilogram of nitrogen resulted in 31 kg and 22 kg of sorghum grain with DAP treatment and compost with microdose application (CPA 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), respectively. Broadcasting treatments with CPA_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP and CP_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP resulted in a nitrogen use efficiency of 8 kg of sorghum grain per unit of nitrogen.

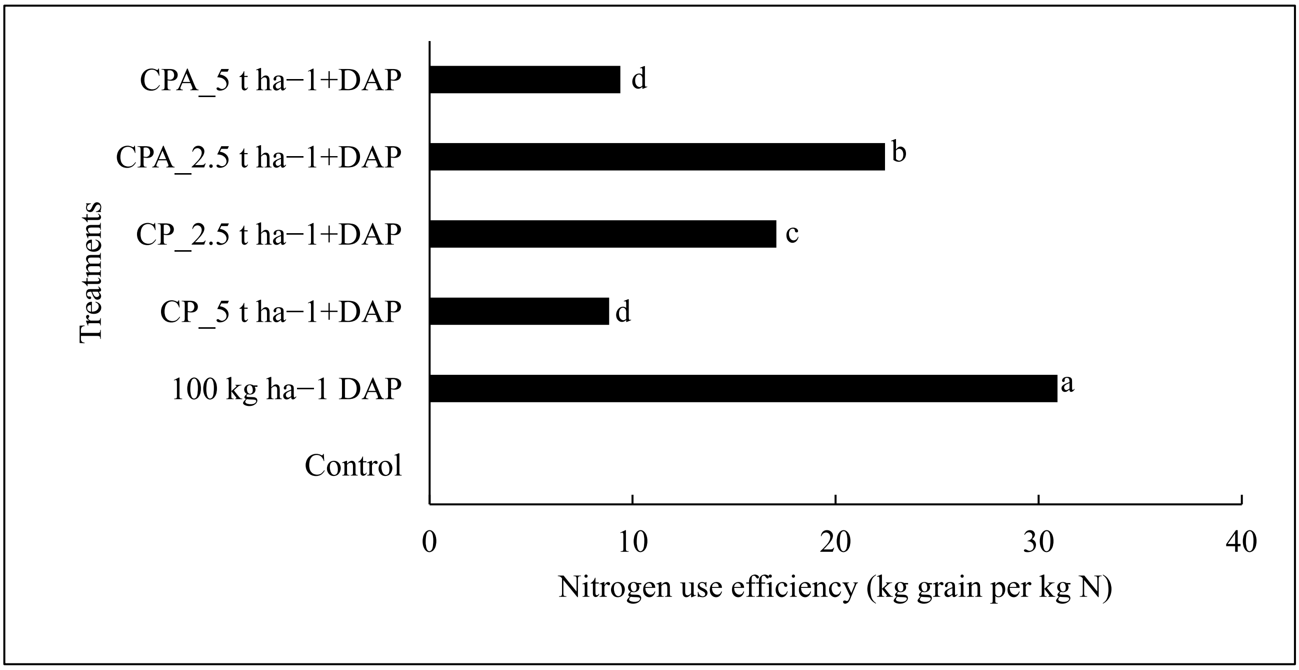


**Figure 3.** Nitrogen use efficiency (sorghum grain per kilogram of nitrogen used (kg per kg N).

### *3.5. Indicators of Sustainable Intensification*

#### 3.5.1. Compost Contribution to Productivity

The use of the improved compost with the microdose application technique (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) resulted in the largest yield of 2320 kg ha$^{-1}$, corresponding to a maximum contribution of 100% to the productivity requirement of the farm (Figure 4), while with the farmer compost (CP_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), the contribution was 90%, which decreased to 80% with the application of farmer compost at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP. For DAP treatment at 100 kg ha$^{-1}$ and the control, the contribution decreased to 75% and 50%, respectively, compared to that of the improved compost microdose (Figure 4).

