International Journal of Scientific Research and Management (IJSRM)
||Volume||11||Issue||01||Pages||AH-2023-379-388||2023||
Website: www.ijsrm.in ISSN (e): 2321-3418
DOI: 10.18535/ijsrm/v11i01.ah01

Characterization of New Sugar Sorghum Varieties (*Sorghum Bicolor (L.*) Moench) For Grain And Sugar Yield Under Two Growing Conditions In The Sudano-Sahelian Zone Of Samanko, Mali

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Abstract

Sorghum (*Sorghum bicolor*) constitutes a food source for millions of people. Nowadays, sweet sorghums have the same interest as sugarcane. Traditional sweet sorghums have a high level of juice and sugar but a low grain yield. In order to evaluate the effect of phosphorus on some agronomic and biochemical parameters of some new sweet sorghum varieties, a study entitled "Characterization of new sweet sorghum varieties (*Sorghum bicolor* (L.) Moench) for their grain and sugar yield under two growing conditions in the Sudano-Sahelian zone of Samanko, Mali" was carried out. The trial was set up in an alpha lattice design with 2 replications. The treatments consisted of 48 sweet sorghum varieties, with 3 grain varieties as controls. Observations focused on agro-morphological parameters and sugar yield components. The results showed a high significance difference between lines for all variables measured except vigor at emergence. On soil with Di-Ammonium Phosphate (DAP) application, 50% of the lineages with a cycle of 263 to 273 Julian days had a grain yield higher than 2 t/ha. Only one lineage (L17) was earlier and more stable in both environments with a cycle of 271 to 273 Julian days. On soil without DAP application, only lineage L40 had an average yield gain of 2t/ha above the local control (Tieblé). The best performances in sugar concentration were obtained in High-P with 10 lineages whose Brix varied from 18% to 20.25% and 15.3% to 17.7% in Low P.

Keywords: sweet sorghum, grain yield, sugar yield, High-P, Low-P

Introduction

Sweet sorghum (*Sorghum biocolor* (L.) Moench) consider as a C4 plant and Characterized by high stalk and sugar yield [1]. There are about 4000 sweet sorghum cultivars distributed throughout the world [2]. Sweet sorghum becoming popular among researchers, farmers, and entrepreneurs [3]. It can be grown easily on all continents, in tropical, subtropical, temperate, semi-arid regions as well as in poor quality soils [4]. The sweet sorghum production showed its adaptability to both arable and marginal areas [5]. This crop can be processed as biofuel or valuable coproducts, while not affecting the production of grain as food, fuel, and fodder [6]. Also, Swet sorghum are mainly used for producing sorghum syrup [7]. It's stalks have high sugar content compared with other sorghum [8]. Some sweet sorghum lines attain juice yields of 78% of total plant biomass, containing 15 to 23% soluble fermentable sugar [9]. Sweet sorghums have nowadays the same interest as sugarcane and maize, because they are among the species used in the manufacture of ethanol's for biofuel [10]. In Mali, sweet sorghums are traditionally produced in farmers' fields and the stalk is sold at local markets as "sweet mouth sorghum. These traditional varieties of sweet sorghum are mostly of the *bicolor* race and produce few grains with a quality not appreciated for culinary preparation because of the low flouriness of the grains. Sweet sorghums introduced in Mali have shown an interesting potential in sugar and grain yield [11]. However, these varieties are poorly adapted to the complex production conditions in West Africa and their grain quality is not well appreciated. International Crops Research Institute for Semi- Arid Tropics (ICRISAT)-Mali's sorghum program has hence focused on the development of multipurpose varieties that combine quality grain, sufficient biomass and an acceptable sugar yield.

The present study was carried out to evaluate the effect of phosphorus on grain yield, biomass and sugar content of these new varieties in order to provide better advice to producers for whom phosphorus is a limiting factor in sorghum production.

Materials And Methods

1.1 Material

1.1.1 Test location

The study was carried out in Samanko at the research center of ICRISAT, Mali. The trial was implanted on a sandy-silty soil. The climate is Sudan-Sahelian characterized by a long dry season from November to May and a short rainy season from June to October. Over the last 5 years, annual rainfall varied from 1019.9 mm in 2011 to 1080.9 mm in 2015 with an average of 1033.98 mm/year.

1.1.2 Plant materiel

The plant material was comprised of 48 varieties including 45 sweet sorghum varieties developed by ICRISAT-Mali and three grain sorghum varieties as controls (Table 1). The controls were namely: Lata (improved variety), “Tiéblé” (local variety) and Fadda (hybrid).

