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Genetic variability and identification of potential drought-tolerant Burkina Faso sweet grain sorghum genotypes at the post-flowering stage using morphoagrophysiological traits

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Abstract

Sweet grain sorghum is mainly grown in Burkina Faso for consumption of its sweet grain at the pasty grain stage. This orphan crop productivity is strongly limited when Drought occurs post-flowering. Since stay-green is one of the key parameters determining the adaptation of Sorghum to this abiotic stress, this study was initiated to identify potential drought-tolerant sweet grain sorghum genotypes based on stay-green traits. Alpha lattice experimental design, replicated three times, was used to evaluate 50 sweet grain sorghum genotypes and 04 stay green controls using 25 agromorphophysiological traits. The descriptive analysis showed significant variability among sweet grain sorghum genotypes. A strong positive correlation was observed between stay green traits, the number of green leaves at the pasty grain stage and the percentage of green leaves retained (0.91). Each of these traits is positively correlated with stem diameter and negatively with the number of internodes, tillering traits, lodging and plant height. The sorghum genotypes are organized into four different genetic pools, of which group I contains two (02) stay green controls (B35, E36-1) and two (02) sweet grain sorghum genotypes (PBO4, YOH8), and group II, the two (02) others stay green controls (ICSV1460024, Soubatimi) and one (01) sweet grain sorghum genotype (SBR5). The sweet grain sorghum genotype SBR5 showed high stay green performance, as did the two best controls. The three potential drought-tolerant sweet grain genotypes identified could be exploited in the sweet sorghum breeding program.

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Introduction

In Africa, the agricultural sector evolves in the context of permanent climatic risks (Taylor *et al.,* 2017). The observed climate changes mainly concern the rainfall regime, which is more and more unevenly distributed in time and space (Lalou *et al.,* 2019; Kaboré *et al.,* 2019; Traoré *et al.,* 2023). In Burkina Faso, crop production is dependent on rainfall; about 98% of the cultivated areas are occupied by rainfed crops (DGESS/MAAH, 2022). The progressive shift of the isohyets towards the southern locations is the consequence of aggravated climatic instability almost over the country (Somé 1989; Zongo 1991). The adaptation of cereal production to current climate conditions, therefore, remains a priority for farmers.

Sorghum (*Sorghum bicolor* [L.] Moench) is one of the most widely grown cereals in Sub-Saharan countries, especially in regions where poor harvests are frequently recorded due to climate change (Djè *et al.,* 2007; FAO 2017). It is a staple food for millions of food-insecure people living in such environments (Barnabás *et al.,* 2008; Barro-Kondombo, 2010). In Burkina Faso, Sorghum is ranked first in terms of cultivated area, estimated to be more than 1.8 million hectares, and occupies the second position in terms of production quantity after maize with a production of more than 1,6 million tons (DGESS/MAAH, 2022). Diverse sorghum varieties with various utilizations are grown but unknown or neglected (Nandkangré, 2009; Barro-Kondombo, 2010; Nebié, 2014; Sawadogo *et al.,* 2014a). Sweet grain sorghum is one of the neglected Sorghum characterized by the accumulation of large amounts of carbohydrates such as sucrose, glucose, and fructose in its grain (Sawadogo, 2015). The panicles harvested at the pasty grain stage are shelled and can be directly eaten fresh (Nebié *et al.,* 2012; Sawadogo *et al.,* 2014b). The marketing of panicles harvested at the pasty grain stage offers substantial income for farmers and sellers (Sawadogo *et al.,* 2017). Also, its straw is an excellent feed for livestock (Tiendrebéogo *et al.,* 2018). Despite the nutritional and socio-economic benefits of sweet grain sorghum, its production remains marginal in Burkina Faso compared to other food and cash crops. It is very little exploited by the population, and its cultivation is still practiced on small plots surrounded by farmers' huts (Sawadogo *et al.,* 2014a). The various research works previously carried out on this Sorghum mainly concern the endogenous knowledge associated with its management (Sawadogo *et al.,* 2014a), its genetic diversity (Nebié *et al.,* 2012; Sawadogo *et al.,* 2014b; Sawadogo *et al.,* 2018), the biochemical composition of grain (Sawadogo *et al.,* 2017; Sawadogo *et al.,* 2020) and straw (Tiendrebéogo, 2020), the effect of mineral fertilizers on its grain and fodder production (Tiendrebéogo *et al.,* 2018; Tiendrebéogo *et al.,* 2020), its genetic relationships with other cultivated Sorghum (Sawadogo *et al.,* 2022a; Sawadogo *et al.,* 2022b; Tiendrebéogo *et al.,* 2022) and photoperiodism of genotypes (Tondé *et al.,* 2023a). However, many challenges still remain to be addressed regarding this neglected crop, in particular, its response to the contrasting Sahelian climatic conditions where droughts occur more and more (Tondé *et al.,* 2023b).

Water stress is one of the most important yield-reducing factors in the arid tropics, although Sorghum is considered a drought-tolerant cereal crop (Assefa *et al.,* 2010; Rahal-Bouziane *et al.,* 2013; Abreha *et al.,* 2022). Sorghum yield loss due to Drought in the tropics alone exceeds 17% and can reach 60% in severely affected regions (Assefa *et al.,* 2010; FAO, 2017; Hadebe *et al.,* 2017). Over the last three decades, droughts periods have been recurrent and accentuated, characterized either by a delay in the onset of rains and/or its early withdrawal of rains (Sivakumar et Gnamou, 1987; Kaboré *et al.,* 2019). The decrease in average annual rainfall and the reduction in the length of the rainy season led to the adoption of improved varieties with a shorter cycle than traditional cultivars (Lacy *et al.,* 2006), in addition to agronomic methods of moisture conservation such as the laying of stone cordons, the zaï and the collection of rainwater (Dugué 1986; Roose *et al.,* 1993; Kaboré *et al.,* 2019). Agricultural extension programs encourage farmers to use early-maturity varieties that are resilient during bad seasons (Soumaré *et al.,* 2008). In contrast, the best-characterized form of drought tolerance during the late stages of crop growth is stay-green (Tao *et al.,* 2000; Xu *et al.,* 2008; Keneni, 2020), which is the ability to resist premature plant senescence (keep the leaf surface green). Indeed, post-flowering drought tolerance in Sorghum is linked to the stay-green trait (Thomas and Howarth, 2000; Emendack, 2007), which has been associated with resistance to lodging, charcoal stalk rot (Mughogho *et al.,* 1984; Reddy *et al.,* 2014) and improving grain filling and grain yield under water stress (Luche *et al.,* 2015; Abdelrahman *et al.,* 2017). Therefore, drought control by different options remains a main strategy due to climate change and variability. Considerable work has been done on identifying stay-green genotypes, mapping and identifying quantitative trait loci (QTLs) associated with this trait (Xu *et al.,* 2008; Kamal *et al.,* 2021; Munarti *et al.,* 2022), opening new perspectives breeding for drought tolerance in breeding programs. This study is, therefore, conducted to (i) assess the level of genetic variability of sweet grain sorghum cultivated in Burkina Faso and (ii) identify potential drought-tolerant sweet grain sorghum genotypes at the post-flowering stage based on agromorphophysiological traits.