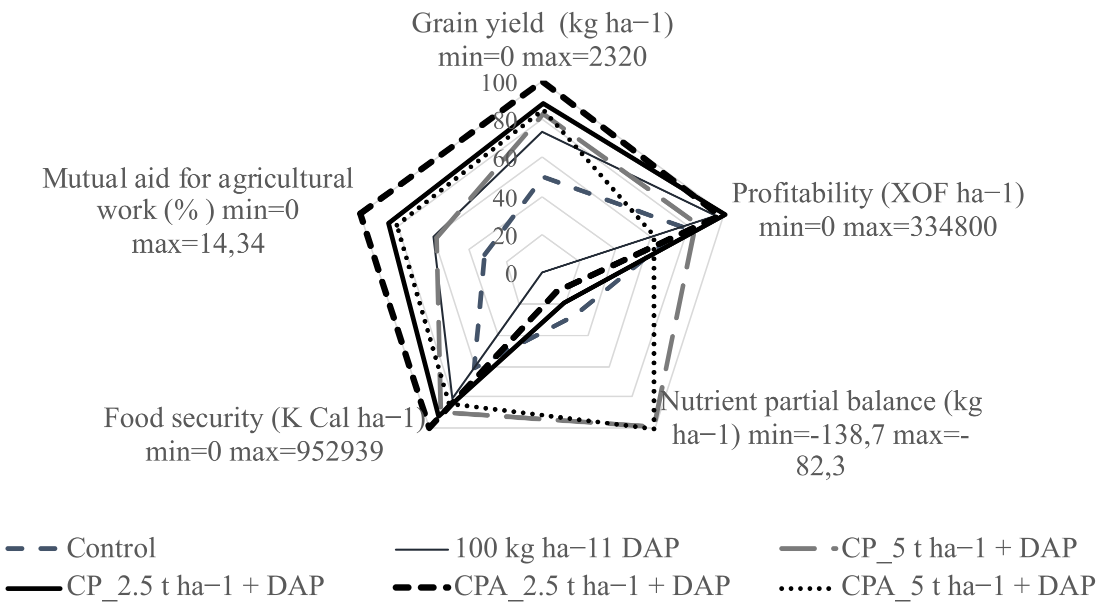


**Figure 4.** Sustainable intensification for compost application under sorghum production system in southern Mali.

3.5.2. Cost-Effectiveness of the Compost

With 334,800 XOF/ha, microdosing with farmer compost (CP 2.5 t ha$^{-1}$) or improved compost (CPA 2.5 t ha$^{-1}$) generated the highest gross margin. This profitability is comparable to that of the 100 kg ha$^{-1}$ DAP treatment (Figure 4). These technologies contributed 95–100% to the economic profitability of the production system. However, this profitability dropped to 80% with the application of farmer compost by the broadcasting system (CP_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) and the control. The contribution of improved compost in broadcasting (CPA_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) was the least profitable, with a contribution of about 60% of economic profitability.

3.5.3. Effect of Compost Application on the Environment

Despite the existence of significant differences between treatments ($p < 0.001$), the partial nitrogen balance was negative in all treatments, with values ranging from −82.3 to −138.7 kg ha$^{-1}$. The broadcasting of compost (improved and farmer practice) at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP had the largest contribution (100%) to the improvement of the nitrogen balance of soil (Figure 4). The unfertilized control plots and the microdosing treatments of improved compost (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) and farmer practice (CP_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) still contributed to the improvement of the balance to 30%, 20%, and 10%, respectively. As for the sole use of DAP fertilizer at 100 kg ha$^{-1}$, it had absolutely no contribution to the improvement of the nitrogen balance but rather drew on the soil reserve.

3.5.4. Labor Assistance for Compost Application

For field activity, the mutual labor assistance received by families is of the order of 14.34% maximum, particularly for agricultural work. This contribution corresponds to 100% of the labor assistance needs and would be required for work on improved compost microdose plots (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), which showed the highest grain and biomass yields. For the DAP treatment at 100 kg ha$^{-1}$ and farmer compost in broadcasting (CP_5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP), labor demand significantly decreased ($p = 0.0147$) to 60%.