Table 1: List of plant material used in the trial

No	Pedigree	No	Pedigree
1	F5.3 SSM10-13/7-1	25	F5.3 SSM10-31/2-3
2	F5.3 SSM10-14/1-1	26	F5.3 SSM10-31/6-3
3	F5.3 SSM10-15/5-1	27	F5.3 SSM10-33/3-1
4	F5.3 SSM10-16/1-1	28	F5.3 SSM10-4/4-1
5	F5.3 SSM10-18/2-1	29	F7.5 SSM096-2/3-1-2-PL
6	F5.3 SSM10-20/2-1	30	F7.5 SSM095-3/3-2-1-2
7	F5.3 SSM10-21/4-1 tan	31	F7.5 SSM095-3/3-2-3-3
8	F7.5 SSM09-1-1/2-1	32	F7.5 SSM09-5-3/4-1-1-1
9	F7.5 SSM09-1-1/4-1	33	F7.5 SSM09-5-3/4-1-1-3
10	F7.5 SSM09-1-1/7-1	34	F7.5 SSM09-5-3/4-1-2-2
11	F7.5 SSM09-1-1/9-2	35	447(471)496
12	F5.3 SSM10-24/2-1	36	ICSR 93034
13	F7.5 SSM09-1-1/6-1	37	F221
14	F5.3 SSM10-21/6-1	38	F60
15	F5.3 SSM10-21/10-1	39	IS23541
16	Mult-11 36461-2-1	40	IS23519
17	F5.3 SSM10-9/1-3	41	IS23525
18	F5.3 SSM10-12/2-3	42	IS23555
19	F5.3 SSM10-8/1-5	43	IS23562
20	F5.3 SSM10-8/3-2	44	IS23574
21	F5.3 SSM10-1/1-8	45	SPV 422
22	F5.3 SSM10-1/5-1	46	Fadda
23	F5.3 SSM10-1/6-1	47	Tiéblé
24	F5.3 SSM10-1/6-6	48	Lata

1.1.3 Rainfall conditions during the study year

Globally, rainfall in 2016 was acceptable in Samanko, even though some drought periods were recorded towards the end of August. The season started from the first decade of May and ended in October with some traces of rain in November (Figure 1).

Figure 1: Distribution of rainfall in Samanko, 2016

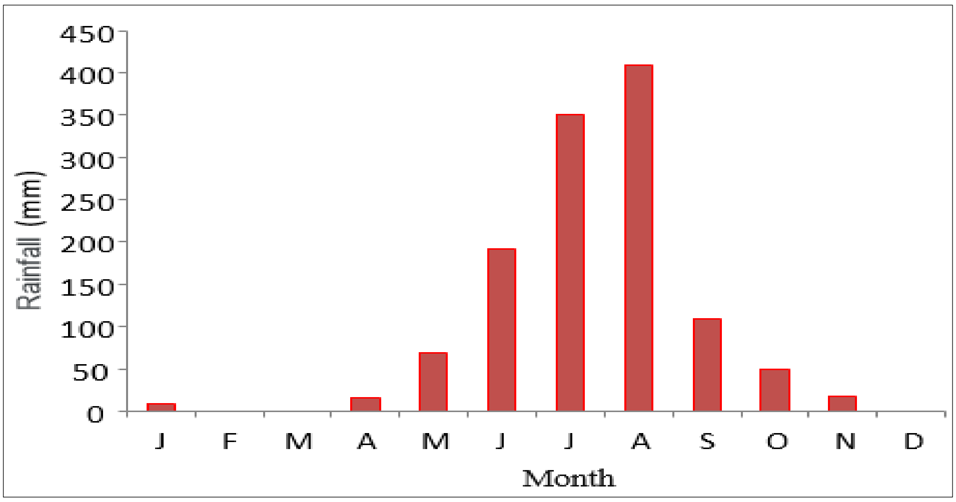
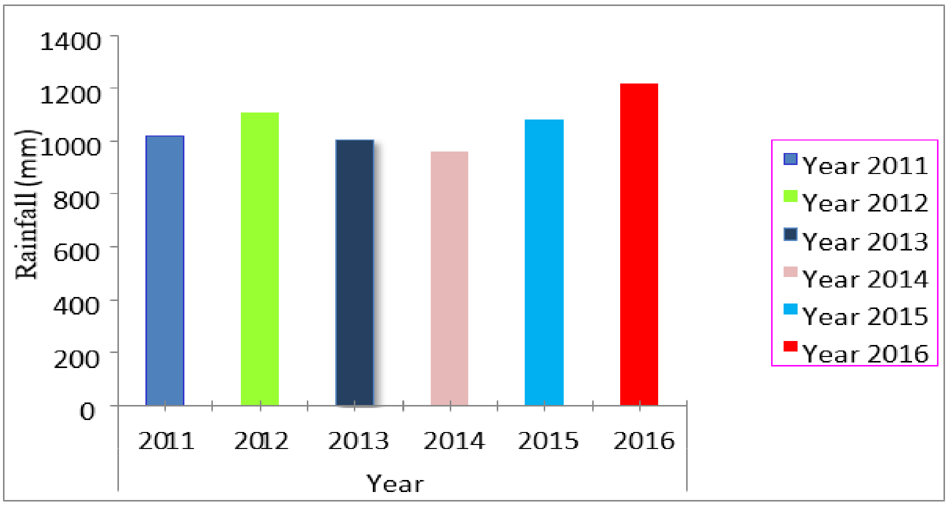


