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Received: 16 May 2021 | Accepted: 6 August 2021

DOI: 10.1002/agj2.20850

Agronomy Journal

ARTICLE

Agronomic Application of Genetic Resources

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Assigned to Associate Editor David Clay.

Abstract

Sorghum [*Sorghum bicolor* (L.) Moench], a staple food crop in Mali, has low yields for several reasons including that many farmers do not have the financial resources to purchase state-of-the-art genetics and fertilizers and information is not available on how to optimize yields for heirloom variety. To improve their economic and environmental sustainability, Mali farmers need to understand how to invest their limited resources. In many situations this involves the use of open-pollinated varieties that have a range of tillering capabilities. This study determined the best population density and nitrogen (N) fertilization combinations for eight locally available sorghum varieties. The research was conducted in 2018 and 2019 and the experimental design was split-split-plot randomized block, the treatments were two plant densities (26,600 and 53,300 plants ha^{-1}), three N levels (0 kg ha^{-1}, 89 kg ha^{-1}, and 178 kg ha^{-1}), and eight varieties that had a range of tillering characteristics. Each treatment was replicated three times and six of the varieties were open pollinated. Results showed that each variety had a different yield response to plant density and N rate. For example, the tall guinea (hybrids FADDA and PABLO) and the short *durra-caudatum* A12-79 cultivar produced higher yields when planted at 53,300 plants ha^{-1} and

Abbreviations: D1, 26,600 plants ha^{-1}; D2, 53,300 plants ha^{-1}; MRR, marginal rate of return; N0, nitrogen rate of 0 kg ha^{-1}; N1, nitrogen rate of 89 kg ha^{-1}; N2, nitrogen rate of 178 kg ha^{-1}.

fertilized with 178 kg N ha^{-1} N2D2 treatment. For the short guinea-*caudatum* improved varieties C2_007-03 and C2_075-15 and *caudatum* GRINKAN and SOUMBA varieties the optimum seeding rate was 53,300 plants ha^{-1} that were fertilized with 89 kg N ha^{-1} (N1D2). For the tall local *guinea* TIEBILE variety the highest yields were observed when it was seeded at a rate of 26,600 plants ha^{-1} and fertilized with 89 kg N ha^{-1}. Grain yield increase was associated with yield components and growth traits for eight varieties studied. Panicle numbers per square meter and chlorophyll index were associated with grain yield in *guinea* hybrid. Grain number per panicle and 1,000 grain weight were involved in increasing grain yield in *caudatum* varieties. Nitrogen rate and planting density combination in terms of grain yield varied with different sorghum [*Sorghum bicolor* (L.) Moench] varieties studied. Knowledge of optimum combinations will help producers decide which option to promote to booster sorghum production in Mali.

1 | INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is a major staple cereal crop in the Sahelian and savannah zones of West Africa, where it constitutes the main food of millions of rural populations (Belton & Taylor, 2004; Kante et al., 2017). In Mali, the amount of cultivated grain sorghum increased 51% from 1990 to 2020 (FAOSTAT, 2020). This increase is attributed to the increased cultivation of marginal soils (Gigou et al., 2004; Kante et al., 2019). Grain yields are very low and average 930 kg ha^{-1} (FAOSTAT, 2020). The low yields are the result of low use of improved varieties (13–33% nationwide), highly variable rainfall, and the low use of chemical inputs (Ibrahim et al., 2014; Macauley & Ramadjita, 2015). For rural communities there is a critical need to increase grain yields to meet the growing demand (Iqbal et al., 2012).

Increasing sorghum yields requires a combination of factors including the adoption of improved hybrids and matching the plant population and nitrogen (N) rate to the climate (Sallah et al., 2007). Information on how to optimize the cultivar selection, seeding rate, and N rate in semi and arid regions is lacking (Fernandez et al., 2012; Sallah et al., 2009). Extensive research on the relationship between seeding rates and N rates have been conducted in humid climate worldwide. However, this research cannot be directly applied to African steppe because complex interactions between cultivar, seeding rate, soil, and N influence yields. This problem is further confounded by producers that are growing crops on marginal soils are often limited by access to commercial fertilizers and current varieties. For example, many of the locally available varieties are open pollinated and have a range of tillering capabilities. Seeding rate recommendations will be very different in varieties with high and low tillering capacity. In addition, due to financial and cultural habits, farmers are hesitant to discontinue historical farming techniques. This paper provides information needed to improve the food and economic security of Mali farms.

Numerous studies have demonstrated the importance of plant density and N fertilization on sorghum grain yield (Arunakumari & Rekha, 2016). Previous studies reported that optimum plant density depends on each crop (Biswas et al., 2014), beyond which the competition between plants for light, water, and nutrients becomes important and can lead to decreased crop yields (Li et al., 2016). Nitrogen is also one of the most important nutrients which must be used in an optimal quantity depending on plant density as its lack or excess can reduce crop productions (Ferraris & Charles, 1986; Sher et al., 2016).

During the last decades, to maintain soil fertility, Malian producers relied on organic manure, low quantities of mineral fertilizers, long-term fallows, and low seeding rate (10,000 plants ha^{-1}) of a local open-pollinated sorghum cultivar (Coulibaly et al., 2019; Dumont, 1966) to produce sorghum (Ibrahim et al., 2014; Macauley & Ramadjita, 2015). The current recommendation of sorghum grown in Mali is a seeding rate of 26,600 plants ha^{-1} of an open-pollinated variety and the application of 89 kg ha^{-1} of N (Chantereau et al., 2013; Kouyate & Wendt, 1991). What is unknown is will recommendations designed for local open-pollinated sorghum cultivars be appropriate for modern hybrid and improved open-pollinated sorghum varieties. To our knowledge, this is the first study that highlights optimum combinations of plant densities and N rates on different sorghum varieties responses on grain yields in the Sudan–Sahelian area of Mali for grain yield increase. Therefore, it is relevant to define an optimum combination of plant density, N, and sorghum varieties (hydrids, opened-pollinated improved and local varieties) on grain yields grown in different Mali production zones. The objectives of this study were to: (a) determine the optimum combination of plant density and N fertilization responses of eight sorghum varieties grain yield and (b) identify the grain yield contributing parameters from each variety under the two combinations.

Core Ideas

- Hybrid and durra varieties produced better yield under high N rate and plant density.
- *Caudatum* varieties produced better grain yield with N and plant density moderate use.
- Local *guinea* variety produced better grain yield with moderate use of N and low plant density.
- Panicle number and SPAD value were traits explaining grain yield increase of hybrid varieties.
- Grain number and grain weight were traits explaining grain yield increase of *caudatum* varieties.