3.5.5. Compost Contribution to Food Security

The largest amount of food energy obtained was 952,939 Kcal ha$^{-1}$ (Figure 4) and was obtained with compost application by microdosing (CPA_2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP). Except for the control, whose contribution to the food energy requirement was 60%, that of other treatments varied from 80% to 90% (Figure 4).

## 4. Discussion

### *4.1. Effect of Compost Application on Sorghum Growth*

The findings of this study showed that the best daily growth rates of sorghum were obtained with compost application by microdosing (2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) and broadcasting (5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP) treatment applications. This was observed from 15–90 DAS. The variability of the daily growth rate of the plants between treatments can be explained by the response rate of the sorghum variety to the nutrient contribution from compost. This situation has led to a good biomass yield [24,25]. The observed general decrease in the growth rate observed beyond 75 DAS can be linked to the slow growth rate of the stems due to the translocation of nutrients for the construction of the panicle [26]. At harvest, plants that received compost treatments (improved or farmer practice) in microdoses of 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP were significantly taller than those of the control. This difference in size could be due to the effect of the availability of nutrients provided by compost, owing to its mineralization, which was also favored by sufficient rainfall [27]. However, environmental factors, such as the rainfall or drought sequence, can determine the growth of internodes and the height of sorghum, thus limiting the effects of mineral inputs.

### *4.2. Effect of Compost Application on Sorghum Yield*

The application of compost by microdosing (improved or farmer practice) at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP and by broadcasting at 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP both produced an average grain sorghum yield of 2061 kg ha$^{-1}$. This shows that compost application by microdosing at 2.5 t ha$^{-1}$ can produce an equal grain yield to that of broadcasting at a dose of 5 t ha$^{-1}$. This performance of microdose technology would be related to the concentration of nutrients in the surface part of the soil and at the level of the active surface of the root system, allowing better absorption of nutrients and water [28,29]. The lowest grain yield of 1160 kg ha$^{-1}$ obtained with the control treatment highlights the importance of fertilizer input and soil poverty in organic matter (0.34–0.61%). Since farmers have difficulties in disposing manure [30], it would be advantageous to adopt organic input based on the application of the compost by microdosing at 2.5 t ha$^{-1}$ to a larger area of cultivated land, compared to the broadcasting method, which uses the double dose of 5 t ha$^{-1}$.

Our results show that all treatments, except the control, showed the same biomass yield of 11,168 kg ha$^{-1}$, 24% higher than that of the control. This difference is linked, on the one hand, to the effect of the compost (improved and farmer practice) and, on the other hand, to the dual-use feature of the sorghum variety "Soubatimi", which values the best manure [31]. In retrospect, only microdose treatments (improved and farmer practice) showed the best biomass yield of 12,708 kg ha$^{-1}$, 10% higher than that of broadcasting. This observation could be linked to the significant effect of the mineralization of the stock of organic matter that was placed basally in the seeding holes [28,32]. Compost with microdosing at 2.5 t ha$^{-1}$ is also critical for the development of above-ground biomass under sufficient rainfall conditions, which would be beneficial to agro-pastoralists, especially for animal fodder.

### *4.3. Sustainability of the Production System*

In the present study, the greatest economic profitability of 334,800 XOF ha$^{-1}$ was achieved with the application of a microdose of 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP of improved compost with cotton stems and farmer compost. The profitability was significantly increased by 27% compared to that obtained with the broadcasting of 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP of farmer compost. These results can be attributed to the nitrogen use efficiency of 22 kg of sorghum grain per kg of nitrogen with the application of the compost microdose at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP, compared to only 8 kg of grain per kg of nitrogen with the application of 5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP. The application of 56.25 g of compost per plant hole ensures a concentrated supply of nutrients to the plants, reduces losses [33,34], and improves the chemical, physical, and biological properties of soils for subsequent crops in the rotation [35,36]. Although the benefits of microdosing have been demonstrated by several studies [29,37], we found that its contribution to the soil fertility restoration, especially nitrogen (N), was less than that of the application of 5 t ha$^{-1}$ by broadcasting. This can be explained by the absolute amount of organic matter provided per unit area. Comparatively, applying the same dose of organic matter by microdosing and broadcasting would allow the microdose to gain an additional 100% of fertilized area. In the present study, there was no excessive application of nitrogen and hence no negative impacts on the environment [38–40]. When compost is applied as top dressing, followed by a slight soil cover, it mixes with the soil and contributes more to the improvement of the nitrogen balance and the sustainability of the system. The minimal addition of 100 kg ha$^{-1}$ DAP did not improve the nitrogen stock but replenished the nitrogen deficit in the soil since the soil was initially low in nitrogen. Under favorable rainfall conditions, this is explained by the high solubility and leaching losses, as well as volatilization losses [41–43].