Figure 2: Rainfall in 2016 compared to the average of the last 5 years in Samanko



Rainfall in 2016 was the most abundant (1215.3 mm) in the last 5 years in terms of total amount (Figure 2).

1.1.4 Technical Material

The technical equipment was consisted of: ropes and stakes for the dimensioning of the elementary plots; a pruning shears to cut the stems and panicles; a rope to tie the harvested stems; a juice extraction machine; a refractometer to measure the Brix sugar rate = % of soluble matter; a 10 kg scale to weigh panicles, biomass samples; a 25 kg scale to weigh the complete stems; a 4 kg precision scale to weight juice; a plastic container to collect the juice; polyethylene bags to dry the panicles; distilled water to clean the refractometer after use; a 2 L test tube to measure the volume and a tablet for data collection in the field.

1.2 Methods

1.2.1 Experimental Design

The design used was an alpha-lattice with 2 replications consisted of two lines with 3 m long and spaced by 0.75 m rows. The grains of sorghum were sown on the ridges spaced by 1.5 m. The area of each elementary plot was 4.5 m^2 with eleven pockets per ridge. The distance between pockets was 0.30 m. The randomization of the trial was done using the statistical analysis software BMS (Breeding- Management -System).

A single factor taken at two levels of variation was studied: 48 lineages under two different conditions (with and without phosphorus supply).

1.2.2 Seed Preparation

The seed quantity for the trial was weighed and treated with Aprons star (thiamethoxan, metalaxyl-M, difenoconazole), an insecticide fungicide at the rate of 10 g per 4 kg of seed. Then the seeds were put in the mini grip.

1.2.3 Soil Preparation

Using a disc tractor, a flat ploughing was carried out in the two plots of the trial, namely High-P and Low-P. The High-P plot was the plot where phosphate was applied and the Low-P plot which had not received any phosphate application. The ridging was done with a hoe set at 0.75 m for all the plots in the trial.

1.2.4 Picketing

Plot delimitation was achieved with tape and stakes on June 30, 2016, using the 3,4,5 Pythagoras theorem method. For each plot, a stake with a label was planted, to identify the environment, replication, plot and variety that were planted.

1.2.5 Sowing

Sowing was done on both trials on ridges at 5.0 cm depth with four to five seeds per pocket.

1.2.6 Hoeing and Weeding

Crop maintenance work consisted mainly of weeding, removal of weeds, reconstitution of ridges and filling in of missing pits. Pockets were started with two plants per pocket.

1.2.7 Fertilization

The DAP: $(NH_4)_2HPO_4$ of formula (18- 46 - 0) was applied during ploughing as baseline fertilizer at the rate of 100 kg/ha for the trial with phosphate fertilizer (High-P), i.e. 4.17 g on the 2 lines of each elementary plot. Urea $CO(NH_2)_2$ was applied in both environments at a rate of 50 kg/ha, i.e. 2.1 g /2 lines. To compensate in Low-P, the quantity of nitrogen brought in High-P due to the fertilization of the field in DAP, a correction dose of 18% was brought in the trial without bringing in phosphate fertilizers (Low-P).

1.2.8 Harvest

The harvest was performed progressively and consisted of cutting the plants by varieties whose seeds had become mature. The first and last pockets of each elementary plot were not harvested. Once the stems were cut at about 5 cm from the ground, they were tied up and then transported to the extraction areas the same day.

1.2.9 Observations and Measurements

Observations were made on the two useful lines during the whole trial in accordance with the experimental protocol, except for the measure of morphological characteristics and sugar yield components for which five representative plants of the central clusters were randomly selected.

Observations on Brix, volume, juice weight and fresh weight of the stems were made just after harvest to avoid losses due to water evaporation from the stems.

