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Development and Use of a Planter for Simultaneous Application of Seed, Fertilizer and Compost in Pearl Millet Production in Niger—Effects on Labor Use, Yield and Economic Return

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Abstract: Sowing and application of mineral and organic fertilizer is generally done manually in the Sahel, resulting in low precision and delayed application. The objective of this paper is to present a new mechanical planter (Gangaria) for the combined application of seeds and soil amendments (mineral fertilizer, compost, etc.), and to assess the effects of using this planter in pearl millet on labor use, yield and economic return. The labor study showed that the mechanized application of seeds and compost reduced time use by a factor of more than six. The on-station experiments were completely randomized experiments with six replications and six treatments: T0 (control), T1 (0.3 g NPK hill^{-1}), T2 (25 g compost hill^{-1}), T3 (25 g compost + 0.3 g NPK hill^{-1}), T4 (50 g compost hill^{-1}) and T5 (50 g compost + 0.3 g NPK hill^{-1}). Treatments T1 to T5 were sown by the planter with seeds that were primed in combination with coating of seeds with a fungicide/insecticide. The treatment T5 increased grain yield and economic return compared to the control by 113% and 106%, respectively. The advantages for farmers using this approach of agricultural intensification are timelier sowing of dryland cereal crops, easy application of organic fertilizer and more precise delivery of input, thereby making this cropping system more productive and less vulnerable to drought.

Keywords: planter; millet; microdosing; seed priming; weeding; soaking; labor saving; mechanized sowing and fertilizer application; yield; economic return

1. Introduction

Niger covers an area of 1,267,000 km^2, of which only 12% is suitable for agricultural activities. The main cereal crops in the country are millet and sorghum. The production of pearl millet (*Pennisetum glaucum* (L.) R. Br.) is estimated at around 3.5 million Mg per year, placing Niger as the second largest producer of the crop in West Africa after Nigeria [1]. Millet represents 73% of the country's cereal production [2], but average yield in 2018 was only 548 kg ha^{-1} [2]. Most soils are sandy and low in organic matter and available phosphorus [3]. Many studies have shown the importance of using mineral fertilizer, but application is limited, due to high costs and low availability in rural areas [4]. The traditional method for sowing pearl millet in Niger is to place the seeds in clusters (hills) that have an intrarow and interrow spacing of one meter. Microdosing consists of applying small amount of fertilizer next to the seed clusters (hills). The recommended doses of fertilizer for pearl millet is microdosing of 2 g DAP hill^{-1} or 6 g of NPK hill^{-1} [5]. However, a study showed that a microdose of

2 g DAP hill^{-1} gave a negative economic return in 36% of the cases in on-farm experiments in Niger [6]. On the other hand, it has been shown that lower doses of microdosing can give good results, and a 46% increase in millet yield was achieved with a dose of 0.6 g NPK hill^{-1} in central Mali [7]. In that study, a higher dose did not increase yields. In Sudan, a dose of 0.3 g NPK hill^{-1} gave a yield increase of 31.3% compared to the control [8]. Microdosing increases fertilizer use efficiency as fertilizer is placed next to the seeds, thereby increasing the uptake of fertilizer. Application of mineral in rows (banding) is another approach to increase fertilizer-use-efficiency [9]. Specialized planters have been developed for simultaneous sowing and banding of fertilizer, and the method is widely practiced in mechanized agriculture under both temperate and tropical conditions. These planters cannot place seeds and fertilizer at a distance of one meter and the price of these planters is also too high for the farmers in Niger. Banding of fertilizer will be less efficient in dryland cereal crops due to the long distance between each cluster of seeds.

Many studies in Niger have shown the importance of applying organic manure to improve soil quality [4,9–11]. The efficiency of mineral fertilizer can also be improved by combining it with organic fertilizer [12]. Another approach to increasing yield under Sahelian conditions is to use seed priming [7] and seed coating with a fungicide/insecticide [8,13].

Agronomic research by national and international research institutes has concentrated mostly on plant breeding and soil fertility management; as a result, the mechanization of farm operations for small-scale farmers has not been on the research and development agenda for at least the last 30 years. One important technology is the development and application of microdosing with mineral and organic fertilizer, but despite the high labor requirement of this method, there have been no attempts to mechanize it. To sow one hectare requires walking 10 km if there are 10,000 hills ha^{-1}, and if fertilizer is applied, the walking distance doubles. The average farm size in Niger is about 4 ha, which is equivalent to walking 40 km for two persons placing the seeds at a one-meter distance within the row. As a result of this high labor demand, sowing is often not undertaken at the most appropriate time. One way to minimize the labor demand in applying fertilizer is to mix seeds and mineral fertilizer, but this cannot be practiced unless very low quantities of fertilizer are used. Microdosing with manure/compost is even more labor-demanding than microdosing of mineral fertilizer, as larger quantities are needed.

The use of mechanical planters is not new in Niger and other Sahelian countries [14]. Metal workshops were established to produce planters when they were first introduced to Niger in the 1950s, and the planters were used mostly in connection with groundnut production. Although it is still possible to find old planters in use in Niger, most farm households do not possess one. The most common planter in West Africa for dryland crops has been the Super-eco planter, but this has only one disc inside the hopper, which makes the simultaneous application of seed and fertilizer difficult. It can be used to sow a mixture of seeds and fertilizer, but only if small quantities of fertilizer (0.3 g hill^{-1}) are used, since high doses will burn the seeds. ICRISAT has been recommending 2 g DAP hill^{-1}, but this requires opening a pocket next to the seeds and placing the fertilizer in the pocket [15].

Two research questions were developed to orient the research. The first research question was to assess if a low-cost planter can be developed that can deliver seeds and fertilizer simultaneously, and the second was to assess the effects of using this planter for sowing, compost application and weeding on labor use, crop establishment, yield and economic return.

2. Materials and Methods

The methods used in the study included a labor study, 3 on-station experiments, 24 on-farm experiments and an economic analysis.

2.1. On-Station Experiments

These experiments were conducted between the 12th and 14th degrees north latitude at three research stations of the Institut National de Recherche Agronomique du Niger (INRAN). The sites were Konni (N 13°49′10.53″ and E 5°17′22.1″), N'Dounga (N 13°22′29.6″ et E 2°14′51.1″) and Lossa

(E 13°54′58.5″ and N 1°35′3.1″), The experiments were conducted for two years. Rainfall in Konni, N'Dounga and Lossa were 452 mm, 406 mm and 395 mm in 2018, respectively, while rainfall for these sites were 437 mm, 419 mm and 320 mm in 2019.

The on-station experiments had a randomized block design with six replications and six treatments at each site (Table 1). The elementary plots measured 5 m × 10 m each (50 m^2).

Table 1. Description of the six treatments in the on-station experiments.