Materials and methods

Plant material

The plant material consists of 50 sweet grain sorghum genotypes and four stay-green sorghum control genotypes chosen for their drought tolerance at the post-flowering stage. The sweet grain sorghum genotypes were obtained from the gene bank of the Genetics and Plant Breeding Team (EGAP) located at Joseph KI-ZERBO University. Among the four controls, two genotypes (B35 and E36-1) were obtained from the Institute of Environment and Agricultural Research (INERA)/Burkina Faso, and the other two (ICSV1460024, Soubatimi) from International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)/Mali.

Experimental site

The experiment was carried out under rainfed conditions in 2021 at the experimental station of Gampèla. The station is located in the North Sudanian climatic zone (Sivakumar and Gnamou, 1987; Thiombiano and Kampman, 2010) with geographical coordinates of 12°25' North latitude and 1°12' West longitude and at an altitude of 273 m above sea level (IGB/BNDT, 2012). The soil of the site is very heterogeneous, deep, of low chemical fertility, and mostly sandy-loamy texture with a pH ranging from 5 to 6.3 (BUNASOLS, 1988; Kiébré, 2016). During the 2021-2022 rainy season, temperatures fluctuated between 22°C and 38°C (ANAM, 2021), and rainfall of 978.3 mm were recorded (IDR, 2021). The precipitation diagram of the experimental site during the year 2021 is summarized in Fig. 1. It indicates that the rainfall was early and poorly distributed over time. The rains reached their peak in August (378.3 mm), then became rare in September (< 85 mm).

Experimental design

The experimental design used for the study was a fully randomized alpha lattice with three replications. A distance of 2 m was left apart from each replication, while each replication was divided into two sub-blocks with 1 m apart. Each entry was sown on one line of 5.2 m in length, and a total of 54 lines were counted, corresponding to the number of entries. The inter and intra rows spacing was 80 x 40 cm, and 14 holes per row were recorded. The trial was bordered on either side by two lines of sweet-grain sorghum genotypes. The dimensions of the trial, including the two border lines, were 22.4 m x 38.2 m, giving a total area of approximately 856 m².

Cultivations practices

The experimental plot was plowed after the spreading of manure at a dose of 2 t/ha. Manual hoeing and plot leveling were done prior to sowing. Sowing was done on July 17, 2021, after sufficient rain the day before. Thinning at one plant and the first weeding was done 14 days after sowing, (DAS) and the second weeding on 35 days after sowing (DAS). Then, ridges were built at the end of the vegetative development of the plants in order to conserve soil moisture and counter lodging caused by violent winds. NPK mineral fertilizer (14-23-14) was applied to each weeding at a rate of 50 kg/ha, and nitrogen fertilizer (urea) was added at a dose of 50 kg/ha at the same time as hilling.

Data collection

Twenty-four quantitative traits were scored. These traits are related to the maturity cycle, to the characteristics of the vegetative organs, in particular the stay-green, and to the components of yields, divided into 10 morphological traits, 05 physiological traits, and 09 agronomic traits. The data were collected on 46 of the 50 genotypes of sweet grain sorghum because of the low number of raised holes recorded at the level of four genotypes (YOH1, PLA3, YTA3, and KDO12) and on the 04 controls.

Morphological traits

The 10 morphological traits were measured on five randomly selected plants per line and labeled. These are on the stem, main stem diameter (DIS), internodes number (NIN) and length (LIN), vegetative tillers number (NVT), productive tillers number (NPT), and plant height (PLH). Also, measurements such as the length (LEL) and the width (LEW) of the third leaf under the panicle taken at flowering, the number of green leaves at the swelling, start of the reproductive period (NGS) and at harvest (NGP) corresponding to the swelling stage and the pasty stage respectively were noted.

Physiological traits

The 05 physiological traits were determined by counting or calculation. Phenological traits such as plant emerging date (NDL), number of days from sowing-to appearance of the flag leaf (NDS), and number of days from sowing to -flowering (NDF) were noted by observation on all the plants of the entire line. The leaf area (LAG) was estimated using a correction factor of 0.70 (Mahalakshmi and Bidinger, 2002; Srinivas *et al.,* 2009) according to the formula $LAG = 0,70\ (LEL\ X\ LEW)$ where LEL = leaf length and LEW = leaf width. The rate of green leaves retained (RLG) was estimated by calculating the ratio between the number of green leaves at the pasty stage (NGP) and that at swelling (NGS) (Srinivas *et al.* 2009), expressed as a percentage, according to the formula $RLG(\%) = \frac{NGP}{NGS}x100$.

Agronomic traits

The following yield components were measured on the five randomly selected plants. These are peduncle length (LPE), main panicle weight (PAW), productive tillers panicle weight (PTW), main panicle grain weight (WGP), and productive tillers weight (WGT) determined at the pasty grain stage. The grain weight per hole (WGQ) was calculated by summing the weight of the grains of the main panicle and the tillers (WGP and WGT), according to the formula $WGQ = WGP + WGT$. The 100-grain weight (WGH) was determined by weighing 100 grains in the dry state at a moisture content of not more than 12%. The percentage of plants having lodged PHL (%) was determined just before harvest by calculating the ratio between the number of plants whose inclination relative to the vertical is greater than an angle of 30° (Ni) and the total number of plants in the line (Nt) according to the formula $PHL\ (\%) = \frac{Ni}{Nt} \times 100$ (DGPV, 2010). The degree of susceptibility to lodging (DSL) was then estimated on a scale from 1 (very weak) to 5 (very high) according to the percentage of plant having lodged, i.e., from 1 = 1 to 10% of plant lodged to 5 = 76 to 100% of plant lodged (House, 1985).