1.2.9.1 Agro/morphological characters

- ✓ **Delay 50% Heading (DH)**

It represents the number of days (Julian calendar) between sowing and the day when 50% of the plants present at least one panicle emergence. It was determined by visiting the plots every two days after the emergence of the first panicle until the emergence of 50% of the panicles. It was obtained by visual counting on the 2 seedling lines.

- ✓ **Height of Plants (HPL)**

The height of the plants from the ground to the summit of the panicle was measured at the doughy grain stage using a graduated ruler (in cm). It was carried out on 5 plants selected from the two central pockets of the plot.

- ✓ **Weight of Panicles (WoP)**

After drying, the weight of the panicles was determined before threshing using a precision scale. It allowed to determine the panicle yield but also the percentage at threshing which is the quotient between the grain weight and the panicle weight.

1.2.9.2 Sugar Yield Components

- ✓ **Extraction of Juice**

Juice extraction was performed on the stalk already stripped of leaves. The sorghum juice was obtained after passing the stems through the drums of the sugarcane juice extraction machine made in Mali. This operation and the weighing of the stems were done immediately after harvesting in order to avoid losses of juice and even sugar levels if the stalks are left for a long time in the open air or in the sun.

- ✓ **Volume of Juice (VJ)**

The volume of juice was quantified in milliliter (cc or mL) per lot of 5 stems using a 2 L graduated test tube.

- ✓ **Brix**

The Brix was measured with the refractometer in percent and consisted in placing one or more drops of the juice sample on the glass surface of the refractometer then closing the plastic valve on the liquid while expelling the air. The reading was taken by placing the eyepiece in front of the eye. The intersection line between two colors (one purple and one white) indicated the Brix. The Brix degree (°B) is used to determine the sugar fraction in a liquid, in other words the percentage of soluble dry matter. The Brix represents the concentration of soluble dry substance which is mainly sugar.

1.2.10 Statistical Data Analysis

Results were analyzed using Excel and Breeding-Management-System, BMS version 3.0.9.

Results And Discussion

1.3 Effect of Phosphorus on Some Agronomic and Biochemical Characteristics of Sweet Sorghum Varieties

The result of the analysis indicated that the data collected in both High-P and Low-P were of high quality with respect to high heritability. In general, the difference was significant between the lineages in each environment, which explains that the different lineages have different performance (Table 2). According to Leiser et *al*. (2012) [12], Sorghum exhibits significant genetic variability for adaptation to low-P conditions, allowing breeders to select for improved productivity under low-input conditions. Aly et *al*. (2008) [13] reported that sweet sorghum varieties show significant differences in leaf area, plant height and diameter, percentages of sucrose, purity, juice and syrup extraction, as well as stripped stalk, juice and syrup yields.

The heritability of the studied characters in the various environments is high (above 50%) excluding the volume of juice per plant in low P (42%) and according to Johnson et *al*. (1955) [14], Stanfield (1975) [15], the heritability is high above 50%, low below 20% and average between 20 and 50%.

Table 2: General performance of varieties in both environments (with DAP and without DAP)

Environment	Character	Min	Mean	Max	H^2	Prob
High-P (HP)	Delay 50% heading	256.0	271.0	285.0	0.93	0.00
	Height of plant	168.6	255.3	388.7	0.89	0.00
	Grain yield	80.60	266.4	461.4	0.65	0.00
	Volume of juice /plant	0.00	61.8	114.0	0.80	0.00
	Brix	0.00	15.88	21.0	0.69	0.02
Low-P (LP)	Delay 50% heading	261.0	283.0	303.0	0.93	0.00
	Height of plant	122.0	178.6	279.4	0.88	0.00
	Panicular yield	0.00	87.0	290.8	0.71	0.00
	Volume of juice /plant	2.00	29.2	127.0	0.42	0.03
	Brix	5.30	13.76	19.0	0.62	0.00

Min=minimum; Max=maximum; H^2=heritability; Prob = probability.

1.4 Performance of Lineages Based on Grain Yield

Analysis of variance revealed a significant difference between lineages for grain weight in the DAP trial. Grain weight ranged from 303,29g to 444,9 g/m² with an average yield of 2.65 t/ha. These results are similar to those of Kouressy et *al*. (2020) [16] where the mean grain yield of improved sorghum varieties (2560 kg/ha) is significantly higher than that of local varieties (1416 kg/ha). The difference between the grain yield of the L2 lineage with “Tiéblé” was greater than the DAP trial. This means that this lineage has a statistically higher yield than the control. The analysis showed that the other 9 best performing lineages for grain weight had about the same yield as the best local control “Tiéblé” (Table 3).

