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RESEARCH ARTICLE

PHENOTYPIC SCREENING OF 32 WEST AFRICAN SORGHUM GENOTYPES FOR DROUGHT TOLERANCE

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Abstract

This study evaluated the agro-physiological responses of 32 sorghum genotypes subjected to water stress applied at the critical stage of transition to panicle initiation. The objective was to identify sorghum adaptation mechanisms under such stress and to determine potentially tolerant genotypes. Analysis of physiological and agro-morphological traits revealed significant inter-genotypic variability. Under stress, leaf water potential decreased from –0.59 to –4.84 MPa, indicating differentiated tolerance levels. Genotypes V1, V2, V12, V16, V22, and V28 maintained good water status and exhibited the lowest rates of leaf desiccation after stress.Stress also induced reductions in stomatal conductance (−25%), photosynthesis (−13%), and transpiration (−40%), reflecting adaptive strategies in the genotypes. However, a marked decrease in grain yield (−47%) was observed, underscoring the limits of adaptive mechanisms to sustain productivity. Combined analysis of tolerance indices (SSI, STI) and agro-physiological traits identified genotype V26 as elite, combining low stress sensitivity with high yield. Other tolerant but less productive genotypes (V2, V6, V10, V11, V12, V14, V16, V18, V24, V30, V32) may serve as gene reservoirs for breeding improvement. In addition, principal component analysis distinguished three groups of genotypes according to their adaptive profiles.These findings highlight the relevance of an integrated approach combining agro-physiological traits, tolerance indices (SSI, STI), and multivariate analyses for the selection of genotypes adapted to water stress conditions.

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Introduction:-

Sorghum (Sorghum bicolor [L.] Moench) is the fifth most cultivated cereal worldwide after wheat, maize, rice, and barley (FAO, 2015). It is also the most important crop in the semi-arid Sudanian-Sahelian zones of Africa and Asia (Mindaye et al., 2016). It is primarily grown for both its grain and biomass, which are used for human and animal consumption(Megnonhou et al, 2025a). Despite the multiple benefits of this crop, its production remains threatened by various biotic and abiotic constraints. The effects of these constraints are increasingly exacerbated by climate change, mainly through the increased frequency of extreme events such as droughts and heavy rainfall (Deng et al., 2024; Qiu et al., 2021). Furthermore, several authors (Ben Mariem et al., 2021;Megnonhou et al, 2025b;Pickson et al., 2023) have reported that climate change, through rising temperatures, negatively impacts agricultural production, particularly cereals.Sorghum plants employ different morphological and physiological adaptation strategies to survive intermittent or continuous drought occurring during their growth cycle. One key adaptation strategy is the reduction of water loss through transpiration when atmospheric demand increases (Raymundo et al., 2024). Several studies have previously reported mechanisms underlying this trait and its positive impact on sorghum yield (Choudhary et al., 2013;Mwamahonje et al., 2021; Sinclair et al., 2017).

These investigations summarize the expression of adaptation mechanisms through stomatal closure, development of a deep root system, and reduction of leaf area under water stress. Consequently, drought tolerance in sorghum is reinforced by multiple genes, each contributing partially to this tolerance (Phuong et al., 2019).Genetic improvement of sorghum for drought tolerance thus relies on integrating numerous traits, such as the "stay-green" trait, leaf rolling, and reduced transpiration. However, these traits are negatively correlated with sorghum yield under water-stressed conditions (Mwamahonje et al., 2021). Moreover, sorghum's response to water stress depends on the species, growth stage, type, intensity, and duration of the stress (Dos Santos et al., 2022; Gano et al., 2021a). Several recent studies have shown that exposure of sorghum to water stress shortly after germination leads to significant reductions in seedling growth, leaf emergence, transpiration, and photosynthesis, often accompanied by early leaf senescence (D. Chen et al., 2015; Zhang et al., 2024).Additionally, Gano et al. (2021) found that early water stress, around 30 days after germination, causes a significant reduction in vegetative growth, decreased photosynthesis, early leaf senescence, and lower grain yield.

Other authors (de Souza et al., 2021; Kamal et al., 2018; Sanjari et al., 2021; Tovignan et al., 2016) reported that post-flowering drought negatively affects sorghum, mainly reducing grain yield, biomass, and stem sugar accumulation.However, limited data exist on the impact of early drought occurring during the transition stage toward panicle initiation and structuring. This stage, which corresponds to the differentiation of the growth point and marks the beginning of panicle development, is particularly sensitive to water stress (Abreha et al., 2022; Tovignan et al., 2016). A better understanding of drought effects at this critical stage is essential, as it could compromise the formation of reproductive organs, leading to reduced panicle weight, fewer fertile flowers, and consequently lower final yield (Ndlovu et al., 2024; Tovignan et al., 2016).Identifying sorghum varieties tolerant to water stress at this specific stage would help guide breeding programs toward targeted genetic improvement, thereby enhancing crop resilience to climatic hazards in the Sahelian and Sudanian-Sahelian regions. The objective of this study was to evaluate the effect of water deficit occurring during the transition stage toward panicle initiation and structuring on sorghum, in order to determine the main adaptation mechanisms and the useful methods and criteria for agro-physiological phenotyping under water stress conditions. It also aimed to select, using drought tolerance indices, the sorghum genotypes that remain productive under drought conditions.