Statistical analysis

The data collected were analyzed by using the R-studio software package. The analysis of variance (ANOVA) using the agricolae library (Steel *et al.,* 1997) was carried out to assess the variability of the plant material studied and to determine the traits that discriminate sweet grain sorghum genotypes. A trait correlation calculation was performed to determine the degree of relationship between the studied traits. The Pearson correlation matrix was thus visualized using the metan package (Emerson *et al.,* 2012). Redundant traits that bring the same information were eliminated before multivariate analyses using ggplot2 and FactoMineR packages (Lê *et al.,* 2008; Wickham, 2016). Principal component analysis (PCA) identified the most relevant traits. Well-represented traits were used to group genotypes through an

Ascending Hierarchical Classification (AHC) based on Ward's distance between individuals. The groups obtained were finally characterized by discriminant factor analysis (DFA). A Student-Newman-Keuls (SNK) test using the agricolae library was also used to compare the potential drought-tolerant sweet grain sorghum genotypes identified in AHC with the four stay green sorghum genotypes (controls).

Results

Variation of morphological traits

Table 1 reveals the results of the analysis of variance of the 46 sweet-grain sorghum genotypes based on morphological traits studied. Significant differences ($Pr < 0.5$) were observed between genotypes for all morphological traits assessed. Large differences are observed between the minimum and maximum values of the measured traits, indicating a strong differentiation between the genotypes. Indeed, the plant height (PLH) varied from 226.7 cm to 446.7 cm with an average of 324.9 cm, and the main stem has an average thickness of 2.59 cm.

The stems emitted 11 to 16 internodes with an average of 13 internodes, which are 16.50 cm to 29.83 cm long. All the genotypes produced, on average, 02 vegetative tillers for 01 productive tiller. The average length and width of the leaves (LEL and LEW) vary from 47 to 89 cm and from 5.6 to 10.5 cm, respectively. The genotypes retained 5 to 15 green leaves at the start of the reproductive period and 3 to 11 green leaves at the pasty/milky stage. The traits, vegetative tillers number and productive tillers number (CV = 42.12% and CV = 53.34%) presented high coefficients of variation (CV > 30%).

Table 1. Results of the descriptive analysis of morphological traits.

Traits	Minimum	Maximum	Mean	CV (%)	F Value	Pr(>F)
PLH (cm)	226.70	446.70	324.90	21.00	5.677	1.81e-12 ***
DIS (cm)	1.30	4.10	2.59	23.93	2.705	3.32e-05 ***
NIN	11.33	16.00	13.63	6.78	2.431	0.000189 ***
LIN (cm)	16.50	29.83	22.95	21.32	4.889	9.85e-11 ***
NVT	1.22	5.33	2.614	42.12	1.476	0.004 **
NPT	0.22	3.33	1.55	53.34	2.226	0.000689 ***
LEL (cm)	47.00	89.00	73.61	11.22	1.924	0.00452 **
LEW (cm)	5.60	10.50	9.07	13.28	2.133	0.00123 **
NGS	5.00	15.67	9.88	23.07	4.881	1.03e-10 ***
NGP	3.00	11.00	5.75	35.82	10.540	<2nd-16 ***

*PLH: plant height; DIS: stem diameter; NIN: number of internodes; LIN: length of internodes; NVT: number of vegetative tillers; NPT: number of productive tillers; LEL: leaf length; LEW: leaf width; NGS: number of green leaves at the swelling stage; NGP: number of green leaves at the pasty stage; CV: coefficient of variation; F Value: Fischer probability; Pr : probability of the factor; ***: very highly significant.*

Variation in physiological traits

The results of the analysis of variance recorded in Table 2 revealed variability of the plant material for the physiological traits. Indeed, most physiological traits significantly discriminated genotypes at 1% threshold, except the number of days to emergence ($pr = 0.158$). The differences between the minimum and maximum values of each of the traits studied showed a significant dispersion around their mean. The leaf area (LAG) varied from 265.2 to 635 cm^{2,} and the percentage of green leaves preserved at harvest was, on average, 55.13%. The vegetative period of the genotypes lasted from 37 to 72 days. The genotypes have an average cycle (number of days 50% flowering) of 68 days. The earliest genotype flowered 49 days after sowing, and the latest at 84 days after sowing. The number of green leaves at the pasty stage (CV = 35.82%) and the percentage of green leaves retained (CV = 32.48%) showed high coefficients of variation (CV > 30%).

Table 2. Results of descriptive analysis of physiological traits.

Traits	Minimum	Maximum	Mean	CV (%)	F Value	Pr(>F)
LAG (cm2)	265.20	635.00	450.10	20.79	2.402	0.000226 ***
RLG (%)	39.76	91.30	55.13	32.48	5.647	4.51e-14 ***
NDL	3.00	4.00	3.05	7.07	1.348	0.117ns
NDS	37.00	72.00	58.67	7.10	10.39	<2nd-16 ***
NDF	49.00	84.00	68.55	6.03	10.21	<2nd-16 ***

*LAG: leaf area; RLG: percentage of green leaves retained; NDL: number of sowing-emergence days; NDS: number of days semi-appearance of the flag leaf; NDF: number of sowing-flowering days; CV: coefficient of variation; F Value: Fischer probability; Pr: probability of the factor; ***: very highly significant.*

Variation in agronomic traits

The results of the analysis of variance recorded in Table 3 revealed that all the agronomic traits significantly discriminated the sweet grain sorghum at the 5% and 1% thresholds. Indeed, genotypes have peduncles length ranging from 27 cm to 67.33 cm. The mean values of panicles weight (PTW) and productive tillers grain weight (WGT) were 127.76 g and 105.3 g, respectively. The main panicles, which weighed 112 g to 283.7 g, produced grains weighing from 103 g to 219.61 g, with an average of 126.3 g per main panicle. The 100-grain weight (WGH) ranged from 1.08 g for the light-grained genotypes to 3.03 g for the heavy-grained ones, almost three times that. The percentage of seedlings having lodged varied from 10% to 100%. All genotypes were susceptible to lodging but from less susceptible to highly susceptible. High coefficients of variation (CV > 30%) are observed for yield components such as panicle weight (CV= 55.48%), productive tillers grains weight (CV= 61.17%), grain weight per hole (CV=32.41%), percentage of plants having lodged (CV = 42.75%) and degree of sensitivity to lodging (CV = 40.25%). The coefficients of variation are also high (CV> 25%) for panicle weight (CV= 25.5%) and main stem grain weight (CV= 27%).

