

Article

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

Moumini Guindo ^{1,*}, Bouba Traoré ^{1,2}, Birhanu Zemadim Birhanu ², Alou Coulibaly ³ and Ramadjita Tabo ²

¹ Institut d'Economie Rurale (IER), Centre Régional de la Recherche Agronomique de Sikasso, Bamako BP 16, Mali; b.traore@cgiar.org

² International Crops Research Institute for the Semi-Arid Tropics ICRISAT, Niamey BP 12404, Niger; z.birhanu@cgiar.org (B.Z.B.); r.tabo@cgiar.org (R.T.)

³ Institut Polytechnique Rurale de Formation et de Recherche Appliquée (IPR/IFRA) de Katibougou, Koulikoro BP 06, Mali; coulibalynalou@gmail.com

* Correspondence: moumini.guindo1@gmail.com; Tel.: 00223-21260107

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 (farmer 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 334800 XOF ha⁻¹, which was 27% less 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.

Citation: Guindo, M.; Traoré, B.; Birhanu, B.Z.; Coulibaly, A.; Tabo, R. Microdosing of Compost for Sustainable Production of Improved Sorghum in Southern Mali. *Agronomy* **2022**, *12*, 1480. <https://doi.org/10.3390/agronomy12061480>

Academic Editors: Umberto Anastasi and Aurelio Scavo

Received: 12 May 2022

Accepted: 14 June 2022

Published: 20 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

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

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.

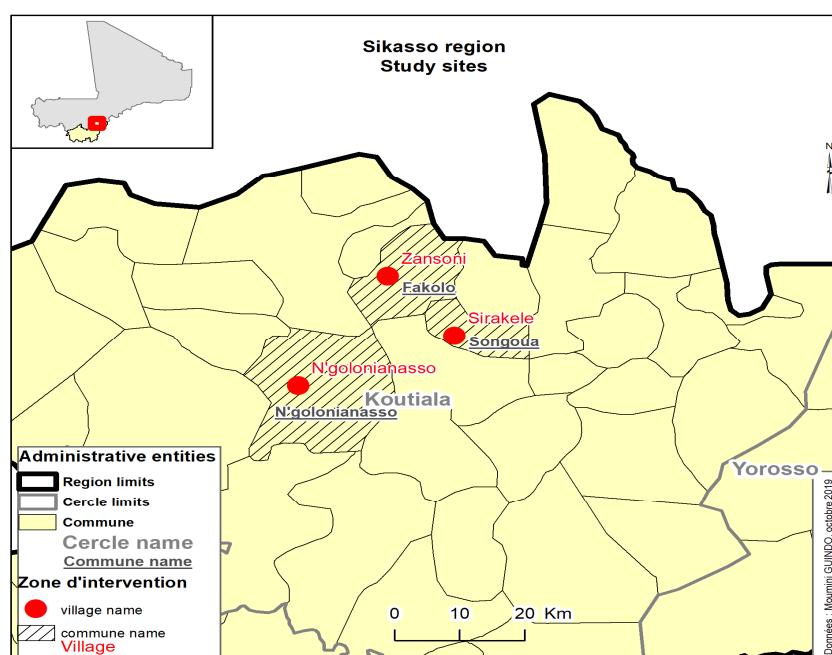


Figure 1. Study sites.

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.

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 NH₄OAc 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 *Pennisetum pediselatatum*. 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 *Pennisetum pediselatatum*, 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 (seedling-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]:

$$\text{Nitrogen Use Efficiency} = \frac{\text{Yield with nitrogen (kg ha}^{-1}\text{)} - \text{Yield without nitrogen (kg ha}^{-1}\text{)}}{\text{Amount of nitrogen applied (kg ha}^{-1}\text{)}}$$

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 ($\Sigma \text{Inputs} - \Sigma \text{Outputs}$, 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.