Treatments	Sowing Method	Seed Priming	Seed Treatment	Fertilizer Application	Weeding Method
T0	Manual sowing	No seed priming	No seed coating	No mineral fertilizer	Manual weeding
T1	Mechanical sowing	Seed priming	Seed coated with fungicide	Microdosing 0.3 g NPK hill^{-1}	Mechanical weeding
T2	Mechanical sowing	Seed priming	Seed coated with fungicide	Microdosing 25 g compost hill^{-1}	Mechanical weeding
T3	Mechanical sowing	Seed priming	Seed coated with fungicide	Microdosing 0.3 g NPK and 25 g compost hill^{-1}	Mechanical weeding
T4	Mechanical sowing	Seed priming	Seed coated with fungicide	Microdosing 50 g compost hill^{-1}	Mechanical weeding
T5	Mechanical sowing	Seed priming	Seed coated with fungicide	Microdosing 0.3 g NPK and 50 g compost hill^{-1}	Mechanical weeding

The control treatment (T0) was sown using a small-bladed hoe and weeding was undertaken by using the hiliare, which is a traditional weeding instrument. Seed priming consisted of soaking the seeds in water for 8 h in ambient temperature. After soaking, the seeds were dried on a canvas in a shaded airy place for two h. Thereafter, they were coated with the combined insecticide/fungicide Calthio D5 (20% lindane and 25% thiram).

The soils Konni and N'Dounga had a sand content above 90% (sandy soil) whereas the soil type at Lossa was a silty loam. The soil organic carbon content was below 0.25% for all three soils. Available P (mg/kg) for Konni, N'Dounga and Lossa were 6.1, 12.3 and 6.7, respectively.

The compost was made from *Sida cordifolia* L. (75% of the biomass), organic manure (20% of the biomass) and ash (5% of the biomass). *Sida cordifolia* is a very common weed at the study sites. The final compost had a chemical composition of 1.11% nitrogen, 11.25 mg kg^{-1} available phosphorus, 26.3 cmolc dm^{-3} K and a C/N ratio of 11.25. The compost was dried in shade for two to three days prior to use. Debris was then removed from the compost. The mineral fertilizer was crushed before mixing with the compost. Prior to sowing, the fields were ploughed and leveled. The seeds were placed in the smallest hopper of the Gangaria planter while the mineral fertilizer and compost filled the largest hopper.

The Gangaria planter was also used for weeding. This was undertaken by mounting tines to the frame of the planter to make it suitable for intra-row weeding. In addition, it was necessary to undertake manual within-row weeding.

The observations included germination rate 2.5 days after sowing, grain yield and stover yield. The germination rate was estimated by counting the number of hills per elementary plot. The grain- and stover biomass were sun-dried and weight determined.

2.2. On-Farm Experiments

The on-farm experiments were conducted in the regions of Maradi, Tahoua and Tillabery during the rainy season 2019. The study villages were Karosofoua, Danja, Kandoussa and Aguié (in Maradi); Arewa and Sabon Gida (in Tahoua); and Lossa and N'Dounga (in Tillabery). In each village, three farmers were chosen to host the test, with only one replication for each farmer. In each field, three elementary plots of 250 m^2 (5 m × 50 m) were demarcated. The tests included three treatments (Table 2).

Table 2. Description of the three treatments in the on-farm experiments.

Treatments	Sowing Method	Seed Priming	Seed Treatment	Fertilizer Application	Weeding Method
T0	Manual sowing	No seed priming	No seed coating	No mineral fertilizer	Manual weeding
T1	Manual sowing	No seed priming	No seed coating with fungicide/insecticide	2 g NPK hill^{-1} and 150 g compost hill^{-1}	Manual weeding
T2	Mechanical sowing	Seed priming	Seed coated with fungicide/insecticide	Microdosing 25 g compost hill^{-1}	Mechanical weeding

The time used for sowing was measured on the six lines of all the elementary plots in the farm experiment, for all treatments. The planter was pulled by an ox. For T0, the working time was only the time used for sowing because there was no fertilizer application. For T1, the working time included sowing and manual microdosing of mineral fertilizer and compost. For T2, the working time included the time used to apply seeds and compost by the Gangaria planter.

2.3. Economic Evaluation

The income was calculated by taking into consideration the value of the produce (grain and straw). Based on an average market price in the villages, the price of millet grain and stover was set to 200 and 8.2 CFAF kg^{-1}, respectively (1 Euro = 656 CFA franc). Costs were related to inputs, labor, capital and machinery. Input costs included seeds, fertilizer and fungicide; labor costs included sowing, thinning, weeding, harvesting, transport of harvest and threshing/winnowing. The price of seeds was 1000 CFAF kg^{-1}; compost 70 CFAF kg^{-1}; NPK 15-15-15 fertilizer 400 CFAF kg^{-1}; and fungicide/insecticide 300 CFAF ha^{-1}. Labor costs were 2500 CFAF man-day^{-1}, which covers the harvesting, transport of harvest and threshing/winnowing for 150, 100 and 200 sheafs^{-1}, respectively. For mechanized sowing, there is no labor cost related to thinning because of a lower seed rate compared to manual sowing.

The annual cost of machinery was calculated by taking into consideration the depreciating value of the machine, useful life, interest costs, repair costs and the cost of operating the machine [14]. The useful life of the machine was set at 10 years and the interest rate to 12%, which is a rate typically used in small-scale agricultural credit schemes in Niger. The price of the Gangaria planter is 120,000 CFAF, and the annual depreciation cost was set to 9% of the price of the machine. The annual repair cost was set to 13% of the price of the machine.

The net income was calculated by the following formula:

$$\text{Net income} = \text{Total income} - \text{fixed machine costs} - \text{variable costs}$$

2.4. Statistical Analysis

The data collected from the trial were analyzed using Microsoft Excel and Genstat version 9.2 (VSN International, Hemel Hempstead, UK). The average values for each variable were tested for their normal distribution by using the Shapiro-Wilk test. A threshold value of 5% was used in the analysis of variance. The analysis of variance of the on-station experiments included the following factors: treatments (6), replication (6), location (3) and years (2). The on-farm experiments included the factors: treatments (3) and locations (8) (one-way ANOVA). The separation of means was done calculation confidence interval. The box plot analysis shows the distribution of data and the outliers.

3. Results

Results on planter development, labor saving from using the planter, agronomic effects and economic return are presented. The sustainability of using the planter in combination with improved soil fertility management is discussed.

3.1. Development and Use of the Gangaria Planter

The Gangaria planter was designed to be able to sow and apply soil amendments simultaneously. The planter has a main frame to which the different parts are attached (Figure 1). There are two hoppers that allow for independent delivery of seed and compost. At the bottom of each hopper, there is disc (Figure 2). One hopper and corresponding disc is used for seeds while the other hopper and corresponding disc is used for compost/soil amendments. The perforations in the disc for compost are much larger than the perforations in the disc for seeds because the quantities of compost delivered are much higher than the quantities of seeds. The rotation of the wheel axle causes a corresponding rotation of the discs. A furrow opener is attached to the front of the hopper. Tines, which are mounted behind the hopper/disc, cover the seeds and a compaction wheel ensures good contact between the seeds and the soil. In front of the hopper, there is an attachment point for the chain or rope from the harness of the traction animal. The hoppers and the discs can be removed from the frame of the planter and tines suitable for weeding can be attached instead. This ensures multifunctionality of the Gangaria planter, which can therefore be characterized as a multicultivator.