Table 3. Results of the descriptive analysis of agronomic traits

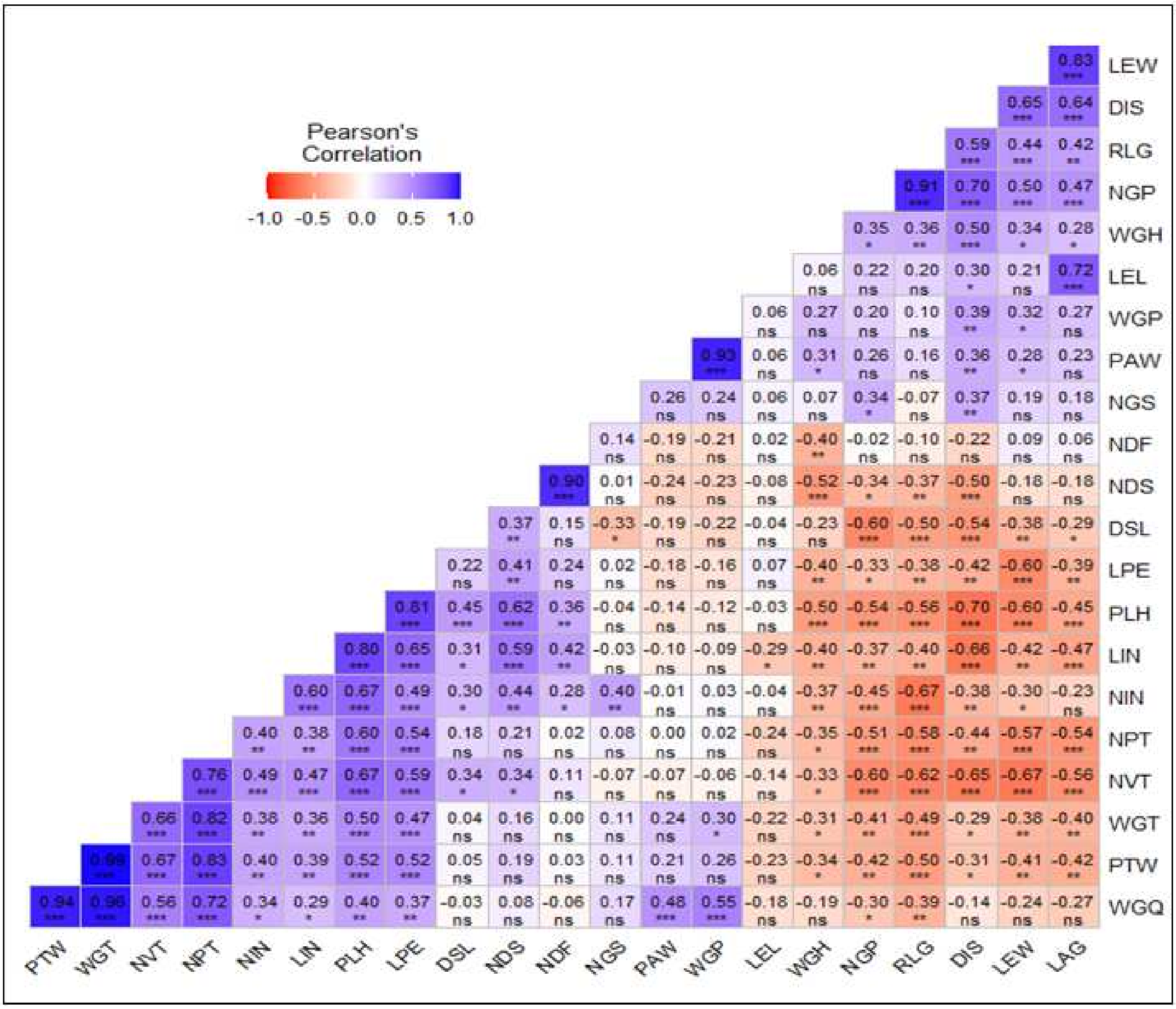
Traits	Minimum	Maximum	Mean	CV (%)	F Value	Pr(>F)
LPE	24.00	67.33	47.61	13.61	9.75	<2nd-16 ***
PAW (g)	82.00	314.00	127.76	55.48	2.135	0.00122 **
PTW (g)	19.30	304.00	105.30	61.17	1.929	0.00437 **
WGP (g)	112.00	283.70	153.40	25.50	1.554	0.0298 *
WGT (g)	103.00	219.61	126.30	26.64	1.686	0.0187 *
WGQ(g)	119.67	451.00	230.31	32.41	2.131	0.00126 **
WGH (g)	1.08	3.03	2.16	19.89	4.69e+28	<2nd-16 ***
PHL (%)	7.14	100.00	53.57	42.75	2.110	<2nd-16 ***
DSL	1.00	5.00	3.27	40.25	8.991	<2nd-16 ***

*LPE: peduncle length; PAW: weight of the main panicle; PTW: weight of productive tillers; WGP: grain weight of the main panicle; WGT: grain weight of productive tillers; WGQ: grain weight per hole; WGH: 100-grain weight; PHL (%): percentage of plant having lodged; DSL: degree of sensitivity to lodging; CV: coefficient of variation; F Value: probability of the factor; nsp >0.05; difference: *p<0.05; **P<0.01; ***p<0.001.*

Correlation between morphoagrophysiological traits

The correlation matrix presented in Table 4 showed the degree of relationship between traits. Thus, the plant height (PLH) is positively correlated to the internodes number (r = 0.67), internodes length (r = 0.80), degree of sensibility to lodging (r = 0.45), number of days sowing - flag leaf appearance (r = 0.62), vegetative tillers number (r = 0.67), productive tillers number (0.60), productive tillers grain weight (r = 0.5) and grain weight per hole (r = 0.40).

Table 4. The correlation matrix between the traits studied.