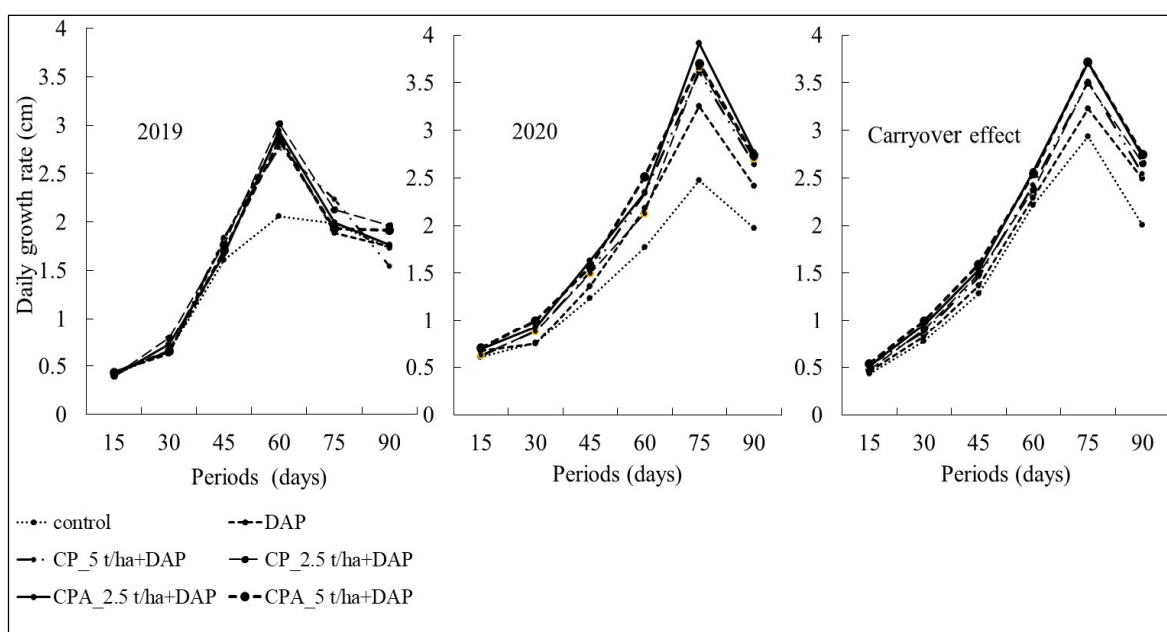


Figure 2. Growth rate for sorghum plant per treatment.

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.

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
<i>p</i> -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
<i>p</i> -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

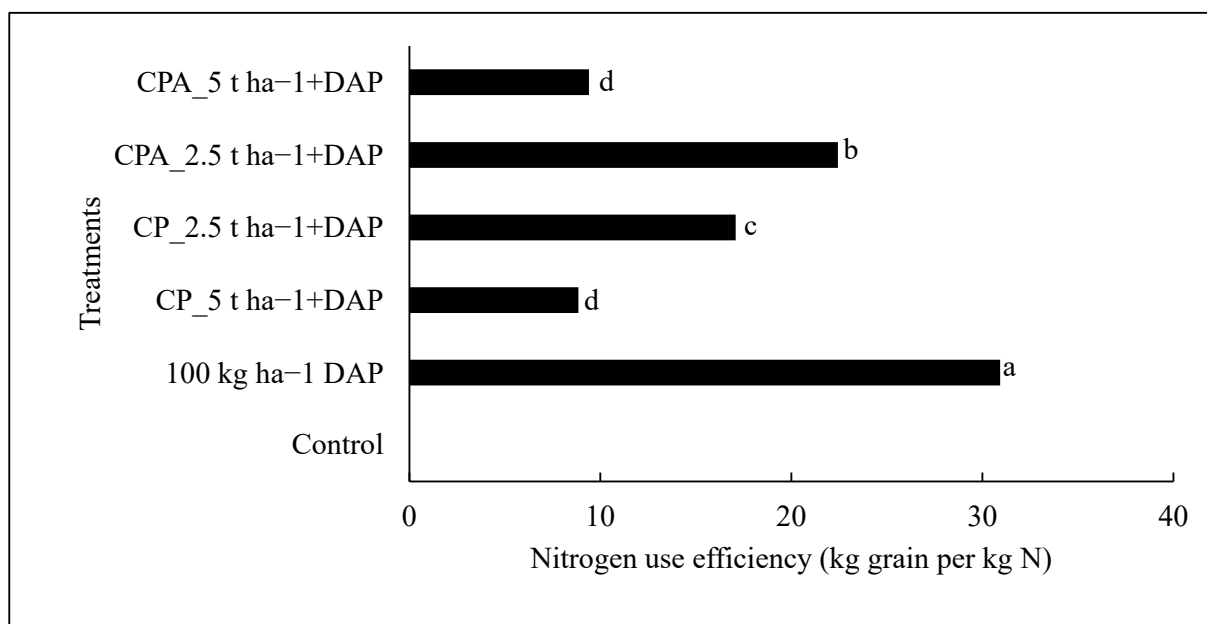
In the carryover effect experiment, the results showed significant differences ($p < 0.001$) between treatments regarding plant height at harvest, grain yield, and biomass yield. The application of improved compost by the microdose technique (CPA_2.5 t ha⁻¹ + 100 kg ha⁻¹ DAP) or broadcasting (CPA_5 t 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 Planting		Grain Yield (kg ha ⁻¹)	Biomass Yield (kg ha ⁻¹)
	(cm)	Density		
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
<i>p</i> -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).