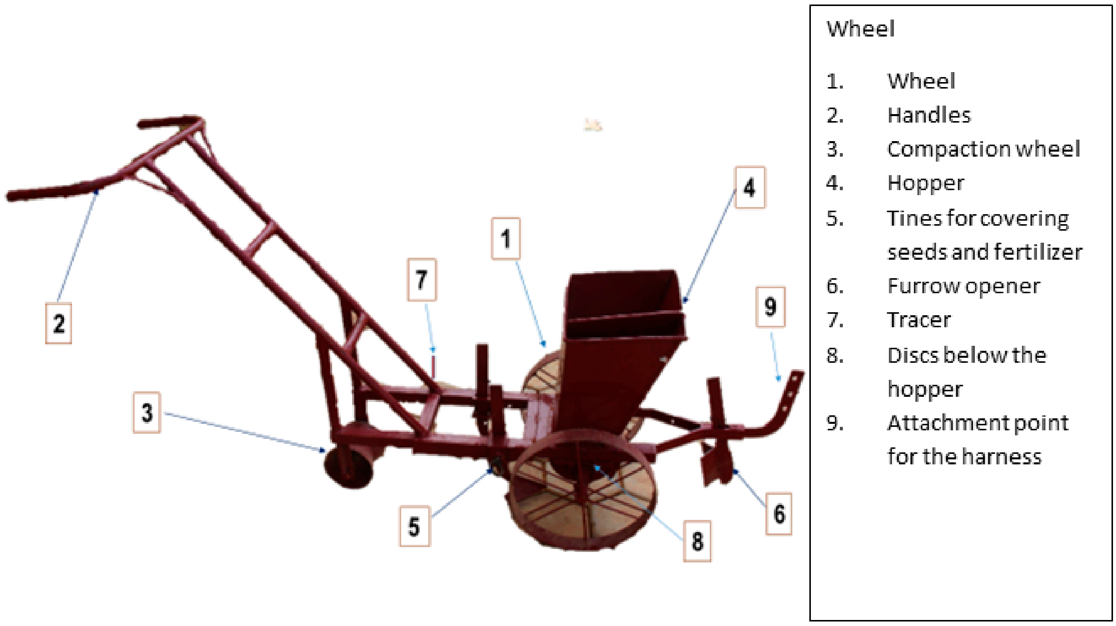

Figure 1. The Gangaria planter with two hoppers: one for seeds and the other for compost/soil amendments.

The two discs for seed and compost/soil amendments are interchangeable, making the planter very versatile as it can sow different crops with different rates of fertilizer/soil amendments (Figure 2). Each type of crop has a disc of specific holes/perforations and the fertilizer/soil amendment disc also has perforations of different sizes to allow for the application of different quantities of these inputs. The planter can be used for applying mineral fertilizer, compost, lime or gypsum. There are multiple possibilities for combining the application of different fertilizer and soil amendments. It is possible to mix seeds and mineral fertilizer in a 1:1 ratio and use the seed disc for application of this mixture, while compost or other soil amendments are applied in the other disc. Another option is to mix mineral fertilizer and compost and apply this mixture. The compost disc can also be adjusted to apply only mineral fertilizer.

The distance between the planting hills can be modified by changing the distance between the perforations in the disc, and the depth of application can be adjusted by changing the depth of the furrow opener. The distance between rows can be changed by adjusting the tracer attached to the frame of the planter. The planter weighs about 20 kg and can be pulled by a donkey or an ox. Because of its light weight, it is particularly suitable for the light sandy soils typically found in the Sahel.

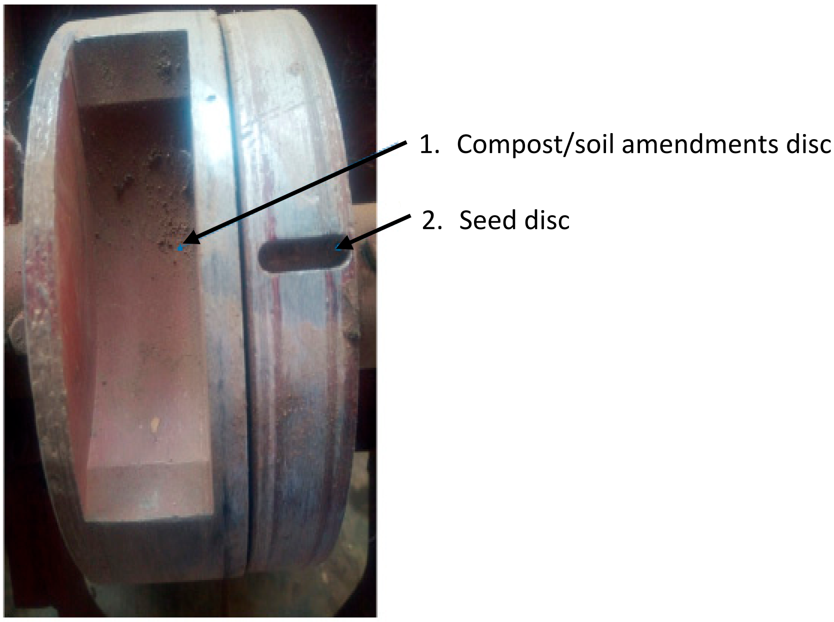

Figure 2. The disc to the left place the compost/soil amendments (1) and disc to the right applies seeds or a mixture of seed and fertilizer (2).

3.2. Labor Use in Manual and Mechanized Sowing

The planter significantly reduced labor use in all the eight villages. The average labor use for the T0, T1 and T2 treatments were 11.7, 35.4 and 5.7 h ha^{-1}, respectively (Figure 3). The labor demand is six times higher for the T1 treatment compared to the T2 treatment. There was not a great difference in labor use between the eight villages (Table 3).

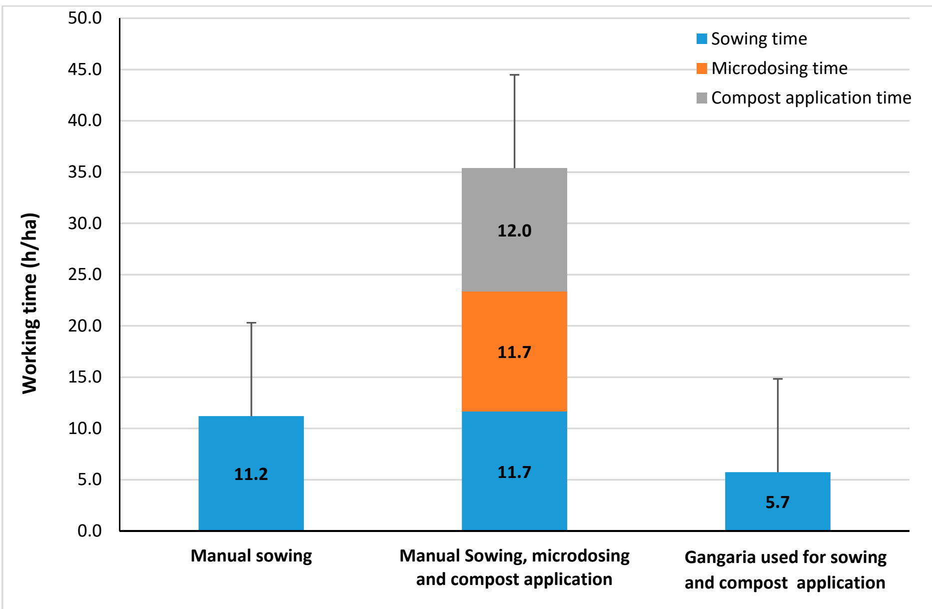

Figure 3. Effect of treatments on working time (h ha^{-1}) for sowing and fertilizer application (average for eight villages).