The study identified 10 lineages that performed better in this environment with higher yields compared to the local control “Tiéblé” (Figure 3).

Figure 3: Grain yield of the 10 best lines under DAP conditions compared to the control “Tiéblé”

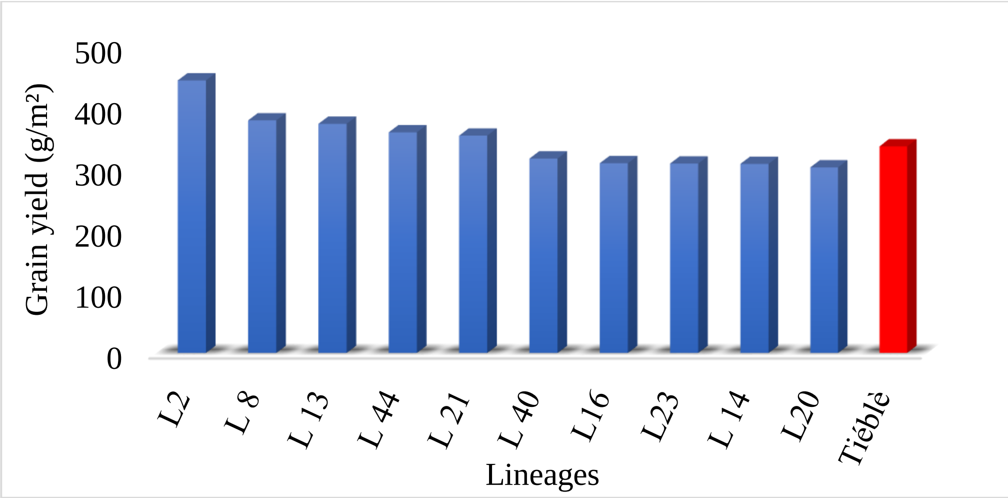


Table 3: Grain yield of the best lines in the High-P environment compared to the best control

Lineages	**Grain yield (g/m^2)**
L2	444.90
L 8	379.81
L 13	374.24
L 44	360.37
L 21	354.96
L 40	317.64
L16	310.03
L23	309.53
L 14	308.95
L20	303.29
Tiéblé	337.48
LSD	117.08

1.5 Performance of Lineages Based on Panicle Yield

Under conditions without phosphate fertilizer, the analysis of variance showed significant differences between treatments. The L40 lineage (Figure 4) had the highest average panicle yield with 206.9 g/m² compared to the most productive control Fadda (171.6 g/m²). The difference between L40 lineage yields with "Tiéblé" was greater than the LSD. This means that in this environment, only lineage L40 had a significantly higher yield than the control (Table 4). The average cycle of the lineages was 283 Julian days and panicle weights ranged from 9 g to 290 g in this environment. There were 10 best performing lineages compared to the local control "Tiéblé" in the DAP-free environment (Table 4).

Figure 4: Panicle yield of the best 10 lineages under DAP-free conditions compared to the control "Tiéblé"

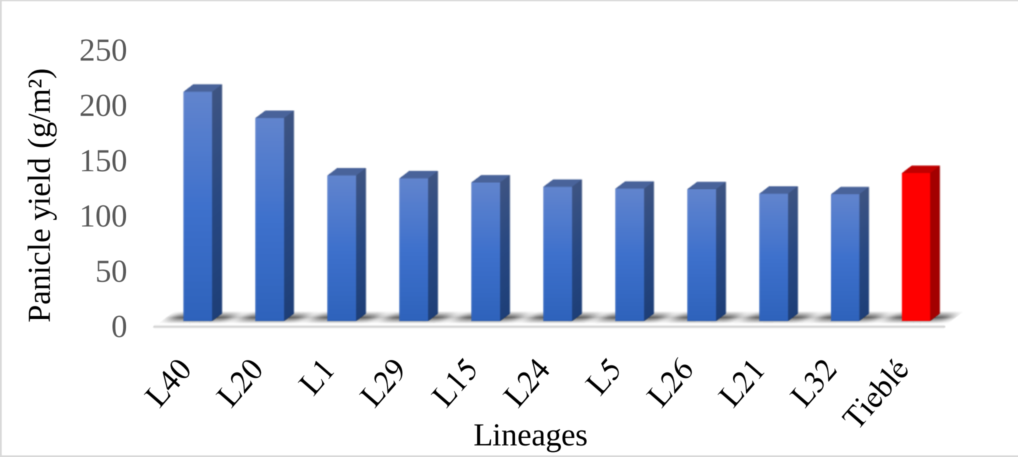
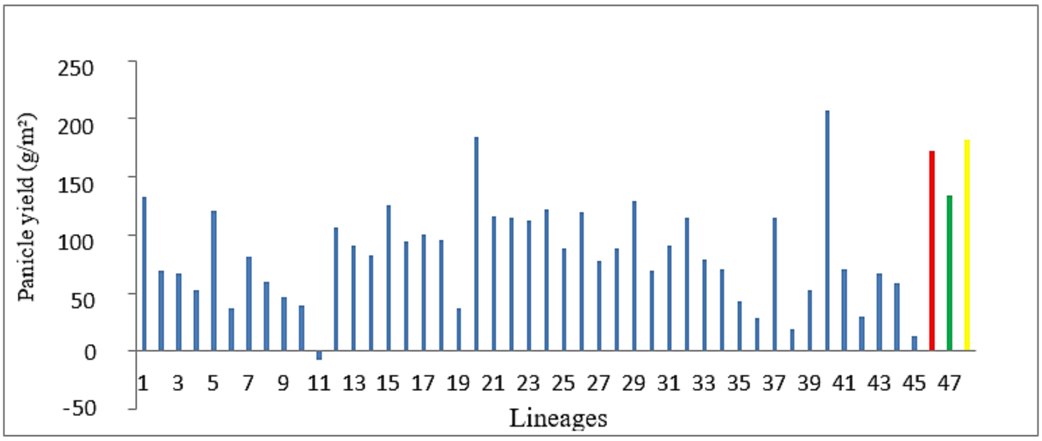