2 | MATERIALS AND METHODS

2.1 | Site characteristics

Two consecutive experiments were conducted during 2018 and 2019 rainy seasons at the Sotuba Agronomic Research Station (12˚39′ N, 07˚56′ W) of the Malian Institute of Rural Economy (IER). The Sotuba site (Bamako) was located in the Sahelo–Sudanian zone with a rainy season between May and October, characterized by poorly distributed rainfall, an average of 866 mm on the period 1981–2010 (Coulibaly et al., 2019). The total annual rainfall of 840 and 1,158 mm were recorded in 2018 and 2019, respectivley (Figure 1). Mean monthly temperatures during the growing season ranged between 27 and 28 ˚C in 2018 and 2019 (Figure 1). The soil of the site was a sandy-loam soil characterized by low levels of soil organic carbon (C), total N, and exchangeable potassium (K), are presented in Table 1. Soil particle size analysis was done by the hydrometer method (Anderson & Ingram, 1993) and pH was determined by the electrometric method in a soil solution with a soil/water ratio of 1/2.5 (Jackson, 1967). Soil organic C was determined using the modified Walkley–Black wet oxidation method (Nelson & Sommers, 1982) and total N was determined by the Kjeldahl digestion method (Bremner &, Mulvaney, 1982). Soil available P was determined by the Bray II method and K was extracted with a neutral ammonium acetate solution and was determined by flame photometry (Benton & Jones, 2001). Experimental soil samples were collected before the trial installation at 0-to-30-cm depth and analyzed by the Soil-Water-Plant Laboratory of the IER in Sotuba. The soils are typical upland soils used for sorghum production in the Sahelo–Sudanian zone of West Africa (Buah & Mwinkaara, 2009).

2.2 | Plant materials

Plant material was composed of eight contrasted varieties representing the diversity of cultivated sorghums in Mali. It includes two tall hybrids (FADDA and PABLO), five short open-pollinated improved varieties (GRINKAN, SOUMBA, C2_007-03, C2_075-15, A12-79) and the tall local variety TIEBILE (open-pollinated) (Table 2). These varieties are widely cultivated by the farmers in West Africa countries due to their adaptability and important agronomic characteristics (CEDEAO-UEMOA-CILSS, 2016; Gano et al., 2021).

2.3 | Experimental design and crop management

A split-split-plot randomized block was the experimental design. Each block was replicated three times and the treatments were two seeding densities as the main factor,

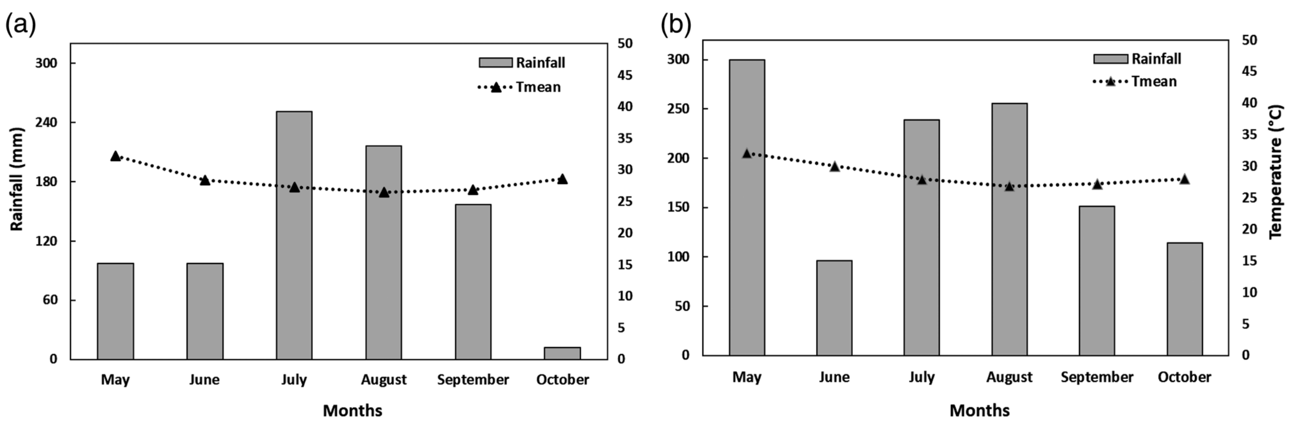

FIGURE 1 Rainfall and temperature mean recorded in (a) 2018 and (b) 2019 rainy seasons at Sotuba in Mali

TABLE 1 Soil properties of the experimental site in Sotuba at soil depth of 0–30 cm in 2018 and 2019 rainy seasons at Sotuba in Mali

Property	Soil depth	Experiment (Sotuba)
	cm	
Sand, %	0–30	75.83
Silt, %	0–30	18.98
Clay, %	0–30	5.19
pH (water)	0–30	5.75
Soil organic C, g kg^{-1}	0–30	0.47
Total N, g kg^{-1}	0–30	0.12
Available P, mg kg^{-1}	0–30	15.80
Exchangeable K, mg kg^{-1}	0–30	20.00

TABLE 2 Characteristics of eight sorghum varieties and hybrids used during 2018 and 2019 rainy seasons at Sotuba, in Mali

Variety	Origin	Race	Plant height	Panicle type	Grain color	Tillering	Grain yield	Photoperiod sensitivity
			cm				Mg ha^{-1}	
FADDA	Mali	*Guinea* (hybrid)	300	loose	light brown	high	4	slightly sensitive
PABLO	Mali	*Guinea* (hybrid)	400	loose	white-yellowish	medium	4	sensitive
GRINKAN	Mali	*Caudatum* (OP)	200	semi-compact	white	low	2.8	slightly sensitive
SOUMBA	Mali	*Caudatum* (OP)	240	semi-compact	yellowish	low	2.8	slightly sensitive
TIEBILE	Mali	*Guinea* local (OP)	360	loose	white	high	2.5	sensitive
C2_007-03	Mali	*Guinea-Caudatum* (OP)	210	loose	white	low	3.3	slightly sensitive
C2_075-15	Mali	*Guinea-Caudatum* (OP)	170	loose	white	high	3.3	slightly sensitive
A12-79	Mali	*Durra-Caudatum* (OP)	175	semi-compact	white	low	4	slightly sensitive

Note. OP, open-pollinated.

three N levels as the subplot, and eight varieties as the sub-subplot. Plant densities were 26,600 (D1) and 53,300 plants ha^{-1} (D2) and N levels were 0 (N0), 89 (N1), and 178 kg ha^{-1} (N2).