Table 3. Effect of the treatments on time use for sowing and fertilizer application in the eight villages (h ha^{-1}). Averages of treatments and corresponding 95% confidence intervals are presented.

				Village					
Trait.	**Aguié**	**Arewa**	**Danja**	**Kandoussa**	**Karosofoua**	**Lossa**	**N'Dounga**	**Sabon Gida**	**Average**
T0	11.1 ± 0.2	11.9 ± 0.3	11.3 ± 0.3	12 ± 0.4	11.5 ± 0.6	11.5 ± 0.2	12.1 ± 0.1	12.1 ± 0.1	11.7 ± 0.4
T1	34.7 ± 0.6	35.9 ± 0.8	34.2 ± 1.4	35.7 ± 0.3	34.9 ± 0.1	34.9 ± 0.9	35.9 ± 0.3	36.8 ± 0.6	35.4 ± 1
T2	5.5 ± 0.3	6.1 ± 0.3	5.4 ± 0.3	5.7 ± 0.2	5.6 ± 0.1	5.7 ± 0.4	5.8 ± 0.4	6 ± 0.4	5.7 ± 0.3
				Df.			**Significance**		
	Treatment (T)			2			<0.001		
	Villages (V)			7			<0.001		
	T × V			14			0.113		
	CV%						2.7		

3.3. Agronomic Experiments on Mechanization Combined with Seed Priming, Seed Treatment and Microdosing of Organic and Mineral Fertilizer

The agronomic study included on-station and on-farm experiments. Results are presented on germination rate and grain and stover yield in the on-station experiments while grain and stover yield is presented in the on-farm experiments.

3.3.1. On-Station Experiments

The on-station treatments differed greatly in percent germination 2.5 days after sowing (Table 4). In the control (T0), the germination rate was 28.0%, while in the improved treatments the percent germination varied from 92.5% to 94.6% (average 93.4%). There was a relatively small variation within the treatments with regard to this parameter and there were no significant interaction between treatments and villages and between treatments and years.

Table 4. Effects of treatments on percent germination 2.5 days after sowing. Averages of treatments and corresponding 95% confidence intervals are presented.

Location	**Year**	**Average Percent Germination 2.5 Days after Sowing**					
		T0	**T1**	**T2**	**T3**	**T4**	**T5**
Konni	2018	20.0 ± 7.1	93.3 ± 6.1	94.2 ± 8.0	99.2 ± 2.0	95.0 ± 4.5	97.5 ± 4.2
	2019	32.3 ± 17.1	100	97.5 ± 4.2	96.7 ± 5.2	95.8 ± 3.8	95.0 ± 6.3
N'Dounga	2018	26.7 ± 12.9	91.7 ± 4.1	92.5 ± 7.6	92.5 ± 8.8	93.3 ± 7.5	93.3 ± 5.2
	2019	25.0 ± 10.5	91.7 ± 7.5	90.8 ± 3.8	86.7 ± 4.1	87.5 ± 5.2	87.5 ± 7.6
Lossa	2018	30.0 ± 6.3	90.0 ± 0.0	87.5 ± 6.1	97.5 ± 4.2	90.8 ± 2.0	97.5 ± 4.2
	2019	34.2 ± 10.1	92.5 ± 7.6	92.5 ± 5.2	90.8 ± 5.8	95.0 ± 4.5	96.7 ± 4.1
Average	2018	25.6 ± 9.7	91.7 ± 4.2	91.4 ± 7.4	96.4 ± 6.1	93.1 ± 5.2	96.1 ± 4.7
	2019	30.5 ± 13.0	94.7 ± 7.0	93.6 ± 5.1	91.4 ± 6.4	92.8 ± 5.7	93.1 ± 7.1
Average 2018–2019		28 ± 11.6	93.2 ± 5.9	92.5 ± 6.4	93.9 ± 6.7	92.9 ± 5.4	94.6 ± 6.1
Fpr			**Df.**			**Significance**	
Treatment (T)			5			<0.001	
Location (L)			2			<0.001	
Year (Y)			1			0.728	
T × L			10			0.071	
T × Y			5			0.014	
L × Y			2			0.011	
T × L × Y			10			0.56	
CV%						8.1	

In terms of grain yield, across the two years in the on-station experiment, the average grain yield for the three sites was 719 kg ha^{-1} for the control (T0), against 1118, 1243, 1353, 1453 and 1530 kg ha^{-1} for the treatments T1, T2, T3, T4 and T5, respectively (Table 5). The respective grain yield increases compared to T0 were 55.5%, 72.9%, 88.2%, 102.1% and 112.7%. Figure 4 shows that the variability in grain yield was lower for the treatments T3, T4 and T5 compared to the treatments T0, T1 and T2. The T0 treatment had a significantly lower yield than the other treatments, as the upper quartile is below the median of the other treatments (Figure 4). The T5 treatment stands out as giving a significantly higher yield than the other treatments.

Table 5. Effects of the treatments on pearl millet grain yield (kg ha^{-1}). Averages of treatments and corresponding 95% confidence intervals are presented.

Location	Year	Average Grain Yield (±SD)					
		T0	T1	T2	T3	T4	T5
Konni	2018	724 ± 82.1	1123 ± 107.1	1269 ± 53.9	1344 ± 36.1	1398 ± 60.4	1475 ± 65.7
	2019	926 ± 145.4	1290 ± 83.5	1262 ± 127.9	1476 ± 48.6	1387 ± 76.2	1647 ± 156.5
N'Dounga	2018	817 ± 67;7	1345 ± 77.1	1434 ± 85.2	1490 ± 55.5	1533 ± 83.3	1655 ± 86.0
	2019	606 ± 71.1	998 ± 121.4	1190 ± 52.1	1296 ± 43.2	1380 ± 29.9	1473 ± 35.0
Lossa	2018	753 ± 60.6	1258 ± 63.5	1347 ± 69.9	1425 ± 85.7	1488 ± 92.9	1591 ± 96.2
	2019	488 ± 60.0	698 ± 98.1	953 ± 90.2	1086 ± 109.7	1219 ± 64.8	1337 ± 35.0
Average	2018	765 ± 77.4	1242 ± 123.1	1350 ± 96.2	1420 ± 84.9	1473 ± 94.6	1574 ± 109.7
	2019	673 ± 212.3	995 ± 266.3	1135 ± 162.5	1286 ± 178.1	1329 ± 97.7	1486 ± 158
Average 2018–2019		719 ± 164.2	1118 ± 239.7	1243 ± 170.8	1353 ± 153.4	1401 ± 119.8	1530 ± 141.3