Table 4: Panicle yield of the best lineages in the Low-P environment compared to the best control

Lineages	**Panicle yield (g/m^2)**
L40	206.9
L20	183.3
L1	131.7
L29	129.1
L15	125.3
L24	121.4
L5	119.7
L26	119.2
L21	115.2
L32	114.7
Tieblé	133.8
LSD	71.96

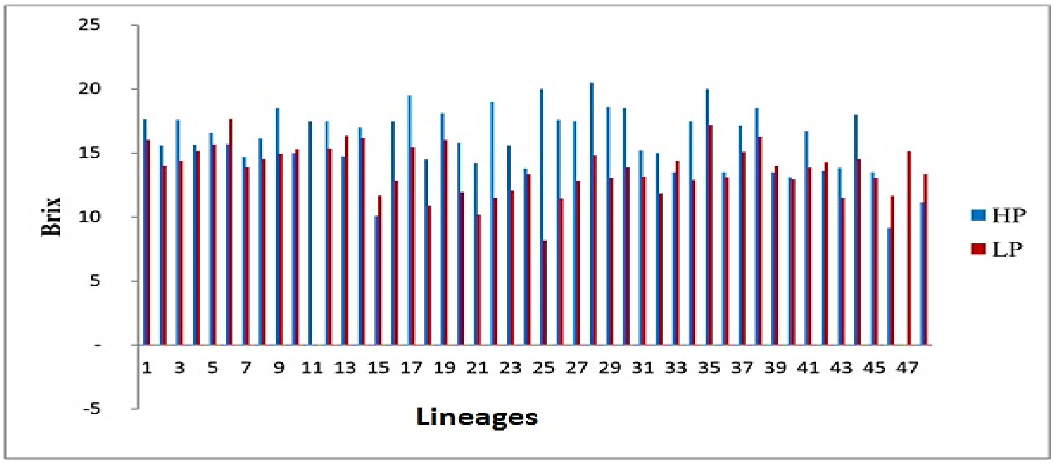
Figure 5: Panicle yield of all lineages compared to the two controls under non-DAP conditions



1.6 Effect Of Phosphorus on The Sugar Concentration of The Varieties

Sugar concentration varied according to the environments. Lineages L45, L40, L39, L36, L24, L7, L5, L4 had very low variation in concentration when placed in High-P or Low-P (Figure 6).

Figure 6: Sugar concentration of lineages evaluated in the two environments



This difference was between 0.15 and 0.5 and not one of the 10 best lines was stable in both environments (Table 5). These results are in agreement with those of UNIFA (2005) [17] that phosphorus influences the quality of the Brix produced, which explains the high sugar concentration in High-P.