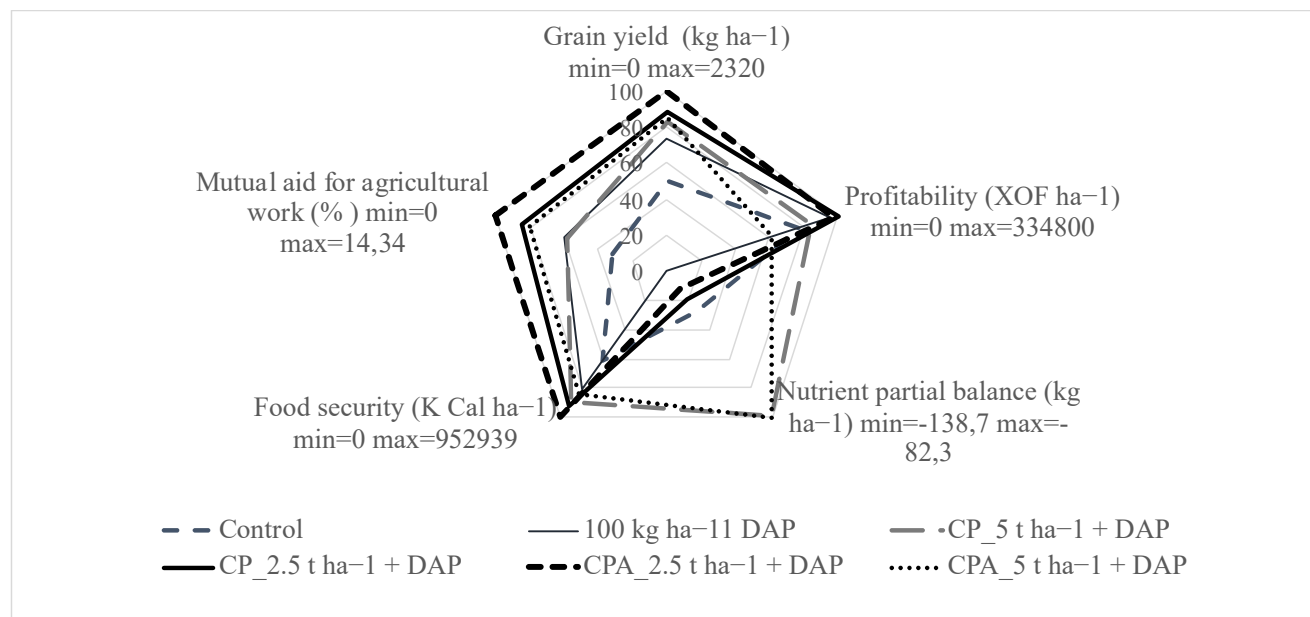


Figure 4. Sustainable intensification for compost application under sorghum production system in southern Mali.

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 $334,800 \text{ XOF ha}^{-1}$ was achieved with the application of a microdose of $2.5 \text{ t ha}^{-1} + 100 \text{ kg ha}^{-1}$ 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 $5 \text{ t ha}^{-1} + 100 \text{ kg ha}^{-1}$ 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 $2.5 \text{ t ha}^{-1} + 100 \text{ kg ha}^{-1}$ DAP, compared to only 8 kg of grain per kg of nitrogen with the application of $5 \text{ t ha}^{-1} + 100 \text{ kg ha}^{-1}$ 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 [38,39,40]. 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 $2.5 \text{ t ha}^{-1} + 100 \text{ kg ha}^{-1}$ 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.