The seeding distances were 0.75 m between rows and either 0.25 (high) or 0.50 m (low) between the plants that were seeded into hills. Experimental unit area was 18 m^2 with six rows length of 4.5 m long and 4 m wide each. The experimental soil was plowed to approximately 30-cm depth. Seedings were done on 18 June 2018 and 5 July 2019 after a rainfall of about 30 mm at a rate of five to six seeds per hill (i.e., 8–10 kg of seed per hectare). Thinning was performed 15 d after sowing to one plant per hill. Nitrogen was applied in the form of urea (46% N) in two fractions, 3 wk after thinning (50%) and 50% before panicle initiation. Basal application of phosphorus (P) (46 kg ha^{-1} P_2O_5) was homogeneously made in all plots before sowing as "phosphate naturel de Tilemsi" (PNT) granulated (31% P_2O_5). Two manual weeding were carried out in each experiment and crop ridging was performed after the second N application. Dikes were realized between each N level and between replications to reduce N exchange and water runoff from plot to plot. All plots were treated with EMACOT 050 WG insecticide (Emamectine benzoate 50 g kg^{-1}) to control legionary caterpillar (*Spodoptera exempta*) attacks.

2.4 | Sampling and measurement

Contiguous plants in the middle of each experimental plot were sampled for measurements towards the end of flowering. Leaf area index was measured on a plot (1 m^2) according to Wilhelm et al. (2000) using Sunscan Septometer (Delta-T Device Ltd) equipped with an external BF5 sensor. SPAD value (chlorophyll index) measurements were done using the portable SPAD-502 (SPAD 502-Minolta) device on the main stem of the third ligulated leaf from top to bottom on three plants taken in each elementary plot. Plant height was measured with a graduated ruler at physiological maturity on the same plants used for the chlorophyll estimation. Grain, straw, and yields components were recorded on an area of 2.25 m^2. They were taken on six hills for low density and on 12 hills for high density. Panicle number per square meter was counted manually before the harvest. After harvest, panicles and aboveground biomass were sun dried for 4 wk. The total biomass (dry biomass and panicles) obtained in each elementary plot was extrapolated in kg ha^{-1}. After threshing panicles, grains were winnowed, weighed, and then extrapolated to kg ha^{-1}. Thousand (1,000) grain weights were obtained by counting grains with an electric counter (NUMIGRAL, Chopin technologies). Number of grains per panicle was based on an average panicle grain weight to its 1,000 grain weight.

2.5 | Statistical analysis

The combined analysis was performed across environments (Venables & Smith et al., 2019) according to the model developed by Carmer et al. (1989). The "Shapiro–Wilk" normality and "Bartlett" residue homogeneity tests were performed to identify and exclude aberrant data for each measured variable. Least Significant Difference (LSD) at the 5% threshold of probability was used to discriminate factors studied (plant density, N, and variety) and the interactions between plant density and N fertilization for each trait. Correlations and linear regression analyses were performed in R software, version 3.6.2.

The partial budget analysis was calculated according to the method proposed by Buah and Mwinkaara (2009) by taking into account cost benefit and marginal rate of returns (MRR %). To estimate the economic parameters, the average price of a kilogram of sorghum grain was evaluated on information basis collected from local prevailing markets in Bamako during 2018 and 2019. Variables cost included N and seed (hydrids and open-pollinated) and labor N application. All cost and benefits were calculated per hectare in US dollars (US$). The following concepts used in the partial budget analysis are defined as follows:

-Average grain yield (kg ha^{-1}) for each treatment excluding treatment N0D2 (0 kg N ha^{-1} and 53,333 plants ha^{-1}).

-Gross benefit per hectare is the product of the sorghum price on the local market and grain yield per treatment.

-Variable costs (VC) is the sum of fertilizer costs, cost of fertilizer (N) application and seed costs.

-Net benefit (NB) for each treatment is the difference between the gross benefit and the variable costs.

-Marginal rate of returns (MRR in percent) is the ratio of the difference between the net benefit of treatments to the difference between the variable costs of the same treatments. It is calculated according to the following expression:

$$\text{MRR (Between level 0 and } n) = \frac{\text{Change in net benefit } (\text{NB}n - \text{NB}0)}{\text{Change in variable costs } (\text{VC}n - \text{VC}0)} \times 100$$

where 0 represents without nitrogen (0 kg ha^{-1}) application at low plant density and n represents nitrogen levels N1 (89 kg ha^{-1}) and N2 (178 kg ha^{-1}) at low and high plant density. NB and VC represent respectively net benefit and variable costs calculated at each N level and plant density combinations.

3 | RESULTS

3.1 | Grain yield and yield components

The analysis of variance showed significant effects of the density, N rate and variety on grain yield, panicle number and weight, 1,000 grain weight (except N), and grain number per panicle. For grain yield, there were significant interactions between N x variety ($P < .001$) and between density x N x variety ($P < .01$), while density x variety was not significant. For panicle number, there were also significant interactions between density x variety, N x variety, and for panicle number and weight there were significant interactions between N and varieties. For panicle weight there was also a significant interaction between density and variety (Table 3).

In terms of grain yield, different varieties responded differently to N rate and planting density. Under different plant density and N fertilizer combinations, the tall *guinea* hybrid varieties FADDA (6,611 kg ha^{-1}), PABLO (4,850 kg ha^{-1}), and short *durra-caudatum* variety A12-79 (5,342 kg ha^{-1}) produced a higher grain yield in N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}) treatment when compared to other treatments (Table 4). However, the short *guinea-caudatum* varieties C2_007-03 and C2_075-15 produced 4,498 kg ha^{-1} and 4,188 kg ha^{-1} under N1D2 treatment. There was no significant difference between N2D2 and N1D2 treatments (Table 4). The short *caudatum* varieties GRINKAN (4,056 kg ha^{-1}) and SOUMBA (3,884 kg ha^{-1}) recorded the best grain yields in N1D2.The tall local variety TIEBILE of *guinea* race produced a statistically identical grain yield in N2D1 (178 kg N ha^{-1} and 26,600 plants ha^{-1}), N1D2, N2D2, and N1D1 (89 kg N ha^{-1} and 26,600 plants ha^{-1}) with an average of 3,634 kg ha^{-1}. All varieties produced lowest grain yields in N0D1 (0 kg N ha^{-1} and 26,600 plants ha^{-1}) compared to the N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}), N1D2 (89 kg N ha^{-1} and 53,300 plants ha^{-1}), N2D1(178 kg N ha^{-1} and 26,600 plants ha^{-1}) and N1D1 (89 kg N ha^{-1} and 26,600 plants ha^{-1}) treatments (Table 4).