	Df.	Significance
Treatment (T)	5	<0.001
Location (L)	2	<0.001
Year (Y)	1	<0.001
T × L	10	0.002
T × Y	5	<0.001
L × Y	2	<0.001
T × L × Y	10	0.001
CV%		7.0

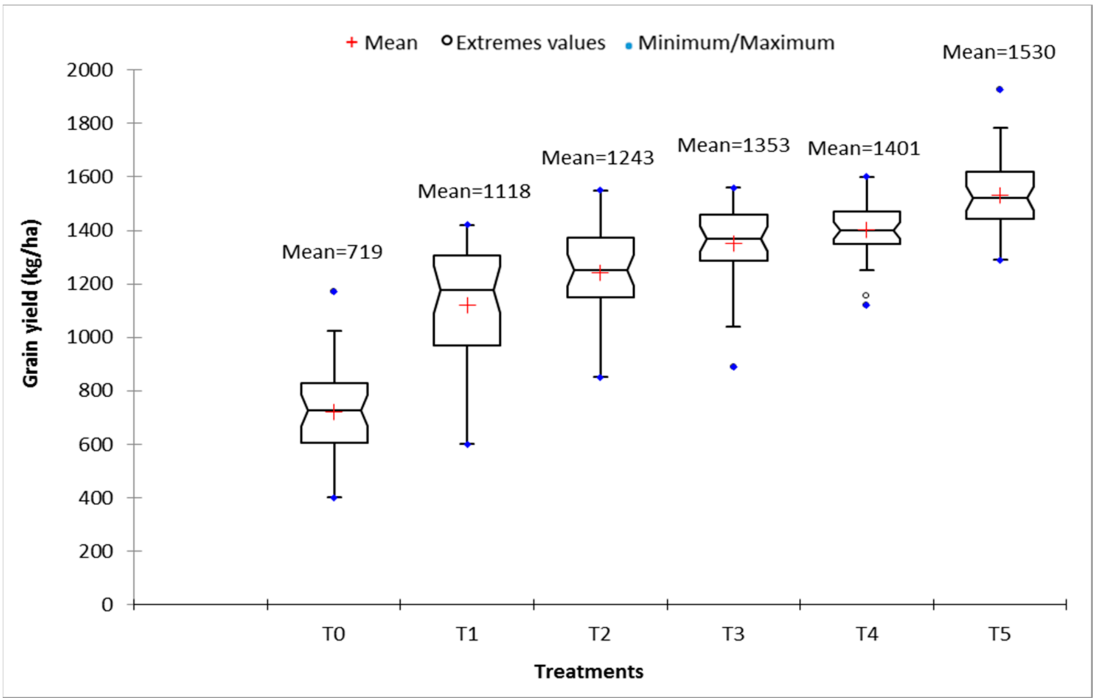

Figure 4. Effects of the treatments on pearl millet grain yield across three sites over two years in the on-station experiments.

The stover yields show similar trends as the grain yields. The average stover yield for the three sites was 1834 kg ha^{-1} for the control (T0), against 2297, 2613, 2912, 3123 and 3470 kg ha^{-1} for treatments T1, T2, T3, T4 and T5, respectively (Table 6). The respective stover yield increases compared to T0 were 25.2%, 42.47%, 58.7%, 70.28% and 89.2%. The treatments T4 and T5 had less variability compared to the other treatments (Figure 5). As for the grain yield, the stover yield of T0 was lower than the other treatments. Significant interactions were observed between treatments and village and between treatments and years.

Table 6. Effects of treatments on pearl millet stover yield (kg ha^{-1}). Averages of treatments and corresponding 95% confidence intervals are presented.

Location	**Year**	**Average stover yield (±SD)**					
		T0	**T1**	**T2**	**T3**	**T4**	**T5**
Konni	2018	1844 ± 272.4	2395 ± 274.3	2595 ± 181.4	2847 ± 273.7	3014 ± 189.1	3198 ± 184.8
	2019	2172 ± 368.0	2732 ± 315.5	2829 ± 432.7	3386 ± 434.1	3251 ± 364.5	3887 ± 600.4
N'Dounga	2018	2374 ± 312.1	3037 ± 235.6	3410 ± 231.9	3534 ± 343.8	3793 ± 338.7	3999 ± 325.6
	2019	1417 ± 80.7	1699 ± 418.8	2137 ± 421.6	2408 ± 310.5	2818 ± 297.9	3203 ± 218.6
Lossa	2018	1986 ± 164.1	2539 ± 331.7	2805 ± 467.6	3113 ± 576.1	3371 ± 545.1	3675 ± 614.2
	2019	1213 ± 199.8	1378 ± 148.5	1903 ± 182.1	2182 ± 260	2495 ± 148.3	2863 ± 96.8
Average	2018	2068 ± 334.0	2657 ± 388.4	2937 ± 465	3165 ± 489.1	3393 ± 488.7	3624 ± 516.7
	2019	1600 ± 483.5	2297 ± 663.9	2613 ± 329.9	2912 ± 626.6	3123 ± 416.2	3470 ± 561.1
Average 2018–2019		1834 ± 473.2	2297 ± 648.8	2613 ± 590.8	2912 ± 610.6	3123 ± 524	3470 ± 553.9
			Df.			**Significance**	
Treatment (T)			5			<0.001	
Location (L)			2			<0.001	
Year (Y)			1			<0.001	
T × L			10			0.592	
T × Y			5			0.118	
L × Y			2			<0.001	
T × L× Y			10			0.918	
CV%						12.4	

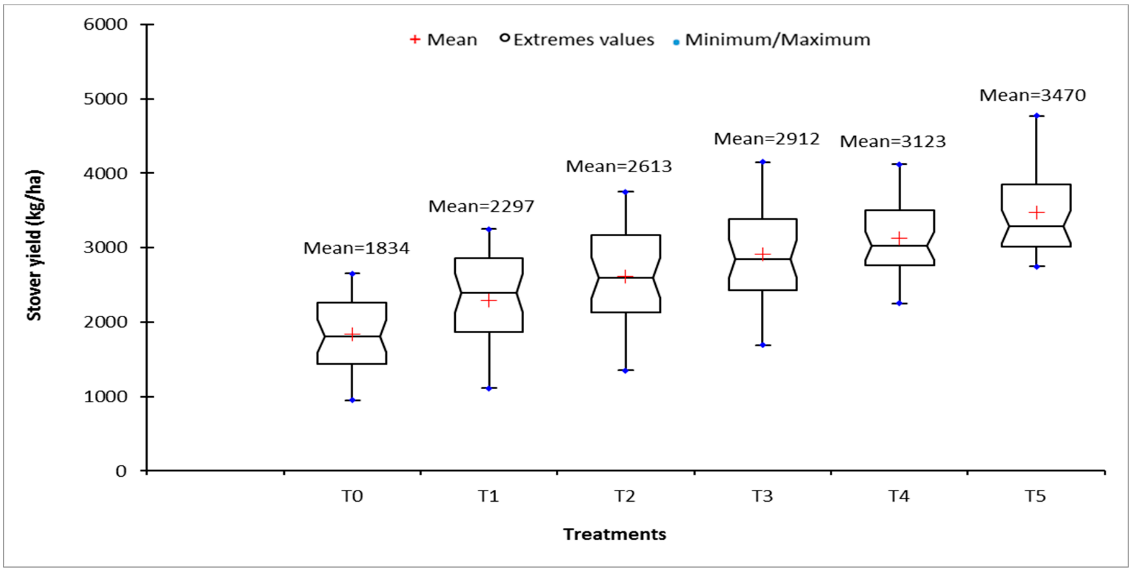

Figure 5. Effects of the treatments on stover yield (kg ha^{-1}) across three sites over two years in the on-station experiments.