Author Contributions: Conceptualization, M.G. and B.T.; methodology, M.G. and B.T.; software, M.G.; validation, M.G. and B.Z.B.; formal analysis, M.G. and B.T.; investigation, M.G.; resources, B.Z.B. and R.T.; data curation, M.G. and B.T.; writing—original draft preparation, M.G.; writing—review and editing, R.T. and A.C.; visualization, B.T.; supervision, B.Z.B. and A.C.; project administration, B.Z.B.; funding acquisition, R.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by USAID, grant number AID-BFS-G-11-00002, and the APC was funded by ICRISAT.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: This work was supported by the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) program in Mali. The authors are very grateful for the financial support provided by the US Agency for Development (USAID) through the International Institute of Tropical Agriculture (IITA). We thank Abdourazak Alio Moussa, colleagues from the N'Tarla research station, and NGO AMEDD for their support. We are also thankful to the anonymous reviewers, whose valuable comments improved the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Kouyate, A.B.; Serme, I. Evaluation de l'efficacité du Phosphate Naturel de Tilemsi (PNT) sous différentes pratiques de travail du sol en zone Sahélienne du Mali. *Innov. Space Sci. Res. J.* **2021**, *34*, 845–857.
2. Kintché, K.; Guibert, H.; Sogbedji, J.; Levêque, J.; Bonfoh, B.; Tiftonell, P. Long-term mineral fertiliser use and maize residue incorporation do not compensate for carbon and nutrient losses from a Ferralsol under continuous maize–cotton cropping. *Field Crop. Res.* **2015**, *184*, 192–200. <https://doi.org/10.1016/j.fcr.2015.04.019>.
3. Leyronas, S.; Boche, M.; Baudet, E. L'Afrique Redécouvre les Communs: Une Lecture des Enjeux Fonciers Ruraux Au Mali. In *Agence Française de Développement (AFD). L'Économie Africaine 2020; La Découverte*: Paris, France, 2020; ISBN 9782348057465.
4. Rufyikiri, G. De l'agriculture de Subsistance à Une Agriculture de Marché En Afrique: Une Mutation Impérative Pour Le Développement Du Continent. In *Afrique Durable 2030; Association Africa 21*: Geneva, Switzerland, 2017; Volume 2, pp. 50–68.