2. Materials and methods:-

2.1. Location of the study

The present study was conducted at the experimental site of the National University of Agriculture (UNA) located in Kétou, in the Plateau department, southeastern Benin. The site is situated at the following geographic coordinates: latitude 7°18′26″ N (7.3072) and longitude 2°36′28″ E (2.6077). The region has a tropical climate with a bimodal rainfall pattern, characterized by two main climatic variants: that of the Middle Zou and the southeastern plateaus. The climate calendar includes a long rainy season from March to July, followed by a short dry season in August. A second, shorter rainy season occurs from September to October, preceding a long dry season from November to February. The average annual rainfall in the commune is estimated at approximately 1073 mm, distributed over 65 rainy days (INSAE, 2016). Furthermore, the experimental site's soil exhibited the physico-chemical characteristics listed in Table 1.

Table 1:Physicochemical characteristics of the experimental soil

Parameters	Unit	Values	Standards
MO	(%)	0.59	2-3
NT		0.05	0.1-0.15
Ca2+	Cmol/kg	1.5	2.3-3.5
Mg2+		0.5	1-1.5
K+		0.2	0.2-0.4
Na+		0.1	0.3-0.7
CEC		5.2	10-25
pH	-	5.5	6.5-7.5
Pass	mg/kg	6.428	10-15

MO: Organic matter; NT: Total nitrogen; Ca^{2+}: Exchangeable calcium; Mg^{2+}: Exchangeable magnesium; K^{+}: Exchangeable potassium; Na^{+}: Exchangeable sodium; CEC: Cation exchange capacity; pH: Hydrogen potential (soil acidity); P ass: Available phosphorus.

2.2. Plant material.

The plant material consisted of thirty-two (32) sorghum genotypes obtained from four agricultural research institutions in West Africa. Table 2 presents the characteristics of the genotypes and their origin.

Table 2: Characteristics and origin of the evaluated genotypes

Codes	Genotypes	Pedigree	Country of Origin	Home Institutions
V1	ICSB 176008	(POPD08-611/02-SB-F5DT-12B)-7-4-3-1-10-6-6-10	Mali	ICRISAT
V2	ICSB 176003	(POPD08-622/02-SB-F5DT-12B)-1-3-1-3-6-7-7-3	Mali	ICRISAT
V3	ICSB 176005	(POPD08-622/02-SB-F5DT-12B)-1-3-1-3-6-7-7-3	Mali	ICRISAT
V4	ICSB 176006	(POPD08-611/02-SB-F5DT-12B)-3-1-7-2-8-7-1-7	Mali	ICRISAT
V5	ICSB 176002	(POPD08-611/PR3009B)-7-3-1-4-1-3-21-3	Mali	ICRISAT
V6	ICSB 176016	(POPD08-611/02-SB-F5DT-12B)-11-1-5-2-5-4-14-3	Mali	ICRISAT
V7	12B	B line	Mali	ICRISAT
V8	ICSB 176031	(POPD08-611/02-SB-F5DT-12B)-11-5-2-9-8-4-9-7	Mali	ICRISAT
V9	ICSB 176001	(POPD08-611/PR3009B)-7-3-1-1-6-3-19-8	Mali	ICRISAT
V10	SAMSORG 45	R line	Nigeria	Institute for Agricultural Research (IAR)
V11	ISS 455	R line	Mali	ICRISAT
V12	ICSV 1360964	[GPN01 S01-267-9-3-1-4-sibvr//(Sambalma(4)/GPN01 S01 267-9-3-1-7)]-5-2-1-1	Mali	ICRISAT
V13	Mamba	SS07(MadouM)Ban-13-v-5-Balla Berthe-v	Mali	ICRISAT
V14	SAMSORG 3	R line	Nigeria	Institute for Agricultural Research (IAR)
V15	Grinkan	R line	Mali	Institutd'EconomieRurale (IER)
V16	Niobougouma	R line	Mali	Institutd'EconomieRurale (IER)
V17	015-SB-CS-F7-127	R line	Mali	Institutd'EconomieRurale (IER)
V18	Seguifa	MALISOR 92-1	Mali	Institutd'EconomieRurale (IER)