Panicle number per square meter produced by A12-79, C2_007-03, C2_075-15, GRINKAN, SOUMBA, and TIEBILE was identical in the N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}), N1D2 (89 kg N ha^{-1} and 53,300 plants ha^{-1}), and N0D2 (0 kg N ha^{-1} and 26,600 plants ha^{-1}) treatments. The panicle number per square meter increased significantly with increasing plant densities and N fertilizer rates and the N2D2 and N2D1 treatments produced the highest values

TABLE 3 Analysis of variance of plant density, N fertilization, variety and their interaction effects on grain yield and its components in 2018 and 2019 at Sotuba in Mali

Source of variation	Grain yield	Panicle no. per m^2	Panicle weight per m^2	1,000-Grain weight	Grain no. per panicle
Density (D)	***	***	***	*	***
Nitrogen (N)	***	*	***	ns	*
Variety (V)	***	***	***	***	***
D × V	ns	**	*	ns	ns
N × V	***	**	**	ns	ns
D × N × V	**	ns	ns	ns	ns

Note. ns, nonsignificant at the .05 probability level.
*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the .001 probability level.

for the FADDA and PABLO varieties, respectively (Table 4). Panicle weight per square meter for all varieties increased with increasing plant densities and N rate. The C2_007-03, C2_075-15, GRINKAN, TIEBILE, and SOUMBA varieties produced highest panicle weight per square meter in N1D2 and N2D2 treatments. For A12-79, PABLO, and FADDA varieties, the highest numeric panicle weight was produced in the N2D2 treatment (but was statistically identical to the N2D1 treatment for FADDA). C2_007-03, C2_075-15, FADDA, GRINKAN, and PABLO varieties produced higher 1,000 grain weights in N1D1 and N2D1 treatments. However, 1,000 grain weight for A12-79 and TIEBILE increased in N1D1 treatment and for SOUMBA variety, it was important in N1D2 treatment. Grains number per panicle increased with increasing plant densities. In each plant density, the grains number per panicle was statistically identical in N1 and N2 levels but it increased from N0 to N1 levels. Grains number per panicle varied among varieties under different treatments. A12-79, C2_007-03, GRINKAN, and SOUMBA varieties produced higher grains per panicle in N2D1 and N1D1 treatments and C2_075-15 in N2D1 treatment. No significant difference was observed among N2D1, N1D1, and N1D2 treatments for grain number per panicle in GRINKAN. In addition, FADDA produced higher grains per panicle in N1D1 and PABLO and TIEBILE varieties performed in the N1D1 and N1D2 treatments. Grain number per panicle obtained by TIEBILE in both treatments (N1D1 and N1D2) was statistically identical to that of the N2D2 treatment (Table 4).

3.2 | Growth and development parameters

Analysis of variance showed significant effects of the density, N, and variety ($P < .05$) on SPAD values, leaf area index, straw yield, and plant height. Interactions effects between density x variety and N x variety were significant for plant height. The N and variety interactive effect was significant on SPAD values, straw yield, and plant height as was between density x N x variety on straw yield (Table 5).

For chlorophyll index estimation (SPAD values), results showed an increase in the SPAD values with increasing N fertilizer and decreased with increasing plant density (Table 6). C2_007-03, FADDA, and PABLO varieties accumulated maximum chlorophyll in N1D1 (89 kg N ha^{-1}) and N2D1(178 kg N ha^{-1}) treatments at 26,600 plants ha^{-1}. A12-79 and GRINKAN varieties recorded more chlorophyll index in N2D1 and N2D2 (178 kg N ha^{-1}) at 26,600 ha^{-1} and 53,300 plants ha^{-1}. The best SPAD values were obtained in N1D1 and N2D2 with C2_075-15, in N2D2, N1D1, and N2D1 with SOUMBA and in N2D1 with TIEBILE. For all varieties, the leaf area index and straw yield increased significantly with increasing plant densities and N fertilizer rates, with N2D2 treatment demonstrating the highest values. The leaf area index produced by SOUMBA and GRINKAN in N2D2 and N1D2 (89 kg N ha^{-1} and 53,300 plants ha^{-1}) treatments, and straw yield produced by C2_007-03 in N2D2 and N1D2 treatments, were statistically similar. Plant height increased with N2D2 treatment for A12-79, C2_007-03, C2_075-15, and TIEBILE varieties. The PABLO variety was arithmetically higher in N2D2, N2D1, and N1D2 treatments (but was statistically identical). However, FADDA and SOUMBA varieties were taller in N2D2 and N1D2 treatments. In addition to, GRINKAN variety was taller under N2D2 and N2D1 (Table 6).

3.3 | Economic analysis

Partial budget analysis was achieved on data from the 2018 and 2019 rainy seasons. Results showed that the net benefits and marginal rate of return (MRR, percentage) for each variety varied between treatments (combination of plant density and N fertilization) except for the N0D2 treatment (0 kg N ha^{-1} and 53,300 plants ha^{-1}) which was not included in this

TABLE 4 Grain yield and yield components of eight sorghum varieties under plant density and N fertilization in 2018 and 2019 at Sotuba in Mali

Variety	Treatments	Grain yield	Panicle no. per m^2	Panicle weight per m^2	1, 000 Grain weight	Grain no. per panicle
		kg ha^{-1}			g	
A12-79	N0D1[a,b]	1,852d[c]	2.67b	267d	20.2ab	2,948cd
	N1D1[d]	3,138c	2.82b	471c	22.4a	4,365ab
	N2D1[e]	3,127c	2.89b	478c	21.8ab	4,720a
	N0D2[f]	2,896cd	5.33a	464c	20.1b	2,531d
	N1D2	4,004b	5.55a	570b	20.8ab	3,545c
	N2D2	5,342a	6.81a	715a	21.3ab	3,216cd
	Avg	3,393BC	4.34C	494B	21.1C	3,554A
C2_007-03	N0D1	2,520c	3.11b	324c	21.1ab	2,678bc
	N1D1	3,237 b	3.41b	415b	23.2a	4,020a
	N2D1	3,390b	3.85b	444b	23.1a	4,007a
	N0D2	3,486b	5.55a	428b	19.9b	2,418c
	N1D2	4,498a	5.92a	541a	21.1ab	3,168b
	N2D2	4,577a	6.22a	548a	21.4ab	3,103b
	Avg	3,618B	4.67C	450BC	21.6C	3,232AB
C2_075-15	N0D1	2,574c	3.59c	420d	19.6ab	2,810c
	N1D1	3,264b	4.64bc	513b	20.3a	3,319b
	N2D1	3,231b	4.52bc	470c	20.3a	3,824a
	N0D2	2,274cd	5.89ab	393e	16.9b	2,323d
	N1D2	4,188a	6.15ab	585ab	19.4ab	3,497b
	N2D2	4,294a	6.66a	609a	18.0ab	3,391b
	Avg	3,304BC	5.24B	498B	19.1D	3,194AB
FADDA	N0D1	2,139e	4.00c	348d	21.5ab	2,335d
	N1D1	4,308c	4.74c	604bc	22.9a	4,308a
	N2D1	5,948b	7.96ab	830ab	22.7a	3,492b
	N0D2	3,154d	6.15b	585c	19.8b	2,901c
	N1D2	4,883c	6.50b	711b	20.5ab	3,682b
	N2D2	6,611a	8.03a	878a	21.6ab	3,133bc
	Avg	4,507A	6.23A	659A	21.5C	3,309AB
GRINKAN	N0D1	2,957cd	2.95bc	420bc	22.1ab	3,063b
	N1D1	3,109c	3.52b	448bc	23.4a	3,337ab
	N2D1	3,469bc	3.86b	476ab	23.1a	3,512a
	N0D2	2,865cd	5.33a	381c	19.3b	2,147c
	N1D2	4,056a	5.78a	531a	22.3ab	3,295ab
	N2D2	3,757b	5.93a	533a	22.3ab	3,150b
	Avg	3,369BC	4.56C	465BC	22.1BC	3,084B
PABLO	N0D1	2,041d	3.16d	341d	24.6ab	2,017c
	N1D1	3,242c	4.67c	491c	25.7a	3,386a
	N2D1	3,941b	5.55b	526b	25.8a	3,136b
	N0D2	3,001c	5.96b	476c	22.3b	2,159c
	N1D2	3,770b	6.55a	539b	24.8ab	3,249ab
	N2D2	4,850a	6.42a	715a	24.0ab	3,148b
	Avg	3,474BC	5.38B	515B	24.5A	2,849C