5. Bationo, A.; Fairhurst, T.; Giller, K.; Kelly, V.; Lunduka, R.; Mando, A.; Mapfumo, P.; Oduor, G.; Romney, D.; Vanlauwe, B.; et al. *Manuel de Gestion Intégrée de la Fertilité des Sols. Consortium Africain Pour La Santé des Sols*; Fairhurst, T., Ed.; CAB International: Oxfordshire, UK, 2015; 179p; ISBN 9781780645278.
6. Guindo, M.; Traoré, B.; Birhanu, Z.B.; Fred, K.; Coulibaly, A. Biomass and Nutrient Flow Dynamics from Households to Farm Fields: An Experimental Study in Southern Mali. *Nutr. Cycl. Agroecosyst.* **2022**, under review.
7. Duan, F. *Aperçu Politique pour le Développement de l'Agroforesterie au Mali*; OXFAM—Research Backgrounder: Boston, MA, USA, 2020; 88p.
8. Ouattara, A. Effets des Techniques de Compostage En Tas Sur La Qualité des Composts et Évaluation de l'Efficacité des Composts Sur La Productivité du Maïs Au Burkina Faso. Mémoire de Diplôme d'Etudes Approfondies, Science Du Sol, MSc thesis, Université Polytechnique de Bobo-Dioulasso, Bobo-Dioulasso, Burkina Faso, 2016; 62p.
9. Diarra, B.; Gian, N.; Konaté, F. Analyse de la Gestion de la Fertilité Organo- Minérale des Sols Dans les Cercles de Koulikoro et de Sikasso (Mali). *Rev. Géographie Trop. D'Environ.* **2019**, *1*, 35–44.
10. Ecofin, A. Production de Coton du Mali. Rapport Provisoire, la Récolte de Coton a Atteint le Niveau Historique de 760,000 Tonnes en 2021/2022 (Exécutif). 2021. Available online: <https://www.agenceecofin.com/Coton/2103-95887-Mali> (accessed on 21 March 2022).
11. Blanchard, M.; Coulibaly, K.; Bognini, S.; Dugué, P.; Vall, É. Diversité de la Qualité des Engrais Organiques Produits par les Paysans d'Afrique de l'Ouest: Quelles Conséquences sur les Recommandations de Fumure? *Biotechnol. Agron. Soc. Environ.* **2014**, *18*, 512–523.
12. Cisse, D. Effets des Amendements à Base de Biochar sur les Paramètres Agro-Pédologiques dans une Rotation Coton-Maïs à l'Ouest du Burkina Faso. Ph.D. Thesis, Université de Liège Gembloux, Agro-Bio Tech, Gembloux, Belgium, 2022; 126p.
13. Diarissio, T.; Corbeels, M.; Andrieu, N.; Djamen, P.; Douzet, J.-M.; Tittone, P. Soil variability and crop yield gaps in two village landscapes of Burkina Faso. *Nutr. Cycl. Agroecosyst.* **2016**, *105*, 199–216. <https://doi.org/10.1007/s10705-015-9705-6>.
14. Sigue, H.; Labiyi, I.; Yabi, J.; Biaou, G. Effet des composantes de la technologie microdose sur la performance économique et financière des exploitations agricoles du Kouritenga et du Zondoma au Burkina Faso. *Afr. Crop Sci. J.* **2019**, *27*, 331–349. <https://doi.org/10.4314/acscj.v27i3.2>.
15. Ibrahim, A.; Pasternak, D.; Fatondji, D. Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel. *J. Agric. Sci.* **2015**, *153*, 1412–1421. <https://doi.org/10.1017/s0021859614001075>.
16. Adams, A.M.; Gillespie, A.W.; Kar, G.; Koala, S.; Ouattara, B.; Kimaro, A.A.; Bationo, A.; Akponikpe, P.B.I.; Schoenau, J.J.; Peak, D. Long term effects of reduced fertilizer rates on millet yields and soil properties in the West-African Sahel. *Nutr. Cycl. Agroecosyst.* **2016**, *106*, 17–29. <https://doi.org/10.1007/s10705-016-9786-x>.