3.3.2. On-Farm Experiments

The on-farm experiments also confirmed the yield-enhancing effect of mechanization in combination with seed priming, seed treatment and microdosing with mineral and organic fertilizer.

The average grain yield was 606 kg ha^{-1} for the control T0, against 1135 and 1238 kg ha^{-1} for T1 and T2, respectively (Table 7, Figure 6). The respective grain yield increases compared to T0 were 87.3% and 104.3%. The improved technological packages T1 and T2 gave a significant higher grain yield than the control treatment. However, there was no significant difference between the T1 and T2 treatments, despite higher input in the T1 treatment (2 g DAP and 150 compost hill^{-1}) than the T2 treatment (0.3 g NPK and 50 g compost hill^{-1}). It is likely that seed priming and seed treatment with fungicide/insecticide compensated to some extent for the lower fertilizer input in the T2 treatment compared to the T1 treatment. The T2 treatment in the on-farm experiment is similar to the T5 experiment in the on-station experiment, and it is interesting to note that both these treatments more than doubled grain yields. For the on-farm experiments, there were no significant interactions between treatments and villages.

Table 7. The effect of the treatments on grain yield in eight on-farm experiments in 2019. (kg ha^{-1}). Average of treatments and corresponding 95% confidence intervals are presented.

	Village								
	Aguié	**Arewa**	**Danja**	**Kandoussa**	**Karosofoua**	**Lossa**	**N'Dounga**	**Sabon Gida**	**Average**
T_0	675 ± 85	727 ± 49	594 ± 49	693 ± 65	604 ± 138	388 ± 133	462 ± 106	703 ± 137	606 ± 145
T_1	1191 ± 118	1290 ± 87	1162 ± 127	1202 ± 44	1253 ± 138	808 ± 151	883 ± 161	1287 ± 64	1135 ± 202
T_2	1312 ± 65	1370 ± 95	1392 ± 78	1287 ± 81	1253 ± 119	933 ± 85	1043 ± 51	1310 ± 60	1238 ± 170
			Df.				**Significance**		
Treatment (T)			2				<0.001		
Villages (V)			7				<0.001		
T × V			14				0.540		
CV%							8.4		

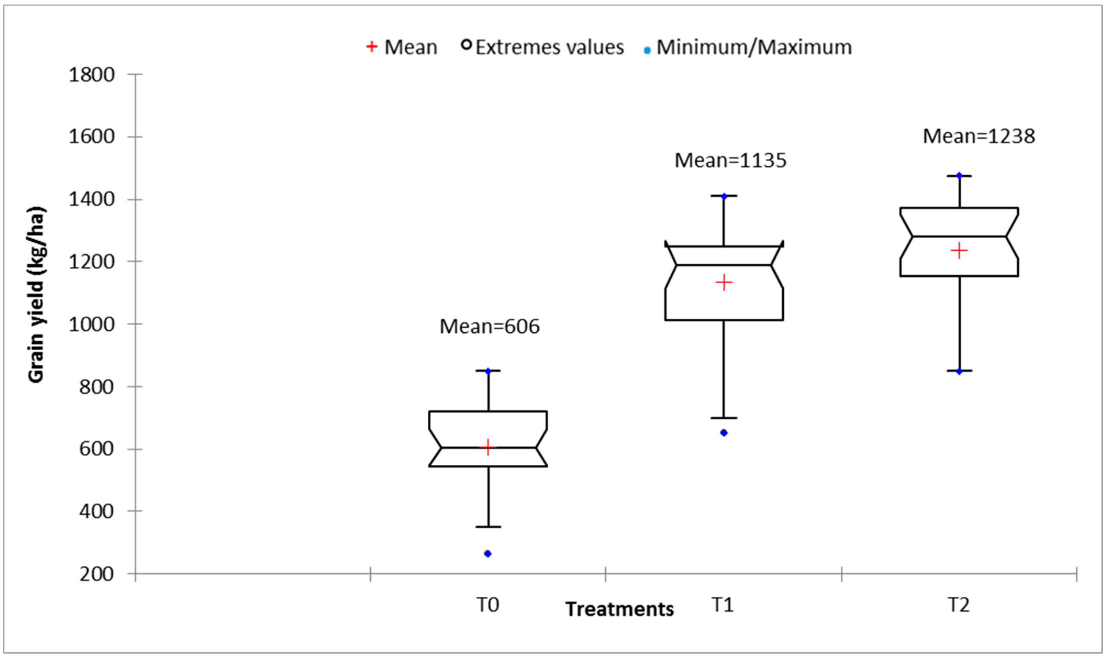

Figure 6. Effects of the treatments on grain yield (kg ha^{-1}) in the on-farm experiments.

The average stover yield in the on-farm experiments was 1682 kg ha^{-1} for the control T0, against 2331 and 2771 kg ha^{-1} respectively for T1 and T2 (not presented in figure). The respective stover yield increases compared to T0 were 38.6% and 64.7%.

3.4. Economic Analysis of On-Station Experiments

The economic analysis of the on-station experiments showed that the economic return for the T0, T1, T2, T3, T4 and T5 treatments were 96,339; 150,515; 158,657; 179,208; 173,789 and 198,534 CFAF ha^{-1} respectively (Table 8). The respective gross margin increases compared to T0 were 56.2%, 64.7%, 86.0%, 80.4% and 106.1%. The better economic performance in the improved treatments was particularly related to increased yield. Although the production costs were higher in the improved treatments, the value of the yield increase more than compensated for these increased costs. The production costs in the improved treatments were related to the depreciation cost of the planter, interest costs and maintenance costs. The economic analysis shows that the machine costs were considerably lower than the variable costs. The input costs related to mineral fertilizer and fungicide were minimal compared to the value of the yield increase. Manual weeding represented the highest production cost in the control treatment.

Table 8. Effects of the treatments on income, production costs and economic return in the on-station experiments.