*PLH: plant height; DIS: diameter of the main stem; NIN: number of internodes; LIN: length of internodes; NVT: number of vegetative tillers; NPT: number of productive tillers; LEL: leaf length; LEW: leaf width; NGS: number of green leaves at the swelling stage; NGP: number of green leaves at the pasty stage; LAG: leaf area; RLG: percentage of green leaves retained; NDS: number of days semi-appearance of the flag leaf; NDF: number of sowing-flowering days; PAW: weight of the main panicle; PTW: weight of productive tillers; WGP: grain weight of the main panicle; WGT: grain weight of productive tillers; WGQ: grain weight per hole; WGH: 100-grain weight; DSL: degree of sensitivity to lodging; CV: coefficient of variation; F Value: Fischer probability; Pr: probability of the factor; nsp >0.05; difference: *p<0.05; **P<0.01; ***p<0.001.*

It is moderately or strongly negatively correlated with the percentage of green leaves retained (r = -0.56), leaf width (r = -0.60), main stem diameter (r = -0.70), and 100-grain weight (r = - 0.50) but slightly to the main panicle grain weight (r = -0.12). Main stem diameter is strongly and positively correlated with leaf width (r = 0.65), 100-grain weight (r = 0.50), number of leaves at the pasty stage (r = 0.70), number of green leaves at the swelling stage (r = 0.37), percentage of green leaves retained (r = 0.59), weight of the panicle (PAW, r = 0.36) and the main panicle grain weight (r = 0.39). It is, however, negatively correlated with the degree of sensibility to lodging (r = - 0.54) and vegetative tillers number (r = - 0.65), and productive tillers number (r = - 0.44). Vegetative (NVT) and productive (NPT) tillers number, which are strongly and positively correlated with each other (r = 0.76), are respectively positively correlated with internodes number (r = 0.49 and r = 0.40), tillers grains weight (r = 0.66 and r = 0.82) and grain weight per hole (r = 0.56 and r = 0.72) and negatively correlated with *the* percentage of green leaves retained (r = - 0.62 and r = - 0.58) and leaf width (r = - 0.67 and r = - 0.57).

Association of morphoagrophysiological traits

The eigenvalue, the variance, and the latent vectors of the traits extracted from the principal component analysis (PCA) presented in Table 5 revealed that the first three factorial axes are significant with eigenvalues > 1. These three cumulated axes allow the representation of approximately 80% overall variability, including 47.042% for axis 1; 19.665% for axis 2 and 12.48% for axis 3.

The variances of the individuals on the corresponding main axes are 7.056 for the 1st; 2.95 for the 2nd and 1.872 for the 3rd axis. The main contributions to the first-factor axis come from 10 traits. This axis 1, which explains 47% of the overall variability, opposes the traits, main stem diameter (r = - 0.768), leaf width (r = - 0.652), number of green leaves at the pasty stage (r = -0, 78) and percentage of green leaves retained (r = -0.800) to the number of vegetative tillers (r = 0.848), plant height (r =0.893), internodes length (r =0.809), number of productive tillers (r = 0.661), peduncle length (r = 0.819) and degree of susceptibility to lodging (r = 0.564). The number of swelling days (r = - 0.580), which is opposed to the main panicle weight (r = 0.672), the weight of grains of productive tillers (r = 0.682) and grain weight per hole (r = 0.848) mainly contribute to the second factorial axis which explains 12.48% of the overall variability. The third axis is correlated with the number of 50% flowering days (r = 0.621).

Organization of variability

The hierarchical ascending classification (HAC) carried out using Euclidean distances with the Ward method as aggregation criterion gave the dendrogram of Fig. 2. The truncation at the first level of the center of inertia made it possible to obtain four groups. Group 1 consists of two sweet grain genotypes (YOH8, PBO4) and two stay green controls (B35 and E36-1) and group 2 of one sweet grain sorghum genotype (SBR5) and two stay green controls (ICSV6460024 and Soubatimi). Groups 2 and 3 contained only sweet sorghum genotypes, with numbers 27 and 16, respectively.

Table 5. Eigenvalues and percentage of variation expressed for the first three axes from the 15 quantitative traits in principal component analysis.

Characters	Main components		
	F1	F2	F3
NDS	0.568	-0.580*	0.502
NDF	0.465	-0.601	0.621*
NVT	0.848*	0.229	-0.037
PLH (cm)	0.893*	-0.019	0.140
DIS (cm)	-0.768*	0.103	0.487
LIN (cm)	0.809*	-0.295	0.224
LEW (cm)	-0.652*	-0.212	0.370
LPE (cm)	0.819*	-0.174	0.245
NGP	-0.780*	-0.072	0.449
RLG (%)	-0.800*	-0.115	0.282
NPT	0.661*	0.553	0.199
PAW (g)	-0.438	0.672*	0.221
WGT (g)	0.595	0.682*	0.319
WGQ (g)	0.334	0.845*	0.359
DSL	0.564*	-0.269	-0.361
Eigenvalue	7.056	2.950	1.872
Variance explained (%)	47.042	19.665	12.481
Cumulative variance (%)	47.042	63.401	79.188

*: significant value.

Fig. 3 shows the position of the genotypes on the ½ plane of the Discriminant Factor Analysis (DFA). Wilks' Lambda test gives an observed F of 7.71, while the critical F is 1.49. The positions of the genotypes make it possible to characterize the groups formed. Group I is made up of genotypes with average values for stay green parameters such as leaf area (LAG), percentage of green leaves retained (RLG), leaf width (LEL) and main stem diameter (DIS). These individuals also showed low tillering capacity (NTV and NTU), low height (HPM), better resistance to lodging (VER) and the shortest cycle. Group II is characterized by high values for stay-green parameters such as the number of green leaves at the swelling (NGS) and the dough stages (NGP), and the percentage of green leaves retained (RLG).

These genotypes also have large leaves (LEL), thick stem (DIS), a high main panicle weight (PAW), medium height (PLH) and relatively long cycles (NDS and NDF). Group III genotypes are characterized by a medium cycle (NDS), high height (PLH), many internodes (NIN) and a long peduncle (LPE). These genotypes were the most susceptible to lodging (DSL) with the low grain weight per hole (WGQ). Group IV is made up of short-cycle genotypes with high tillering capacity (NTV and NTU) and high grain weight per hole (WGH).

Table 6. Performance of stay-green sweet grain sorghum genotypes compared to controls.