17. McLean, E. Soil Ph and Lime Requirement. In *Methods of Soil Analysis*; Page, A.L., Ed.; John Wiley & Sons, Ltd.: Madison, WI, USA, 1983; pp. 199–224.
18. Bray, R.H.; Kurtz, L.T. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* **1945**, *59*, 39–46. <https://doi.org/10.1097/00010694-194501000-00006>.
19. Nelson, D.; Sommers, L. Total Carbon, Organic Carbon, and Organic Matter. In *Methods of Soil Analysis: Part 3 Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA, 1996; pp. 961–1010.
20. Helmke, P.; Sparks, D. Lithium, Sodium, Potassium, Rubidium, and Cesium. In *Methods of Soil Analysis: Part 3 Chemical Methods*; Sparks, D.L., Ed.; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA, 1996; pp. 551–574.
21. Togo, A. Effets de la Fertilisation et de la Date de Semis sur des Variétés de Sorgho à Double Usage. Mémoire, Diplôme d'Ingénieur Agronome, Master's Thesis, Institut Polytechnique Rural de Formation et de Recherche Appliquée, Koulikoroba, Mali, 2019; 50p.
22. Godinot, O. Proposition de Nouveaux Indicateurs d'Efficience d'Utilisation de l'Azote à l'Échelle du Système de Production Agricoles et du Territoire. Ph.D. Thesis, Agro Campus Ouest, Université Européenne de Bretagne, Spécialité Biologie et Agromonie, Rennes, France, 2014; 134p.
23. Hammond, J.; van Wijk, M.; Teufel, N.; Mekonnen, K.; Thorne, P. Assessing smallholder sustainable intensification in the Ethiopian highlands. *Agric. Syst.* **2021**, *194*, 103266. <https://doi.org/10.1016/j.agsy.2021.103266>.
24. Chantreau, J.; Cruz, J.-F.; Ratnadass, A.; Trouche, G. *Le Sorgho*, 1st ed.; Agriculture Tropicale En Poche; CTA, Presses Agronomiques de Gembloux: Passage des Déportés, Belgium, 2013; ISBN 978-2-87016-129-6. Available online: www.pressesagegro.be (accessed on December, 05, 2013).
25. Bazongo, P.; Traore, K.; Traore, O.; Yelemou, B.; Sanon, K.B.; Kabore, S.; Hien, V.; Nacro, B.H. Influence des haies de Jatropha sur le rendement d'une culture de sorgho (*Sorghum vulgare*) dans la zone Ouest du Burkina Faso: Cas du terroir de Torokoro. *Int. J. Biol. Chem. Sci.* **2016**, *9*, 2595. <https://doi.org/10.4314/ijbcs.v9i6.7>.
26. Traore, B.; Serme, I.; Ouattara, B.; Bougma, A.; Ouedraogo, J.; Pouya, B.M.; Ouattara, K. Effet de micronutriments et de nutriments secondaires sur la production du mil et du sorgho en Zone nord soudanienne du Burkina Faso. Effect of micronutrients and secondary nutrients on millet and sorghum production in the North Sudan Zone of Burkina Faso. *Int. J. Biol. Chem. Sci.* **2021**, *15*, 1902–1913. <https://doi.org/10.4314/ijbcs.v15i5.17>.
27. Garba, O.; Mella, M.T.; Kiari, S.A.; Grema, M.H.I.; Zanguina, A. Valorisation de Glume de Mil et Balle de Riz Par Compostage: Caractérisations Physico-Chimiques des Composts. *Afr. Sci.* **2020**, *17*, 29–38.