(Continues)

TABLE 4 (Continued)

Variety	Treatments	Grain yield	Panicle no. per m^2	Panicle weight per m^2	1, 000 Grain weight	Grain no. per panicle
SOUMBA	N0D1	2,310d	2.67c	302d	21.1b	2,497bc
	N1D1	2,758c	3.45b	419b	22.3ab	3,307a
	N2D1	3,116c	4.13b	424ab	22.1ab	3,136ab
	N0D2	2,778c	5.52ab	354c	21.0b	2,150c
	N1D2	3,884a	5.55ab	435ab	25.0a	2,610b
	N2D2	3,404b	5.70a	443a	23.0ab	2,526b
	Avg	3,041C	4.50C	396C	22.4BC	2,704C
TIEBILE	N0D1	2,678b	3.36c	318d	23.2ab	2,128c
	N1D1	3,650a	4.89bc	464b	24.8a	2,914a
	N2D1	3,668a	5.26b	469b	24.0ab	2,703b
	N0D2	2,620b	6.13ab	343c	20.5b	1,882cd
	N1D2	3,676a	7.19a	613a	23.4ab	2,764ab
	N2D2	3,618a	6.30ab	604a	23.5ab	2,724ab
	Avg	3,318BC	5.52B	469BC	23.0B	2,519C

[a]N0, nitrogen rate of 0 kg ha^{-1}.
[b]D1, 26,600 plants ha^{-1}.
[c]Values in a column followed by different letters are significantly different at P < .05. Lower-case and upper-case letters indicate comparisons within treatments of each variety and among varieties, respectively.
[d]N1, nitrogen rate of 89 kg ha^{-1}.
[e]N2, nitrogen rates of 178 kg ha^{-1}.
[f]D2, 53,300 plants ha^{-1}.

TABLE 5 Analysis of variance of the effects of plant density, N fertilization, variety and their interactions on development and growth parameters in 2018 and 2019 at Sotuba in Mali

Source of variation	SPAD value	Leaf area index	Straw yield	Plant height
Density (D)	*	***	***	***
Nitrogen (N)	***	**	***	***
Variety (V)	***	**	***	***
D × N	ns	ns	ns	ns
D × V	ns	ns	ns	***
N × V	*	ns	**	***
D × N × V	ns	ns	**	ns

Note. ns, nonsignificant at the .05 probability level.
*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the .001 probability level.

study (Table 7). Net benefit for the eight sorghum varieties increased with the use of agricultural inputs. For the *guinea* hydrid varieties (FADDA, PABLO) and *caudatum-durra* variety A12-79, the N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}) treatment increased net benefit with respective values of 2007, US$1,435 and $1,607 ha^{-1} and MRR of 1,151, 686, and 877%, respectively. Results indicate that the N2D2 treatment is the most efficient in terms of net benefit and MRR for FADDA, PABLO, and A12-79 varieties than the N1D1 (89 kg N ha^{-1} and 26,600 plants ha^{-1}), N1D2 (89 kg N ha^{-1} and 53,300 plants ha^{-1}), N2D1 (178 kg N ha^{-1} and 26,600 plants ha^{-1}) treatments. On the other hand, the N1D2 treatment was economically more profitable for the *caudatum-guinea* C2_007-03 and C2_075-15 and *caudatum* GRINKAN and SOUMBA varieties with net benefit of $1,263, $1,275, $1,231 and $1,175 ha^{-1}, respectively. The MRR for these varieties in N1D2 were 717, 602, 378, and 584%, respectively, compared to the N2D2, N2D1, and N1D1 treatments. The N1D2 and N1D1 treatments provided the highest net benefits for the TIEBILE *guinea* type variety with amounts of $1,107 and $1,099 ha^{-1} and MRR values of 334 and 323%, respectively, compared to the N2D1 and N2D2 treatments (Table 7).

TABLE 6 Physiological and growth parameters of eight sorghum varieties under plant density and N fertilization in 2018 and 2019 at Sotuba in Mali

Variety	Treatments	SPAD values	Leaf area index	Straw yield	Plant height
				kg ha^{-1}	cm
A12-79	N0D1[a,b]	38c[c]	1.4c	7,704d	124c
	N1D1[d]	45b	2.04bc	11,324c	174b
	N2D1[e]	47a	2.15bc	12,426c	186b
	N0D2[f]	38c	2.23bc	12,150c	158bc
	N1D2	44b	2.55b	15,389b	184b
	N2D2	47a	3.75a	20,167a	217a
	Avg	43BC	2.35BC	13,193C	174D
C2_007-03	N0D1	44c	1.92d	12,444c	205c
	N1D1	50a	2.53c	14,537b	249b
	N2D1	50a	2.82b	15,037b	258b
	N0D2	40d	2.44c	12,533c	229bc
	N1D2	48b	3.03b	18,556a	257b
	N2D2	48b	3.49a	18,593a	295a
	Avg	46AB	2.71AB	15,283B	249C
C2_075-15	N0D1	41b	1.98c	8,778e	156c
	N1D1	44a	2.67b	13,546c	196b
	N2D1	41b	2.59b	13,713c	202b
	N0D2	36c	2.08c	10,333d	159c
	N1D2	41b	2.69b	16,296b	197b
	N2D2	44a	3.16a	17,454a	224a
	Avg	41CD	2.53B	13,353C	189D
FADDA	N0D1	37c	1.75e	9,511e	299b
	N1D1	49ab	2.63d	16,926d	300b
	N2D1	51a	3.23c	21,000b	324ab
	N0D2	36c	2.62d	16,481d	293b
	N1D2	48b	3.65b	19,533c	333a
	N2D2	48b	4.68a	23,511a	341a
	Avg	44B	3.10A	17,827A	315B
GRINKAN	N0D1	38c	1.74d	11,644cd	181b
	N1D1	44b	3.12b	12,210c	194ab
	N2D1	47a	2.53c	16,356b	212a
	N0D2	37c	2.51c	11,093d	191ab
	N1D2	43b	3.26ab	16,259b	204ab
	N2D2	45ab	3.58a	19,074a	216a
	Avg	42C	2.79AB	14,439B	200D
PABLO	N0D1	42c	1.62e	8,648e	241d
	N1D1	52a	3.4b	14,645bc	357c
	N2D1	52a	2.67c	13,907c	414a
	N0D2	42c	1.93d	10,667d	383b
	N1D2	50b	3.22bc	15,259b	409ab
	N2D2	50b	3.78a	19,600a	414a
	Avg	48A	2.77AB	13,787BC	370A