Genotypes / Traits	Sweet grain sorghum			Stay-green controls			
	PBO4	YOH8	SBR5	B35	E36-1	ICSV1460024	Soubbatimi
NDS	41.33e	39.67f	73.33c	45.67d	42.00nd	77.00b	79.33a
NDF	54.67f	51.00g	81.67c	57.67d	56.00e	85.33b	88.00a
PLH (cm)	235.67c	262.11b	285.67a	106.83g	132.66f	197.22e	202.11d
NIN	12.00bc	12.33b	11.89b	13.67a	12.33b	11.00c	10.22d
LIN (cm)	22.22b	24.87a	21.22c	4.83g	7.50f	19.00d	18.17th
LPE (cm)	51.33d	53.00c	43.67e	58.4y	56.00b	41.11f	33.87g
DIS (cm)	2.53e	2.77d	3.03b	2.96c	3.26a	3.30a	3.18ab
LEW (cm)	9.33d	9.53c	10.63b	8.27f	9.00e	10.77a	10.67b
LAG (cm2)	452.61f	460.46e	583.25b	439.16g	469.70d	612.53a	534.00c
NGP	9.33d	8.00th	10.56a	11.33g	10.66f	10.22b	9.89c
RLG (%)	84.81bc	80.54c	91.18ab	86.13bc	85.71bc	92.90a	88.97b
NVT	2.56a	2.33a	1.44ab	0.22c	0.44c	1.33ab	0.89b
NPT	1.52b	2.00a	1.22bc	0.22d	0.44d	1.00c	0.56d
WGT (g)	161.11b	229.00a	109.22c	21.60f	31.20e	58.67d	26.89g
PAW (g)	154.22c	178.20b	202.00a	118.22g	129.33f	143.00d	138.00e
WGP (g)	120.22cd	134.00c	178.20a	98.43e	113.00d	138.22b	119.33cd
WGQ (g)	293.44b	331.00a	289.31c	118.00g	143.00f	176.89d	146.22e
WGH (g)	2.54b	2.62b	2.89b	2.80b	3.30a	3.35a	2.92b
DSL	1a	1a	1a	1a	1a	1a	1a

NDS: number of days semi-appearance of the flag leaf; NDF: number of sowing-flowering days; PLH: plant height; NIN: number of internodes; LIN: length of internodes; LPE: length of the peduncle; DIS: diameter of the main stem; LEW: leaf width; LAG: leaf area; NGP: number of green leaves at the pasty stage; RLG: percentage of green leaves retained; NVT: number of vegetative tillers; NPT: number of productive tillers; WGT: grain weight of productive tillers; PAW: weight of the main panicle; WGP: grain weight of the main panicle; WGQ: grain weight per hole; WGH: hundred grain weight; DSL: degree of sensitivity to lodging.

Identification of potential drought-tolerant sweet grain sorghum genotypes at the post-flowering stage

The dendrogram from the Ascending Hierarchical Classification made it possible to identify three sweet grain sorghum genotypes (PBO4, YOH8 and SBR5) which are classified with the stay green controls (B35, E36-1, ICSV1460024 and Soubatimi) in two different genes pools. The performances of these stay-green sweet grain sorghum genotypes likely to tolerate post-flowering water stress, as well as those of the stay green sorghum controls, are summarized in Table 6. Thus, for the cycle, two sweet grain sorghum genotypes (PBO4 and YOH8) were earlier (sowing-flowering cycle <60 days) than the two short-cycle controls B35 and E36-1 (cycle.>85 days). For plants growth habits, all three sweet grain sorghum genotypes (PBO4, YOH8 and SBR5) presented the highest values for plant height (>230 cm) and average values for the number (NIN) and length (LIN) of internodes as well as for the length of the peduncle (LPE). For stay green traits, the SBR5 sweet grain sorghum genotype expressed the highest values for leaf area (LAG), percentage of green leaves retained (RLG), main stem diameter (DIS) and leaf width (LEW), as did the two stay green controls ICSV1460024 and Soubatimi. The two other sweet grain sorghum genotypes (PBO4 and YOH8) expressed the lowest values of these stay-green traits compared to controls B35 and E36-1, which presented intermediate values.

Regarding grain yield, all three sweet grain sorghum genotypes, despite their low 100-grain weight, were the most productive with the best main panicle grain weight and grain weight per hole. However, no significant difference was observed between the three sweet grain sorghum genotypes and the four stay green controls according to the degree of sensitivity to lodging and grain weight, which were all very weakly susceptible to lodging (< 10% of lodged plants).

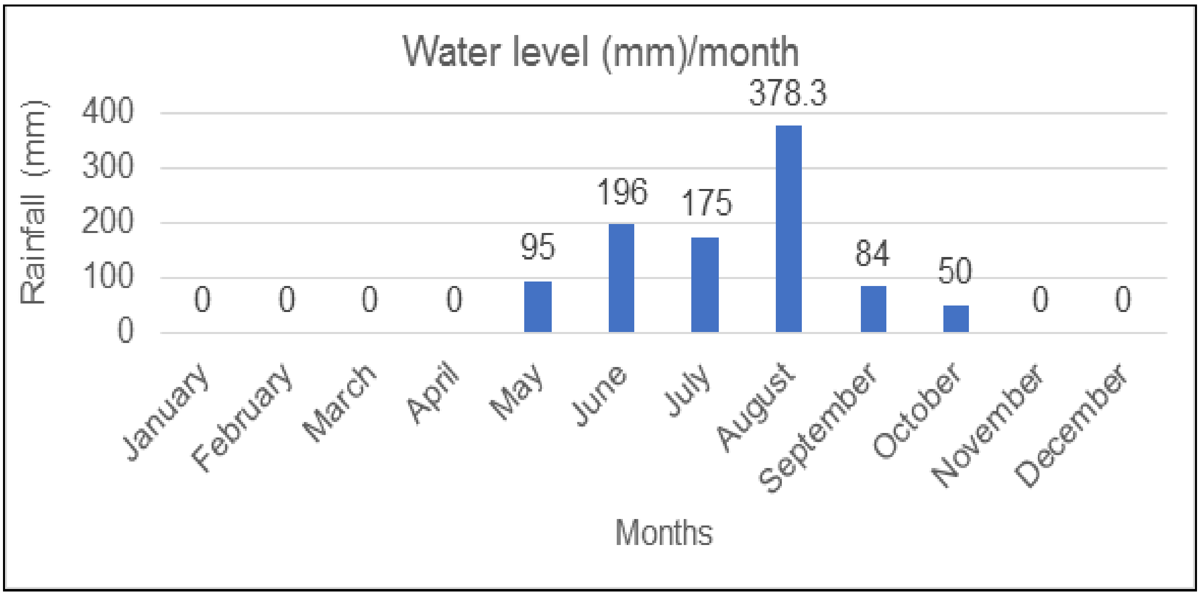


Fig. 1. Rainfall diagram for the Gampèla experimental site in 2021 (IDR, 2021).