Treatments	T0	T1	T2	T3	T4	T5
Income						
Grain	143,000	223,600	248,600	270,600	280,200	306,000
Stover	15,039	18,835	21,427	23,878	25,609	28,454
Total Income	158,039	242,435	270,027	294,478	305,809	334,454
Production Costs						
Fixed costs per year						
Depreciation costs	0	10,800	10,800	10,800	10,800	10,800
Interest costs	0	7920	7920	7920	7920	7920
Repair costs	0	15,600	15,600	15,600	15,600	15,600
Total fixed costs	0	34,320	34,320	34,320	34,320	34,320
Variable costs per hectare						
Ox rental	—	19,450	19,450	19,450	19,450	19,450
Sowing	5850	2850	2850	2850	2850	2850
Seeds	4800	1800	1800	1800	1800	1800
Fungicide	—	300	300	300	300	300
Mineral fertilizer	—	1200	—	1200	—	1200
Compost	—	—	17,500	17,500	35,000	35,000
Thinning	5000	—	—	—	—	—
Weeding	29,100	7100	7100	7100	7100	7100
Harvesting	5850	8700	9750	10,650	10,800	11,700
Transporting harvest	3900	5800	6500	7100	7200	7800
Threshing cleaning	7200	11,600	13,000	14,200	14,400	15,600
Total variable costs	61,700	57,600	77,050	80,950	97,700	101,600
Total costs per hectare	**61,700**	**91,920**	**111,370**	**115,270**	**132,020**	**135,920**
Economic return	**96,339**	**150,515**	**158,657**	**179,208**	**173,789**	**198,534**

4. Discussion

4.1. The Effects of the Planter

The Gangaria planter addresses several challenges related to sustainable farming intensification in the Sahel. In particular, it makes it more feasible for farmers to use organic fertilizer and it ensures timelier and more precise sowing and application of fertilizer. The average cultivated area per farm in the project areas in this study is about four hectares (unpublished data), and it would therefore take about 142 h per farm (equivalent to 18 working days) for manual sowing and fertilizer application (as per T1), while if the Gangaria planter is used, the corresponding time use would be 22.8 h per farm. Farmers cannot spend that much time on sowing and fertilizer applications, particularly as there are few days with optimal sowing conditions in these dryland areas. Manual sowing without the application of fertilizer (as per T0) has twice the labor demand of mechanical sowing. Since labor is also a constraint at the time of sowing, it is likely that farmers who have access to a planter can sow more quickly and at a more optimal time.

Time use in mechanical sowing and fertilizer allocation is similar to results found in Mali, where it has been found that mechanical application of seeds and mineral fertilizer took 7.1 h ha^{-1} [14]. In the current study, time use for sowing and compost application was assessed to 5.7 h ha^{-1}.

The Super-eco planter, which is still in use in Niger and other Sahelian countries, has only one disc and so can apply seeds, but not organic fertilizer. The newly developed Gangaria planter is not a sophisticated planter, but the price is only 125,000 CFAF (190 Euro) and it can be produced and maintained by local blacksmiths. It may therefore be a breakthrough for improved soil fertility management in the Sahel.

4.2. Agronomic Effects

Improved treatments (T1–T5) greatly improved speed of germination compared to the control. This faster germination rate is most likely due to the seed priming effect, as there is no clear difference between the fertilizer treatments. Previous studies have also shown the importance of seed priming for rapid and uniform crop establishment [7,16].

The increased grain and stover yields in these experiments are likely a combined effect of mechanical sowing and weeding, seed priming, fungicide/insecticide seed treatment and microdosing of fertilizer and compost. Mechanical sowing may account for a smaller part of this yield increase, as it was found that mechanized sowing in Mali increased yield compared to manual sowing by 14% [14]. Seed priming may also explain part of the yield increase as seed priming was found to increase pearl millet yield by between 6% and 30% in Mali [7,17], and by 30% in the Sahelian zone of Sudan [8]. Microdosing with mineral and organic fertilizer may explain the major part of the yield increase, according to a review that showed that microdosing with mineral fertilizer in the Sahel increased grain yields in the order of 32.3% to 107.5% [13].

The higher straw production in the improved treatments is of great value for the farmers, because access to fodder is a limiting factor for livestock production in the Sahel [18].

In Mali, it was shown that a combination of mechanized sowing, seed priming and microdosing (0.2 g NPK 15-15-15 hill^{-1}) increased sorghum grain yield by 43.8% [13]. The T1 treatment in the on-station experiment in Niger, which is almost identical to the treatment in the Mali experiment, gave a corresponding increase in pearl millet grain yield of 55.5%.

The importance of using organic fertilizer for maintaining long-term soil productivity is well documented for the Sahel [9,19,20], but the labor demand associated with the application thereof limits its use. Use of straw as a mulch is an alternative approach to increasing carbon input to the soil compared to using compost/manure. However, the free grazing system practiced in the dry season in the Sahel makes retention of crop residues very difficult. The use of compost to increase carbon and nitrogen input is therefore more compatible with the traditional grazing system than mulching with crop residues. The use of Gangaria planter is interesting for the farmers as it facilitates the application of organic fertilizer, while greatly reducing the labor demand.

The Gangaria planter offers different options for soil fertility management. If farmers do not have access to compost, they may use only seed priming, seed treatment and 0.3 g NPK hill^{-1}, as this treatment gave a yield increase of 55.5%. If mineral fertilizer is not available or affordable, they may use 25 g (T2) or 50 g (T4) compost hill^{-1} instead, as these treatments in combination with seed priming and seed treatment increased average grain yield compared to the control by 72.7% and 94.9%, respectively. The difference between 25 and 50 g compost hill^{-1} was, however, not significant.

It appears that the yield increased more with the application of compost than with the application of mineral fertilizer alone. This can be explained by a higher nutrient input in the compost treatments than in the amount of 0.3 g NPK hill^{-1}. The rates of 25 and 50 g compost hill^{-1} are equivalent to 2.77 and 5.55 kg N ha^{-1}, and 0.0028 and 0.0056 kg P ha^{-1}, respectively. The nutrient input of 0.3 g NPK 15-15-15 hill^{-1} is equivalent to 0.45 kg N ha^{-1} and P ha^{-1}. The better effect of the compost treatments

(25 or 50 g) as compared to the mineral fertilizer (0.3 g NPK hill^{-1}) is therefore likely due to higher nitrogen input (10 times higher in the case of 50 g compost hill^{-1}). Previous studies have also shown that hill placement of manure at the rate of 100 g manure hill^{-1} increased millet yields compared to broadcasting manure [20]. Our study also shows that rates as low as 25 g compost hill^{-1} can significantly increase yields. However, the highest yield was obtained when microdosing of compost and mineral fertilizer were combined. The nutrients in mineral fertilizer are directly available to the plant, but compost supplies nutrients over a longer period.

4.3. Economic Effects

The economic return more than doubled when mechanization combined with seed priming and microdosing was introduced. The economic analysis shows that investment in a planter is an interesting option for the farmers. However, raising capital for purchasing a planter may be a problem, as access to credit in rural areas is difficult. Farmers may consider financing a planter by providing services to other farmers for sowing and weeding. The best approach for introducing mechanization is to combine it with the use of yield-enhancing technologies like seed priming, seed treatment, microdosing of NPK and compost application, as these will increase yield, reduce labor demand and increase economic return. Introducing mechanization alone without these accompanying technologies may not be worthwhile, as the return on the investment is likely to be too low. A previous study from Mali has also indicated that mechanization of sowing and fertilizer application is economically feasible [13].