(Continues)

TABLE 6 (Continued)

Variety	Treatments	SPAD values	Leaf area index	Straw yield	Plant height
SOUMBA	N0D1	42c	1.84c	10,111e	220c
	N1D1	48a	2.37bc	14,822b	248b
	N2D1	47ab	2.52b	14,167c	259b
	N0D2	42c	2.58b	10,824d	258b
	N1D2	47b	3.52a	14,556bc	285ab
	N2D2	48a	3.62a	16,711a	297a
	Avg	46AB	2.74AB	13,532BC	261C
TIEBILE	N0D1	35c	2.16d	8,056e	308e
	N1D1	41b	2.58c	17,689c	370bc
	N2D1	46a	3.08b	17,294c	379b
	N0D2	34d	2.21d	11,389d	329d
	N1D2	40b	3.02b	18,352b	353c
	N2D2	40b	3.32a	20,944a	409a
	Avg	39D	2.73AB	15,620B	358A

[a]N0, nitrogen rate of 0 kg ha^{-1}.
[b]D1, 26,600 plants ha^{-1}.
[c]Values in a column followed by different letters are significantly different at $P < .05$. Lower-case and upper-case letters indicate comparisons within treatments of each variety and among varieties, respectively.
[d]N1, nitrogen rate of 89 kg ha^{-1}.
[e]N2, nitrogen rates of 178 kg ha^{-1}.
[f]D2, 53,300 plants ha^{-1}.

3.4 | Linear regression among grain yield, yield component, and growth parameters under plant density and N fertilizer

Linear regression analyses were performed on variables measured under plant density and N fertilization (Table 8). Grain yield was positively and significantly correlated to panicle weight per square meter, leaf area index, straw yield, and plant height (hybrids, open-pollinated improved and local). For tall *guinea* hybrid varieties FADDA and PABLO, grain yield was positively correled with panicle number per square meter. No significant correlation was observed between grain yield and straw yield for TIEBILE, a local check. SOUMBA, an improved *caudatum* type, has been positive and significantly correlated between its 1,000 grain weight and grain yield. GRINKAN, an improved variety has been positive correlation between grain yield and number of grains per panicle. In addition, SPAD values (chlorophyll content) was positively correlated with grain yield in tall *guinea* hybrid varieties FADDA, PABLO, and tall *guinea* local TIEBILE.

4 | DISCUSSION

Plant density by N fertilization rate combinations supported better option for grain yield increase through its contributing parameters across two cropping seasons data collected in 2018 and 2019 in Sotuba, Mali. Results showed that grain yield varied greatly with different plant densities and N fertilization combinations for each variety (Table 4). Grain yield increased from N0D1 (0 kg N ha^{-1} and 26,600 plants ha^{-1}) to N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}). In this study, the highest grain yield under N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}) was obtained with taller *guinea* hybrid FADDA and PABLO and the shorter *durra-caudatum* A12-79 improved varieties compared to the N0D1 treatment (Table 3). These results indicated that the increase in grain yield of these varieties relied on an increase in plant density when the N application rate increased. Similar studies conducted by Fan et al. (2019), Ullah et al. (2020), and Wei et al. (2019) showed the optimum advantages of plant density and N combinations on grain yield increased in improved cereal varieties. The authors indicated that this increase in grain yield was explained by an adaptation of varieties to agronomic practices such as plant density and N rate. In the N2D2 treatment FADDA, PABLO, and A12-79 (except panicle number per square meter) produced higher panicle number per square meter, panicle weight per square meter, leaf area index, and straw yield (Table 6). These varieties under N2D1 (178 kg N ha^{-1} and 26,600 plants ha^{-1}) treatment recorded important SPAD values. This suggests that maintaining the optimum combination of plant density and N allows a better expression of these traits and leads to higher yields (Kaizzi et al., 2012; Kugbe et al., 2019; Sahu et al., 2018). Similar findings were reported by Golla and Chalchisa (2019) and Mahama

TABLE 7 Economic analysis for the combination of plant density and nitrogen fertilization on eight sorghum varieties in 2018 and 2019 at Sotuba in Mali