Discussion

Morpho-agronomical and physiological Traits variability

The variability observed in most of the traits studied, with the exception of plant emerging date, confirms the high genetic diversity of the plant material evaluated and the position of Burkina Faso as a secondary center of cultivated sorghum diversity (Chantereau *et al.,* 1997). This variability is crucial to the success of any genetic improvement program. Indeed, genetic diversity increases the chances of having favorable alleles for the different traits of interest for breeding. This variability results from the farmer's production system, which proceeds by mass selection for seeds, its result a highly genetically diversified population variety. For the FAO (2009), local and indigenous communities, as well as farmers in all regions of the world, particularly those in the centers of origin and crop diversity, have made and will continue to make an important contribution to the sustainable use of resources genetics that form the basis of food and agricultural production worldwide. The high coefficients of variation noted in terms of traits, vegetative tillers (CV = 42.12%), productive tillers (CV = 53.34%), productive tillers weight (61.17%), and main panicle weight (CV = 55.48%)

reflect the heterogeneity of genotypes for these traits. This could be explained by the large difference in tillers production between genotypes. Previous studies (Nébié *et al.,* 2012; Sawadogo *et al.,* 2014b) also showed the variability within sweet grain sorghum, respectively, for the number of vegetative tillers (CV = 53.32% and 58.44%) and the number of productive tillers (CV = 65.14% and 61.55%). The average value of 55.13% of green leaves retained, together with its high coefficient of variation (CV = 32.48%), could indicate the presence of stay-green genotypes, since maintaining a green surface after flowering is one of the main characteristics of stay-green genotypes (Emendack *et al.,* 2017; Cow, 2019).

The average lodging score of 3 obtained could be explained by the great height of certain genotypes. It could also reflect the frequency of extreme climatic phenomena, in particular strong winds causing stem breakage or the uprooting of genotypes.

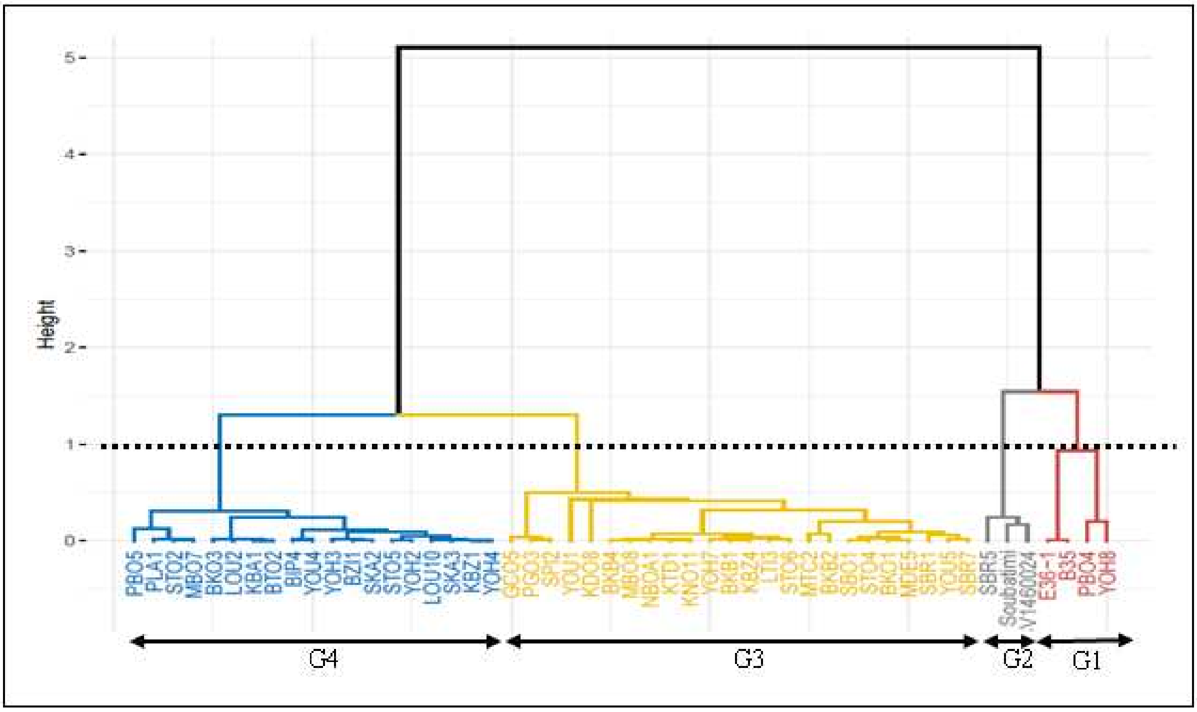


Fig. 2. Dendrogram from the ACH of the genotypes studied.

Association between measured traits and genetic variability structuring

For the breeder, it is not enough just to have variability in the plant material; it is essential to know and understand its structuring in order to effectively manage and direct its use in breeding (Menz *et al.,* 2004; Ali *et al.,* 2008).

The results of the various bivariate and multivariate analyzes provide a set of numerous and disparate information on the various agromorphophysiological traits which are important for selection. A positive or negative correlation between traits is a selection aid. Thus, among the observed correlations, those that strongly and positively associate leaf width and number of green leaves with 100-grain weight and stem diameter are of interest. Indeed, the leaves, seat of photosynthesis (Thomas and Howarth, 2000; Emendack, 2007), allow the production of carbonaceous materials (carbohydrates) stored as reserves in the grain. According to Fiedel *et al.* (1996), carbohydrates represent 80% of the dry matter of the grain, hence the selection oriented towards stay-green genotypes.

The correlations obtained between plant height, internodes number and length, cycle, lodging, tillers production, and grain weight show that these traits are linked. This is due to the fact that the latest genotypes spread their development over a long period which contributes to the development of the habit of the plant, making it susceptible to lodging. Similar results have been reported in several previous studies (Zongo, 1991; Hema, 2005). Also, the selection is oriented today toward short varieties with more robust stem, easier to harvest mechanically, avoiding damage and losses caused by wind or other environmental conditions (Trouche *et al.,* 1999; Hilley *et al.,* 2016; Guindo *et al.,* 2019).