4.4. Overall Sustainability of the Approach

In this study, it has been shown that it is feasible to develop a planter that can simultaneously deliver seeds and fertilizer (research question 1) and that mechanized application of seeds and fertilizer gave improved crop establishment, higher yields and better economic return (research question 2). We think it is a great advantage that the machine can be produced in Niger as this assures easy access to spare parts and local employment and capacity building. The machine can also be maintained by local blacksmiths.

Application of manure and compost is very time consuming and these organic fertilizers are also in short supply. The new planter greatly reduce time use in application of organic fertilizer and also ensures more efficient use of the limited amount of organic fertilizer that is available. This approach will, in the long run, build soil organic matter and thereby contribute to an improved sustainability of the system.

5. Conclusions

In this study, the findings in terms of labor use, agronomic outcomes and economic gains show that the use of the Gangaria planter/multicultivator is highly suitable for the mechanized application of seeds, mineral fertilizer and compost. In addition, the planter can be used for weeding. This planter is the first to our knowledge that can simultaneously sow and apply soil amendments, and it is available and produced locally in Niger at a low price. It thereby addresses the labor constraint related to the application of organic fertilizer. The Gangaria planter may therefore represent a breakthrough for improved soil fertility management in the Sahel and takes agricultural intensification in the Sahel one step further.

This study has shown that mechanization combined with seed priming, seed treatment, application of 0.3 g NPK hill^{-1} and microdosing of compost at a rate of 25 or 50 g hill^{-1} can more than double pearl millet grain yields and gross profit margins. The manual application of compost and mineral fertilizer (on an average farm of four hectares) had a labor demand of more than six times higher than the mechanized application—that is, about 18 man-days compared to about three days, respectively. It is therefore clear that it is very challenging for farmers to practice the manual application of fertilizer and compost.

The study highlights different options for farmers in the management of soil fertility. If compost is not available, farmers may use only seed priming, seed treatment and microdosing of 0.3 NPK hill^{-1}; if mineral fertilizer is not feasible, farmers can elect to replace it with microdosing of compost (in combination with seed priming and seed treatment). The best approach, however, is to combine microdosing of mineral fertilizer and compost. Besides economic gains, these yield-enhancing technologies will make the farming system less vulnerable to climate change because of timelier and more precise farm operations.

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References

1. IRD. *Le mil, aliment du futur au Sahel*; Actualité Scientifique; Fiche No. 325; IRD: Marseille, France, 2009; 2p.
2. FAO-Stat FAO Stat Crops. 2020. Available online: http://www.fao.org/faostat/en/#data/QC (accessed on 27 November 2020).
3. Christiansson, C.B.; Bationo, A.; Baethegen, W.E. The effect of soil tillage and fertilizer use on pearl millet yields in Niger. *Plant Soil* **1990**, *123*, 51–58. [CrossRef]
4. Zeinabou, H. Contribution du niébé et des fumures organiques et minérales à la nutrition azotée et aux rendements du mil dans les systèmes de cultures en zone sahélo-soudanienne au Niger. Ph.D. Thesis, Université de Bobo-Dioulasso, Bobo-Dioulasso, Burkina Faso, 2017; 126p. Available online: http://www.beep.ird.fr/collect/upb/index/assoc/IDR-2017-HAL-CON/IDR-2017-HAL-CON.pdf (accessed on 27 November 2020).
5. ICRISAT. Fertilizer Micro-Dosing. Boosting Production in Unproductive Lands. 2019. Available online: http://oar.icrisat.org/5666/1/Microdosing_Flyer_2009.pdf (accessed on 27 November 2020).
6. Bielders, C.; Gerard, B. Millet response to microdose fertilization in south–western Niger: Effect of antecedent fertility management and environmental factors. *Field Crops Res.* **2015**, *171*, 165–175. [CrossRef]
7. 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. [CrossRef]
8. Aune, J.B.; Ousman, A. Effect of seed priming and micro-dosing of fertilizers on sorghum and pearl millet in Western Sudan. *Exp. Agric.* **2011**, *47*, 419–435. [CrossRef]
9. Quinn, D.J.; Lee, C.D.; Poffenbarger, H.J. Corn yield response to sub-surface banded starter fertilizer in U.S.: A meta-analysis. *Field Crops Res.* **2020**, *243*, 107834. [CrossRef]
10. Buerkert, A.; Bationo, A.; Dossa, K. Mechanism of residue mulch-induced cereal growth increase in West Africa. *Soil Sci. Soc. Am. J.* **2000**, *64*, 346–358. [CrossRef]
11. Bationo, A.; Waswa, B.S. New Challenges and Opportunities for Integrated Soil Fertility Management ISFM in Africa. In *Innovations as Key to the Green Revolution in Africa*; Springer: New York, NY, USA; London, UK, 2011; Volume 1, pp. 3–17.
12. Bationo, A.; Mokwunye, A.U. Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. *Fertil. Res.* **1991**, *29*, 117–125. [CrossRef]
13. Aune, J.B.; Coulibaly, A.; Giller, K.E. Precision farming for increased land and labour productivity in semi-arid West Africa. A review. *Agron. Sustain. Dev.* **2017**, *37*, 16. [CrossRef]
14. Aune, J.B.; Coulibaly, A.; Woumou, K. Intensification of dryland farming in Mali through mechanisation of sowing, fertiliser application and weeding. *Arch. Agron. Soil Sci.* **2019**, *65*, 400–410. [CrossRef]

15. Sims, B.; Kienzle, J. Mechanization of Conservation Agriculture for Smallholders: Issues and Options for Sustainable Intensification. *Environments* **2015**, *2*, 139–166. [CrossRef]
16. Harris, D. Development and testing of "on-farm" seed priming. *Adv. Agron.* **2006**, *90*, 129–178. [CrossRef]
17. Aune, J.B.; Traoré, C.O.; Mamadou, S. Low-cost technologies for improved productivity of dryland farming in Mali. *Outlook Agric.* **2012**, *41*, 103–108. [CrossRef]
18. Bayala, J.; Ky-Dembele, C.; Kalinganire, A.; Olivier, A.; Nantoumé, H. *A Review of Pasture and Fodder Production and Productivity for Small Ruminants in the Sahel*; ICRAF Occational Paper No. 21; Word Agroforestry Center: Nairobi, Kenya, 2014; 87p. Available online: https://www.researchgate.net/publication/262943657 (accessed on 27 November 2020).
19. Yamoah, C.; Bationo, A.; Shapiro, B.; Koala, S. Trend and stability analysis of millet yields with treated with fertilizer and crop residues in the Sahel. *Field Crops Res.* **2002**, *75*, 53–62. [CrossRef]
20. Ibrahim, A.; Abaidoo, R.C.; Fatondji, D.; Opoku, A. Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. *Field Crops Res.* **2015**, *180*, 29–36. [CrossRef]