28. Tovihoudji, P.G.; Akponikpè, P.I.; Agbossou, E.K.; Bertin, P.; Biielders, C.L. Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin. *Field Crop. Res.* **2017**, *213*, 130–142. <https://doi.org/10.1016/j.fcr.2017.08.003>.
29. Coulibaly, A.; Woumou, K.; Aune, J.B. Sustainable Intensification of Sorghum and Pearl Millet Production by Seed Priming, Seed Treatment and Fertilizer Microdosing under Different Rainfall Regimes in Mali. *Agronomy* **2019**, *9*, 664. <https://doi.org/10.3390/agronomy9100664>.
30. Traore, B.; Guindo, M.; Zemadim, B.; Kizito, F. *Farm Nutrient Dynamics in Southern Mali*; International Institute for Tropical Agriculture (IITA): Ibadan, Nigeria, 2022; 15p.
31. Diancoumba, M.; Worou, O.N.; Nebie, B.; Tangara, A.; Sidibe, M.; Togo, A.; Bendiggar, M.; Desmae, H.; Zemadim, B. Response of Dual-Purpose Sorghum Varieties to Fertiliser and Sowing Dates in Mali's Sudanian Zone. In Proceedings of the Tropentag 2021, Prague, Czech Republic, 14–16 September 2022; 5p.
32. Kouyate, A.B.; Ibrahim, A.; Serme, I.; Dembele, S.G. Sorghum responses to different forms of Tilemsi rock phosphate combined with soluble fertilizers in a low-input production system in Mali. *Int. J. Biol. Chem. Sci.* **2021**, *14*, 3285–3296. <https://doi.org/10.4314/ijbcs.v14i9.25>.
33. Sissoko, P.; Berti, F.; Gry, S.; Lebaillly, P. Effets de l'adoption de la technique du microdosage d'engrais sur la disponibilité et l'accessibilité céréalière des exploitations agricoles à base de mil et de sorgho au Mali. *Agron. Afr.* **2018**, *30*, 193–204.
34. Rosy, C. Identification des Facteurs Environnementaux et Agronomiques Affectant la Réponse à la Fertilisation Microdose dans le Sud du Burkina Faso. Ph.D. Thesis, Faculté des Bioingénieurs, Université Catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium, 2019; 104p.
35. Doumbia, S.; Dembele, S.G.; Sissoko, F.; Samake, O.; Sousa, F.; Cicek, H.; Adamtey, N.; Fliessbach, A. Evaluation de la fertilité des sols et les rendements de cotonnier, maïs et sorgho à *Gliricidia sepium* (Jacq.) Kunth ex. Walp. *Int. J. Biol. Chem. Sci.* **2020**, *14*, 2583–2598. <https://doi.org/10.4314/ijbcs.v14i7.17>.
36. Traore, A.; Yameogo, L.P.; Olivier, D.; Traore, K.; Bazongo, P.; Traore, O. Effets Comparés Du Tourteau de Neem [*Azadirachta Indica* (A. Juss)] et du Compost sur le Rendement du Sorgho [*Sorghum Bicolor* (L. Moench)] en Zone Sud-Soudanienne du Burkina Faso. *J. Appl. Biosci.* **2021**, *163*, 16834–16845. <https://doi.org/10.35759/JABs.163.3>.
37. Camara, B.S.; Camara, F.; Berthe, A.; Oswald, A. Micro-Dosing of Fertilizer—A Technology for Farmers' Needs and Resources. *Int. J. AgriSci.* **2013**, *3*, 387–399.
38. Audouin, E.; Vayssières, J.; Odru, M.; Masse, D.; Dorégo, S.; Delaunay, V.; Lecomte, P. Réintroduire l'élevage pour accroître la durabilité des terroirs villageois d'Afrique de l'ouest: Le cas du bassin arachidier au Sénégal. In *Les Sociétés Rurales Face aux Changements Climatiques et Environnementaux en Afrique de L'Ouest*; IRD: Marseille, France, 2015; pp. 403–427.
39. Wu, P.; Liu, F.; Li, H.; Cai, T.; Zhang, P.; Jia, Z. Suitable fertilizer application depth can increase nitrogen use efficiency and maize yield by reducing gaseous nitrogen losses. *Sci. Total Environ.* **2021**, *781*, 146787. <https://doi.org/10.1016/j.scitotenv.2021.146787>.
40. Godinot, O.; Foray, S.; Lemosquet, S.; Delaby, L.; Édouard, N. De l'animal au territoire, regards sur l'efficience de l'azote dans les systèmes bovins laitiers. *INRAE Prod. Anim.* **2022**, *35*, 43–60. <https://doi.org/10.20870/productions-animales.2022.35.1.5498>.
41. Maniriho, A. Productivité, Efficience et Profitabilité des Petites Exploitations Agricoles Dans La Région des Sols de Laves au Rwanda. Ph.D. Thesis, Université de Liège, Liège, Belgium, 2021; 241p.
42. Traore, A.; Bandaogo, A.; Yameogo, P.L.; Anadi, K.R.; Traore, K.; Bazongo, P.; Traore, O. Effects of Zai Hole Sizing on Maize Yield in the South Sudan Zone of Burkina Faso. *Int. J. Innov. Appl. Stud.* **2021**, *33*, 435–442.
43. Carton, S.; Levavasseur, F. *Performances Agronomiques et Environnementales de la Méthanisation Agricole dans un Contexte de Grandes Cultures Céréalières (sans Élevage) et Recommandations de Bonnes Pratiques*; Rapport Étude Commandée par le Ministère de l'Agriculture et de l'Alimentation; AgroParisTech: Paris, France; INRAE: 2022; 87p.
44. Rangé, C. C. *Structures Agraires et Accès des Jeunes à la Terre—Revue de Littérature*; Hal-01870605; Lyon, France, 2018; 29p.
45. Side, C.S.; Havard, M. Développer Durablement la Mécanisation pour Améliorer la Productivité de l'agriculture Familiale en Afrique Subsaharienne. *Int. J. Adv. Stud. Res. Afr.* **2015**, *6*, 34–43.
46. Sissoko, F.; Coulibaly, D.; Cisse, O.; Dugue, P. Évaluation de l'arrière effet de la culture du coton sur la production céréalière en zone cotonnière du Mali. In Proceedings of the AGRAR-2013, 1st Conférence de la Recherche Africaine sur l'Agriculture, l'Alimentation et la Nutrition, Yamoussoukro, Ivory Coast, 4–6 June 2013; pp. 149–160.
47. Dagbenonbakin, G.D.; Djenontin, A.J.; Adjovi, N.A.; Igué, M.A.; Mensah, G.A. Production et utilisation de compost et gestion des résidus de récolte. In *Fiche Technique*; Dépôt Légal No. 6529 Du 18/01/2013; Bibliothèque Nationale (BN) du Bénin: Porto-Novo, Benin, 2013; 10p. Available online: http://www.slire.net/download/2155/ft_n_04_dagb_nonbakin_et_al_compost.pdf (accessed on 18 January 2013).