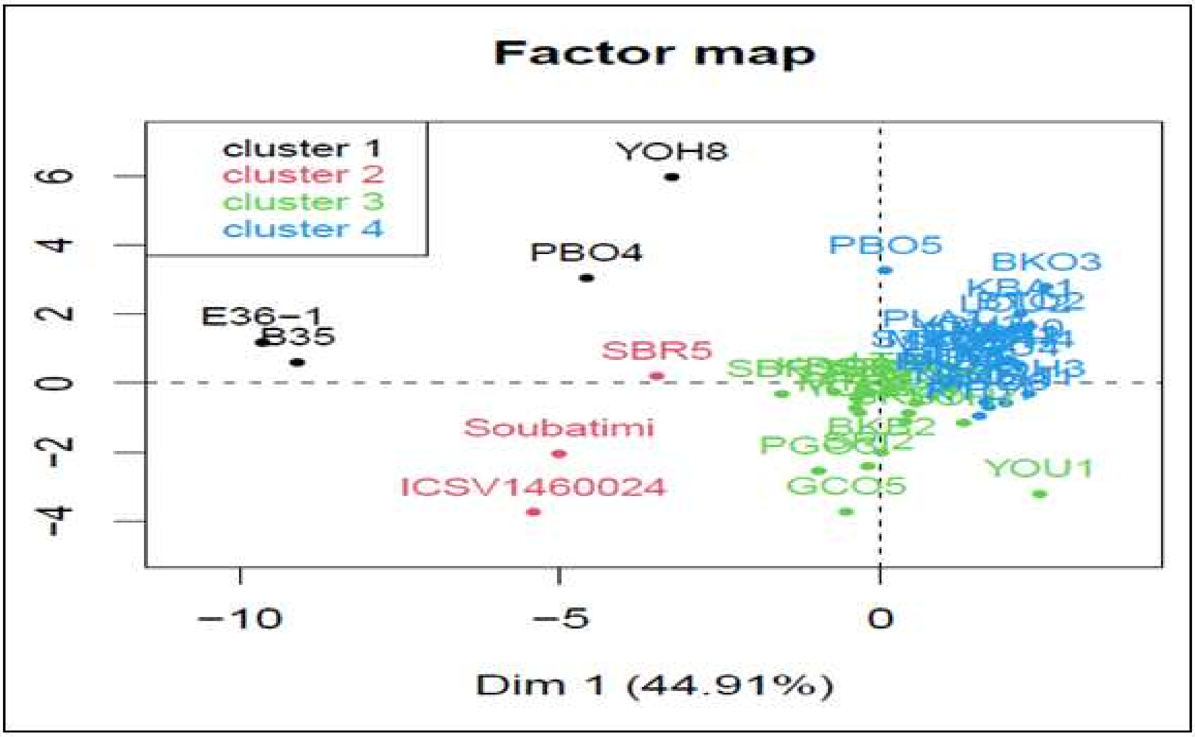


Fig. 3. Representation of groups on the ½ axis of the AFD.

Identification of potential drought-tolerant sweet grain sorghum genotypes

The structuring of sorghum genotypes was evaluated in four groups on the basis of vegetative traits (height of plants, number of leaves, and size of leaves), physiological traits (number of days at 50% swelling and 50% flowering, stay-green), and agronomic traits (tiller production, main panicle, and tiller grain weight) could reflect the existence of four different gene pools. This pattern of variability was also observed by Kouame *et al.* (2011). The result of the DFA carried out on these groups, following Wilks' Lambda test, shows that these groups are different entities from each other. The projection of the genotypes in the 1/2 plan of the DFA made it possible to operate a selection of the genotypes of sweet grain sorghum with important characteristics likely to improve their tolerance to Drought. Indeed, two types of processes, namely those essentially morphological contributing to the plasticity of the development of the vegetative apparatus and the physiological processes, such as the adjustment of the cycle according to the duration of the rains, are identified. Both categories of response have been reported in Sorghum by several previous studies (Kegode and Pearce, 1998). The earliness of the group I genotypes is a characteristic of adaptation to the shortening of the duration of the season. It allows these genotypes to complete the life cycle before a water deficit occurs. In fact, the adaptation of plant phenology to the stressful environment is a key factor in adaptation to Drought. This mechanism, called "drought escape mechanism" is, according to Torquebiau (2015), the main factor of adaptation to Drought. The shortening of the vegetative phase is a characteristic of Sorghum that allows it to escape Drought and is, in fact, a major component of the grain integrity index. For example, in the case where the rains stop early, a difference of one week in the flowering time between two genotypes results in a 30% reduction in the grain filling period and gives the early cultivar a better chance to escape drought stress, while the late cultivar may experience stress before or during reproduction (Kouressy *et al.,* 2008; Gano *et al.,* 2021). However, it seems that selection prospects for earliness are limited due to the low predictability of rainfall in the semi-arid tropics.

There is a need to expand genetic diversity by employing diverse alleles for post-rainfall adaptation of drought-tolerant traits such as stay green. Maintaining a green leaf area helps stabilize production by maintaining a photosynthetically active leaf area (Xu *et al.,* 2008; Luche *et al.,* 2015; Teklay *et al.,* 2021). Indeed, post-flowering drought tolerance in Sorghum is linked to the stay-green trait (Thomas and Howarth, 2000; Emendack, 2007), which has been associated with reduced susceptibility to lodging, charcoal stalk rot (Mughogho *et al.,* 1984; Reddy *et al.,* 2014) and improved grain filling and grain yield under water stress (Luche *et al.,* 2015; Abdelrahman *et al.,* 2017). In the present study, sweet grain sorghum genotypes of groups I and II showed superiority to delayed leaf senescence and constituted genotypes of interest, especially under water-limiting conditions. Since cereal production and lodging are so closely linked, the stay green trait should provide a significant direct benefit to sorghum growers by minimizing water-stress-type lodging or lodging caused by high winds at the end of the cycle. The fairly high performances of sweet grain sorghum genotypes for stay-green traits, even exceeding the reference control B35, show that these genotypes would contain the stay-green gene.

Conclusion

The development of drought-tolerant genotypes is one of the important goals of sorghum breeding worldwide, particularly for rainfed Sorghum in Burkina Faso. This study consisted of the evaluation of the agro-morphological and physiological characteristics of 46 genotypes of sweet grain sorghum in order to choose the most efficient in terms of adaptation to the climatic conditions of the environment compared to controls. The results of the analysis of variance revealed an agro-morphological variability within the sweet grain sorghum studied. Four phenotypic groups have been identified, two of which (groups I and II) contain the stay green control genotypes and three sweet grain sorghum genotypes (PBO4, YOH8 and SBR5) which are characterized by a strong stay-green potential, thus making them able to tolerate post-flowering water stress. An evaluation of sweet grain sorghum genotypes using SNP markers could help to better assess the level of genetic diversity and identify the QTLs conferring drought tolerance. The tolerance of sweet grain sorghum to Drought could also be reinforced and complemented by a post-emergence stress assessment.

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Conflicts of Interest

The authors declare no conflict of interest.

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