Table 5: List of the best lineages in Brix in the two environments compared to the controls

High-P	Brix	Low-P	Brix
L28	20.50	L6	17.70
L25	20.00	L35	17.20
L35	20.00	L13	16.30
L17	19.50	L14	16.20
L22	19.00	L1	16.00
L29	18.60	L19	16.00
L30	18.50	L5	15.70
L9	18.50	L17	05.40
L19	18.10	L12	15.40
L44	18.00	L10	15.30
F60	18.50	F60	16.30
F221	17.15	F221	15.10

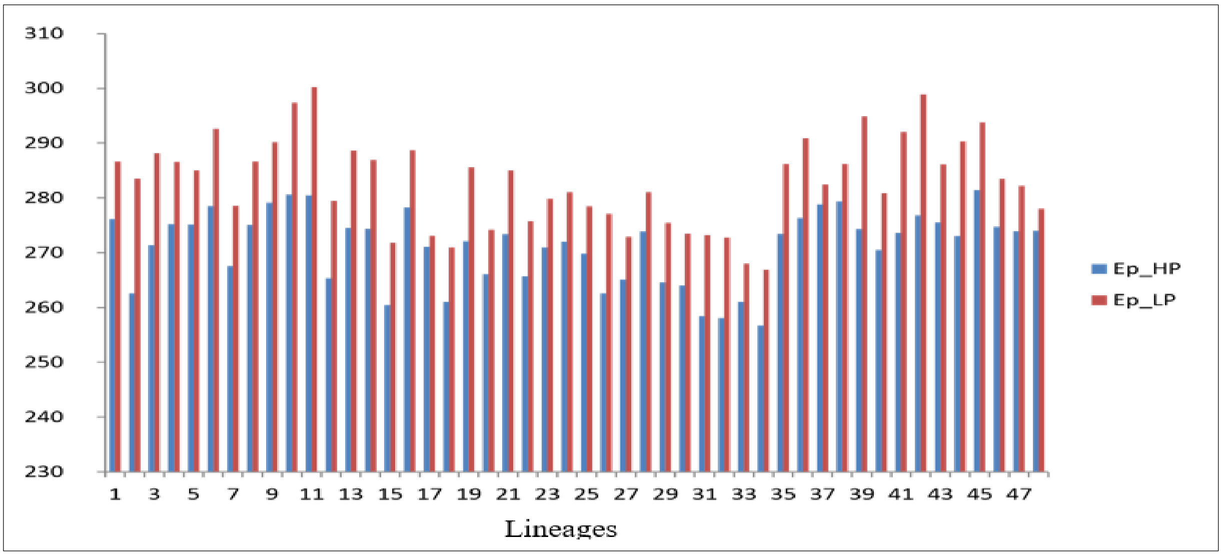
1.7 Effect of Phosphorus on The Cycle of The Varieties

The analysis of variance of the delay 50% heading showed a highly significant difference between the varieties in the two environments. The average time to 50% of heading observed was 271 days (Julian days) in the trial with DAP addition and 283 days (Julian days) without DAP addition, i.e. a difference of 12 days compared to High-P.

In total, 24 lineages with a cycle of 263 to 273 days had a grain yield of more than 2 t/ha, compared to the local control "Tiéblé", which had a yield of 2.6 t/ha; they are therefore well adapted to the conditions of the Sudanian zone, considering their appropriate cycle combined with the high yield recorded.

The results showed that the varieties have tendency to extend their cycle (Figure 7) under conditions without DAP (Low-P). Phosphorus deficiency therefore reduces sorghum growth and delays maturity [18].

Figure 7: Delay 50% of heading of lineages in both environments



Conclusion

The results of the study showed a significant difference for all parameters measured in the conditions with phosphate fertilizer, the lineages were earlier than in the conditions without phosphate fertilizer with a 12 days difference. On soil with DAP, 12.5% of the lineages spiked within 263 Julian days; 39% of the lineages with a cycle between 263 and 273 days had a grain yield higher than 2t/ha while 50 % had a cycle higher than 273 days.

The results revealed a high variability among lines for plant height. The average height was 255 cm in High-P and 178 cm in Low-P. In Low-P conditions, plant height ranged from 122 cm to 279 cm, however in High-P, it was 168.6 cm to 388.7 cm.

The variance analysis of grain yield and panicle yield showed that there was a significant difference between the treatments under DAP and non-DAP conditions, respectively. The study identified 10 best lineages that had a yield greater than 2t/ha compared to the local control “Tiéblé” under DAP conditions. However, in the conditions without DAP, the 10 best lineages had an average yield of 1t/ha.

A large variability for panicle weight was found in the two trials. Grain yield was 444.90 g/m^2 to 303, 29 g/m^2 in the trial with DAP application while it was 206.9 g /m^2 to 12.86 g /m^2 in the trial without DAP application, a difference of 238 g/m^2. In both conditions (High-P and Low-P), there was a positive correlation between grain yield, panicle yield and plant height.