Variety	Treatments	Grain yield	Price of sorghum grain	Gross benefits	Total variable cost	Net benefits	Marginal rate of return
		kg ha^{-1}	US$ kg^{-1}		US$ ha^{-1}		%
A1279	N0D1[a,b]	1,852	0.325	601.9	12.54	589.35	
	N1D1[c]	3,138	0.325	1,019.85	87.37	932.48	459.13
	N2D1[d]	3,127	0.325	1,016.28	128.73	887.54	257
	N1D2[e]	4,004	0.325	1,301.3	87.37	1,213.93	835.65
	N2D2	5,342	0.325	1,736.15	128.73	1,607.42	877.2
C2_007-03	N0D1	2,520	0.325	819	12.54	806.45	
	N1D1	3,437	0.325	1,117.03	87.37	1,029.65	211.73
	N2D1	3,390	0.325	1,101.75	128.73	973.02	143.6
	N1D2	4,156	0.325	1,350.7	87.37	1,263.33	716.52
	N2D2	4,577	0.325	1,487.53	128.73	1,358.79	475.96
C2_075-15	N0D1	2,574	0.325	836.55	12.54	824	
	N1D1	3,264	0.325	1,060.8	87.37	973.43	200
	N2D1	3,231	0.325	1,050.08	128.73	921.34	83.96
	N1D2	4,188	0.325	1,361.1	87.37	1,273.73	601.73
	N2D2	4,294	0.325	1,395.55	128.73	1,266.82	381.6
FADDA	N0D1	2,139	0.325	695.18	25.09	670.07	
	N1D1	4,308	0.325	1,400.1	99.92	1,300.17	842.09
	N2D1	5,948	0.325	1,933.1	141.28	1,791.81	965.45
	N1D2	4,883	0.325	1,586.98	99.92	1,487.05	1,091.84
	N2D2	6,611	0.325	2,148.58	141.28	2,007.29	1,150.91
GRINKAN	N0D1	2,957	0.325	961.03	12.54	948.48	
	N1D1	3,109	0.325	1,010.43	87.37	923.05	–33.91
	N2D1	3,469	0.325	1,127.43	128.73	998.69	43.36
	N1D2	4,056	0.325	1,318.2	87.37	1,230.83	377.82
	N2D2	3,757	0.325	1,221.03	128.73	1,092.29	124
PABLO	N0D1	2,041	0.325	663.33	25.09	638.22	
	N1D1	3,242	0.325	1,053.65	99.92	953.72	421.62
	N2D1	3,941	0.325	1,280.83	141.28	1,139.54	431.46
	N1D2	3,770	0.325	1,225.25	99.92	1,125.32	650.94
	N2D2	4,850	0.325	1,576.25	141.28	1,434.96	685.72
SOUMBA	N0D1	2,310	0.325	750.75	12.54	738.2	
	N1D1	2,758	0.325	896.35	87.37	808.98	94.78
	N2D1	3,116	0.325	1,012.7	128.73	883.97	125.68
	N1D2	3,884	0.325	1,262.3	87.37	1,174.93	584.34
	N2D2	3,404	0.325	1,106.3	128.73	977.57	206.32
TIEBILE	N0D1	2,678	0.325	870.35	12.54	857.8	
	N1D1	3,650	0.325	1,186.25	87.37	1,098.88	322.6
	N2D1	3,668	0.325	1,192.1	128.73	1,063.37	177.2
	N1D2	3,676	0.325	1,194.7	87.37	1,107.33	333.913
	N2D2	3,618	0.325	1,175.85	128.73	1,047.12	163.2

[a]N0, nitrogen rate of 0 kg ha^{-1}.
[b]D1, 26,600 plants ha^{-1}.
[c]N1, nitrogen rate of 89 kg ha^{-1}.
[d]N2, nitrogen rates of 178 kg ha^{-1}.
[e]D2, 53,300 plants ha^{-1}.

TABLE 8 Relationship between grain yield and development, growth and agronomic parameters of each variety under plant density and N fertilization in 2018 and 2019

Variety	Explained trait	Explicative traits: PNm^{-2} R^2		PWm^{-2} R^2		1,000GW R^2		GN/P R^2		SPAD values R^2		LAI R^2		STY R^2		PH R^2	
A12-79	Grain yield	0.45	ns	0.97	***	0.08	ns	0.12	ns	0.43	ns	0.96	***	0.98	***	0.87	**
C2_075-15		0.34	ns	0.97	***	0.02	ns	0.45	ns	0.45	ns	0.82	**	0.91	***	0.77	**
C2_007-03		0.43	ns	0.95	***	0.24	ns	0.11	ns	0.16	ns	0.91	***	0.77	**	0.81	**
FADDA		0.76	**	0.94	***	0.31	ns	0.22	ns	0.70	**	0.82	**	0.91	***	0.72	**
GRINKAN		0.37	ns	0.91	***	0.32	ns	0.59	*	0.39	ns	0.58	*	0.75	**	0.57	*
PABLO		0.61	*	0.89	**	0.03	ns	0.49	ns	0.55	*	0.69	*	0.86	**	0.80	**
SOUMBA		0.45	ns	0.65	*	0.81	**	0.31	ns	0.35	ns	0.84	**	0.58	*	0.79	**
TIEBILE		0.20	ns	0.75	**	0.05	ns	0.41	ns	0.74	**	0.78	**	0.39	ns	0.68	*

Note. PNm^2, panicle number per m^2; PWm^2, panicle weight per m^2; 1,000GW, 1,000 grain weight; GN/P, grain number per panicle; LAI, leaf area index; STY, straw yield; PH, plant height; R^2, coefficient of determination; ns, nonsignificant at the .05 probability level.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

et al. (2014) on improved maize (*Zea mays* L.) and sorghum varieties (Table 4).

The short *guinea-caudatum* improved varieties C2_007-03 and C2_075-15 produced higher grain yield under treatments N2D2 (178 kg N ha^{-1} and 53,300 plants ha^{-1}) and N1D2 (89 kg N ha^{-1} and 53,300 plants ha^{-1}) statistically significant compared to N0D1 (0 kg N ha^{-1} and 26,600 plants ha^{-1}). However, the N1D2 treatment is most beneficial than N2D2 treatment in terms of grain yield for these varieties. The N1D2 treatment increased grain yield over N0D1 treatment by 78% for C2_007-03 and 63% for C2_075-15 (Table 4). C2_007-03 and C2_075-15 had higher panicle weight per square meter in N1D2 and a higher leaf area index, straw yield, and plant height (Table 6) in N2D2 treatment. For *caudatum* races GRINKAN and SOUMBA, grain yield produced per variety under N1D2 treatment was 37 and 68% greater than its N0D1 treatment, respectively (Table 4). Under the N1D2 treatment, panicle weight per square meter, grain number per panicle, and 1,000 grain weight were better expressed in GRINKAN and SOUMBA varieties compared to the N0D1 treatment. The expression of these traits can contribute to increasing grain yield in GRINKAN and SOUMBA varieties. Our results showed that N application of 89 kg ha^{-1} with 53,300 plants ha^{-1} (N1D2) would be the optimum to improve grain yield of C2_007-03, C2_075-15, GRINKAN, and SOUMBA improved varieties. Sai Siddartha Naik et al. (2018) and Zhang et al. (2016) obtained similar results in sorghum crops. According to Ciampitti and Vyn (2011), although significant work has been done on optimizing plant density and N rate, but this remains a difficult issue to resolve due to the large variability of agricultural lands and the strong interaction between variety, density, and N. The local variety TIEBILE obtained statistically the same grain yield under treatments with N application at different plant densities (Table 4). This means that the tall guinea local variety TIEBILE does not need a significant amount of N (178 kg ha^{-1}) and a high plant density (53,300 plants ha^{-1}) to produce the more grains but had increased its height, leaf area index, and straw yield under N2D2 treatment. Nitrogen application of 89 kg ha^{-1} with 26,600 plants ha^{-1} (N1D1) would be beneficial to obtain a good grain yield for TIEBILE. According to Chantereau et al. (2013), Kouressy et al. (2020), and Vaksmann et al. (1996), the essential of local sorghum is characterized by a high straw biomass with low grain yield. However, it is difficult to propose this sorghum type for intensive agricultural practices because of its low N nutrient valorization for grain production. Their findings corroborate with our results where the N application of 178 kg ha^{-1} with a density of 53,300 plants ha^{-1} did not significantly increase TIEBILE grain yield. A high N application with high plant density would not improve grain yield of local variety but seems favorable to vegetative part increase (Table 6). Similar findings were observed by Dawadi and Sah (2012).