One of the pillars of the sustainability of production systems is the social field, generally marked by cohesion through collective aid in labor for agricultural work. In much more productive plots, such as those receiving the compost microdose at 2.5 t ha$^{-1}$ + 100 kg ha$^{-1}$ DAP, the demand for labor assistance is much higher due to the intensity of work and the number of family workers subject to rural exodus [44]. To overcome this constraint of agricultural labor and working time, access to agricultural mechanization (plows, seeders, tractors, and tillers) facilitates the realization of many operations, such as plowing, sowing, weeding, and transport [45]. This involvement of agricultural mechanization makes it possible to increase the cultivated area and enhance the value of the workforce for the diversification of other activities, generating less painful incomes.

### 4.4. Challenges Related to the Production and Use of Compost

In southern Mali, the extension of cropland is no longer possible, and, faced with the need for the sustainable intensification of agricultural production systems, farmers are trying to produce manure through several alternatives (animal pile manure, garbage piles, composting, etc.) to meet the needs of organic input. Given the low production of this organic manure, the burning of crop residue in areas varies from 32% to 62%, depending on the type of farm [6,46]. As a result, composting, which appears to be one of the potential options thanks to its fertilizing quality, is becoming increasingly useful and represents a major challenge on farms with crop residues. However, the collection and transportation of residues, as well as the availability of family labor and water, are some constraints [47].

For field fertilization, the contribution of compost at 5 t $ha^{-1}$ every two years, as recommended by research [5], is generally out of reach for farmers to cover 100% of cultivated areas [6]. During application, the little manure applied to the field is generally not distributed evenly over all areas, thus promoting irregularity in soil fertility management. Although the application of compost by microdosing results in the enhanced extraction of nutrients, with harvests thus depleting the soil, it nevertheless has good performance in grain and biomass yield. However, the implementation of microdosing can take time and requires much more labor, causing an additional burden that may hinder the adoption of the technology on a large scale [14].

## 5. Conclusions

This study evaluated the performance of the technology for applying improved and farmer compost by microdosing at 2.5 t $ha^{-1}$ and by broadcasting at 5 t $ha^{-1}$ in a sorghum production system. It appears that, regardless of the type of compost (farmer practice or improved), the application of compost by microdosing at 2.5 t $ha^{-1}$ can significantly improve the sorghum growth rate, plant height, grain yield, and biomass yield compared to other treatments. The grain yield of 2061 kg $ha^{-1}$ obtained with compost application by microdosing at 2.5 t $ha^{-1}$ or compost broadcasting at 5 t $ha^{-1}$ suggests the possibility of treating 100% of the fertilized field with compost microdosing at 2.5 t $ha^{-1}$. This gain in fertilized surface area may make it possible to overcome the problem of insufficient organic manure in the Sahel. Depending on rainfall, the biomass yield varied significantly, from 10,384 kg $ha^{-1}$ in 2019 to 11,780 kg $ha^{-1}$ in 2020. Compost application with microdose technology showed a higher nitrogen use efficiency of more than 55% and an economic gain of more than 27% compared to broadcasting compost. However, the contribution of compost microdose technology to the improvement of the nitrogen stock in the soil per unit area was less compared to the application of 5 t $ha^{-1}$ of compost by broadcasting. In view of these results, the availability of cotton stems presents an opportunity to intensify compost production to meet the nutrient demands of crops in the Sahel.

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