Sugar concentration varied among environments. Lineages L45, L40, L39, L36, L24, L7, L5, L4 had very little variation in sugar concentration in both environments (High-P or Low-P). This difference was between 0.15 and 0.5 while none of the top 10 lineages identified were stable in both environments. The best performance in sugar concentration was obtained in HP with 10 lineages whose Brix varied between 18 to 20.25% and 15.3 to 17.7% in Low-P.

References

1. Antonopoulou, G., Gavala, H.N., Skiadas, I.V., Angelopoulos, K., and Lyberatos, G. (2008). Biofuels generation from sweet sorghum: fermentative hydrogen production and anaerobic digestion of the remaining biomass. Bioresource technology *99*, 110–119.
2. Rutto, L.K., Xu, Y., Brandt, M., Ren, S., and Kering, M.K. (2013). Juice, ethanol, and grain yield potential of five sweet sorghum (Sorghum bicolor [L.] Moench) cultivars.
3. Beltran, A.K.M., Samson, E.G., Angeles, D.E., Cabahug, R.A.M., and Rivera, H.F.R. (2019). Agronomic and Yield Performance of Sweet Sorghum under Different Fertilizer Schemes. Philippine Journal of Crop Science *44*, 87–92.

4. Vinutha, K.S., Rayaprolu, L., Yadagiri, K., Umakanth, A.V., Patil, J.V., and Srinivasa Rao, P. (2014). Sweet Sorghum Research and Development in India: Status and Prospects. Sugar Tech *16*, 133–143. 10.1007/s12355-014-0302-9.
5. Vermerris, W., and Saballos, A. (2013). Genetic enhancement of sorghum for biomass utilization. In Genomics of the Saccharinae (Springer), pp. 391–425.
6. López-Sandin, I., Gutiérrez-Soto, G., Gutiérrez-Díez, A., Medina-Herrera, N., Gutiérrez-Castorena, E., Galicia-Juárez, M., and Zavala-García, F. (2021). Biomass and sugar production dynamics in sweet sorghum variety Roger. Chilean journal of agricultural research *81*, 92–101.
7. Hunter, E.L., Anderson, I.C., and Janick, J. (2010). Sweet sorghum. Horticultural reviews *21*, 73–104.
8. Wortmann, C.S., and Regassa, T. (2011). Sweet sorghum as a bioenergy crop for the US Great Plains. Economic Effects of Biofuel Production. InTech, Rijeka, Croatia, 225–240.
9. Rao, S.P., Rao, S.S., Seetharama, N., Umakath, A.V., Reddy, P.S., Reddy, B.V.S., and Gowda, C.L.L. (2009). Sweet sorghum for biofuel and strategies for its improvement (International Crops Research Institute for the Semi-Arid Tropics).
10. Rao, P., Rao, S.S., Seetharama, N., Umakath, A., Reddy, S., Reddy, B., and Laxmipathi Gowda, C. (2009). Sweet sorghum for biofuel and strategies for its improvement. Information Bulletin No. 77. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 80 pp. ISBN: 978-92-9066-518-2 Order code: IBE 077. 10.13140/2.1.3039.5845.
11. Dagou, F. (2007). Evaluation de variétés de sorgho pour le rendement grain, la biomasse et la teneur en sucre, Samanko. (IPR/IFRA de Katibougou).
12. Leiser, W.L., Rattunde, H.F.W., Piepho, H.-P., Weltzien, E., Diallo, A., Melchinger, A.E., Parzies, H.K., and Haussmann, B.I. (2012). Selection strategy for sorghum targeting phosphorus-limited environments in West Africa: Analysis of multi-environment experiments. Crop Science *52*, 2517–2527.
13. Aly, M.H., Kamel, A.M., and Hassan, S. (2008). The usage of biofertilizer to minimize the mineral fertilizer for sweet sorghum. Egyptian Journal of Applied Science *23*, 486–499.
14. Johnson, H.W., Robinson, H.F., and Comstock, R.E. (1955). Estimates of genetic and environmental variability in soybeans 1. Agronomy journal *47*, 314–318.
15. Stanfield, W.D. (1975). Génétics Mc Graw-HillInc.
16. Kouressy, M., Sissoko, S., Tekete, M., Sanogo, S., Kamissoko, S., Doumbia, M., Sissoko, A., Thera, K., Dingkuhn, M., and Koné, A.S. (2020). Sélection du sorgho pour une intensification durable au Mali. Apports de la modélisation des cultures.
17. UNIFA (2005). Principaux éléments fertilisants, Parlons fertilisation.
18. Buerkert, A., Moser, M., Kumar, A.K., FuÈrst, P., and Becker, K. (2001). Variation in grain quality of pearl millet from Sahelian West Africa. Field Crops Research *69*, 1–11.