Current study results suggest that the tolerance or response to the N fertilizer and planting density combination in terms of grain yield varied with different sorghum varieties (hybrid, improved, and local). Similar results were reported by Ullah et al. (2020), Zhou et al. (2019), and Dwivedi et al. (2016) in rice (*Oryza sativa* L.) and pearl millet [*Pennisetum americanum* (L.) Leeke] varieties. Knowledge of agronomic practices for determining the optimum density and N combination for each variety is a research activity. The application of these combinations become a necessity by producers through extension agency for sorghum intensive production in Mali based on producer resources, inputs access, and availability.

Among the nutrients, the use of N is crucial in achieving high yield, but the response of cereals (sorghum) to N input is highly variable (Dwivedi et al., 2016). Technically, the N2D2 treatment for FADDA, PABLO, and A12-79 procured the best grain yield; economically, this treatment was the most productive with high net benefit and MRR. However, the N1D2 treatment will be the most interesting option in grain production for C2_007-03, C2_075-15, GRINKAN, and SOUMBA as they have higher net benefits and MRR. Under N1D2 and N1D1 treatments, the local variety TIEBILE obtained higher net benefit and a MRR of 333 and 322%, respectively. The MRR profitability threshold for adoption of new technologies is 200% (Coulibaly et al., 2008). These treatments can be considered as economically satisfactory for these respective varieties. Mankoussou et al. (2017) revealed that economic gain of fertilizers decreased with increasing doses and led to net benefit and MRR decrease. Our results indicated that economic gain depends on both fertilizer (N) and genetic material type. The results showed that in addition to agronomic practices, knowledge of the economic gain for determining the optimum for each variety would be a necessity to reduce expenses and increase the grain yield and net benefit of sorghum producers in Mali.

Grain yield depends on variety agronomic practices, in particular plant density and N fertilization. Its improvement relied on its components but also on growth traits. The regression analysis explained relationship among grain yield and yield components, and between grain yield and growth traits for each variety (hybrids, improved, and local) under all treatments (Table 8). This confirms strong dependences of grain yield on growth parameters and yield components under plant density and N in the botanical sorghum races used in our study (Sadeghi & Bahrani, 2002). According to Trachsel et al. (2016), a faster crop growth is indicative of assimilate availability potentially resulting in greater prolificacy and higher grain yield.

The panicle number per square meter and SPAD values are components that best explained grain yield in the *guinea* hybrid FADDA and PABLO. This result showed that the N rate and planting density had greater effect on SPAD values and panicles number in tall *guinea* hybrid varieties FADDA and PABLO (Table 8). Nitrogen improves chlorophyll content (SPAD values) allowing plants to make their photosynthesis (Tajul et al., 2013); and panicle number promoted mainly by tillering, while planting density improves panicle number thus causing plant numbers increase per area unit (Manjeet et al., 2017; Zhou et al., 2019). These results are in agreement those of Srivastava et al. (2019) in maize. For *caudatum* improved varieties GRINKAN and SOUMBA, grain yield was explained specifically by grains number per panicle and 1,000 grain weight. According to Kondombo et al. (2017), panicle number per square meter and 1,000 grain weight are the major components associated in grain yield of *guinea* improved varieties. Therefore, grains number per panicle is the best grain yield predicator in *caudatum* improved varieties. Senior researchers on sorghum (Kouressy et al., 2008; Shamme et al., 2016; Vadez et al., 2012) reported that variation between sorghum varieties for different yield components and growth traits to improvement grain yield may be due to the plant genetic constitution, agronomic practices and to its capacity to exploit water.

5 | CONCLUSIONS

This current study showed that grain yield and its yield components, chlorophyll index and growth parameters varied depending on plant density, N fertilization, and variety. It can be concluded that 178 kg N ha^{-1} and 53,300 plants ha^{-1} combination produced better grain yield and high marginal rate of return for taller *guinea* hybrid varieties FADDA and PABLO and shorter *durra-caudatum* variety A12-79. The application of 89 kg N ha^{-1} with 53,300 plants ha^{-1} is the optimal combination to acquire the higher grain and marginal rate of return for short *guinea-caudatum* improved varieties C2_007-03 and C2_075-15 and short *caudatum* improved varieties GRINKAN and SOUMBA. These varieties can be used by producers wanting increased sorghum production with a moderate use of N. Rate 89 kg N ha^{-1} with 26,600 plants ha^{-1} is the economically beneficial treatment for taller local *guinea* variety TIEBILE. The local variety has a low response to agricultural improvement practices. Panicle weight per square meter, leaf area index, plant height, and straw yield were the main traits associated with varieties grain yield increase studied. Panicle number per square meter and SPAD value were the specific traits associated with grain yield in the *guinea* hybrid FADDA and PABLO. Grain number per panicle and 1,000 grain weight were the specific traits associated with grain yield in the *caudatum* GRINKAN and SOUMBA. These findings will help producers which option to promote to booster sorghum production in Mali.

ACKNOWLEDGMENTS

We are thankful to undergraduate all students, technicians and workers of Sotuba agroclimatology unity that helped us in achievement this work. This work constitutes part of doctoral research studies funded by DAAD, the German exchange service program. This research activity was also funded in part by Bill and Melinda Gates foundation under Sorghum Genotyping Tools project and benefit the facilities of the Centre d'Etude Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS).

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Joseph Sékou B DEMBELE: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Writing-original draft. Boubacar GANO: Conceptualization; Formal analysis; Methodology; Software; Writing-review & editing. Mamoutou Kouressy: Funding acquisition; Project administration; Supervision; Writing-original draft. Léonce Lamine DEMBELE: Data curation; Formal analysis; Software. Mohamed DOUMBIA: Data curation; Formal analysis. Komla Kyky Ganyo: Writing-review & editing. SékouBa SANOGO: Data curation; Formal analysis. Adama TOGOLA: Writing-review & editing. Karim TRAORE: Writing-review & editing. Michel VAKSMAN: Conceptualization; Methodology; Project administration; Supervision; Writing-review & editing. Niaba TEME: Conceptualization; Methodology; Project administration; Resources; Writing-review & editing. Diaga Diouf: Supervision; Writing-review & editing. Alain AUDEBERT: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing-review & editing

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Dembele, J. S. B., Gano, B., Kouressy, M., Dembele, L. L., Doumbia, M., Ganyo, K. K., Sanogo, SBa, Togola, A., Traore, K., Vaksman, M., Teme, N., Diouf, D., & Audebert, A. Plant density and nitrogen fertilization optimization on sorghum grain yield in Mali. *Agronomy Journal*. 2021;1–16. https://doi.org/10.1002/agj2.20850