V19	Diamadjigui	R line	Mali	Institutd'EconomieRurale (IER)
V20	SARIASO14	R line	Burkina Faso	Institut de l'Environnement et de Recherches Agricoles (INERA)
V21	019-SB-CS-AVANCE-22	R line	Mali	Institutd'EconomieRurale (IER)
V22	Tiandougou Coura	04-SB-F5DT-105	Mali	Institutd'EconomieRurale (IER)
V23	Sariaso 16	R line	Burkina Faso	Institut de l'Environnement et de Recherches Agricoles (INERA)
V24	Lata 3	R line	Mali	ICRISAT
V25	ICSV 206056	(Tiandougou Coura/015-CS-SB-BC1F1-15)-B-SS1-SS1-7-2-2	Mali	ICRISAT
V26	ICSV 111	[(SPV 35 x E35-1) x CS 3541]	Mali	ICRISAT
V27	ISS 3187	R line	Mali	ICRISAT
V28	BC36-080	GR/(GR/SC566-14) BC1F3:5-BC36-080	Mali	Institutd'EconomieRurale (IER)
V29	ICSV 206084	(Narichita/PI 639719 02 SD)-B-SS1-SS1-3-1-3	Mali	ICRISAT
V30	SAMSORG 49	R line	Nigeria	Institute for Agricultural Research (IAR)
V31	Soubatimi	Check	Mali	ICRISAT
V32	Jakumbè	Check	Mali	ICRISAT

2.3. Methodology:-

2.3.1. Experimental Design

The trial was conducted using a randomized complete block design (RCBD) with a two-factor factorial arrangement: water regime and genotype. The experiment was carried out in two distinct environments, namely a control (well-watered) environment and a water-stressed environment, each comprising three replicate blocks. The 32 sorghum genotypes were sown in November to avoid the water stress period coinciding with rainfall. Each genotype was sown on an experimental plot 3.6 m long, consisting of 10 hills spaced 0.4 m apart. The plots consisted of a single row with an inter-row spacing of 0.8 m. Genotypes were randomly assigned within each block and replicate.The two water treatments (normal irrigation and water stress) were separated by a 10 m buffer to prevent accidental irrigation of stressed plots. For the control treatment, plants were irrigated twice a week with 25 mm per irrigation until physiological maturity. In contrast, for the water-stressed treatment, irrigation was withheld for one month starting from 45 days after sowing (DAS). After this stress period, optimal irrigation was resumed until physiological maturity, following Gano et al. (2021). In total, 350 mm of water were applied to plants under water stress, compared to 550 mm for well-watered plants.Field management was limited to fertilization and weeding. Fertilization followed the recommendations of the National Agricultural Research Institute of Benin (INRAB), with 100 kg/ha of NPK applied 14 days after sowing, followed by 50 kg/ha of urea applied at 45 DAS. Weeding was carried out as needed.

2.3.2. Collected Data:

Meteorological Data

The automatic weather station at CRA-PP Pobè, located near the experimental site, was used to continuously record the climatic variables necessary for characterizing water stress. Measured variables included air temperature (Temp, in °C), relative humidity (RH, in %), solar radiation (Rad, in $W \cdot m^{-2}$), rainfall (Pluv, in mm), and wind speed (Vent, in $m \cdot s^{-1}$).

Soil Moisture Monitoring

Soil moisture was monitored using two complementary tools: piezometers and a multifunction digital soil tester (Sonkir MS02). In each experimental block, three piezometers were installed at strategic locations to ensure representative measurements of soil moisture conditions. Each piezometer was installed vertically to a depth of 1.20 m. These devices allowed tracking of soil moisture changes at different times during the experiment,

particularly during the water stress period. Measurements were taken daily to assess deep soil moisture and evaluate the effects of water deficit on the soil moisture profile.

Additionally, the multifunction digital soil tester was used for spot measurements of surface soil moisture (topsoil layer), temperature, and pH. This device features a backlit LCD screen with digital readout, allowing simultaneous display of the three parameters.

Morphological Parameters:
Morphological traits of the plants were measured weekly after the induction of water stress on five tagged plants per plot. Evaluated parameters included the number of leaves emerged (NFA), collar diameter (DAC, in cm), and plant height (HP, in cm). The number of dried leaves (NFD) was recorded at the end of the stress period. Specific leaf area (SLA, in $cm^2 \cdot g^{-1}$) was determined from the last ligulated leaf by dividing its leaf area by its dry biomass.

Physiological parameters:
Physiological parameters were measured at the end of the water stress period, always on the last ligulated leaf, using the portable photosynthesis system ADC BioScientificLCpro-SD. Measurements included: photosynthetic capacity (A, in $\mu mol \cdot m^{-2} \cdot s^{-1}$), leaf temperature (Tleaf, in °C), transpiration (E, in $mmol \cdot m^{-2} \cdot s^{-1}$), and stomatal conductance (gs, in $mol \cdot m^{-2} \cdot s^{-1}$). Additionally, leaf water potential (Ψf, in MPa) was measured for each genotype and irrigation regime using a pressure chamber (model 3005F01) between 2:00 and 6:00 a.m. Values were recorded in bars and then converted to megapascals (1 bar = 0.1 MPa). The classification of Kramer & Boyer (1995) and Blum (2010) (Table 3) was used to assess levels of water stress according to the leaf water potential (Ψf) values of the different genotypes under each irrigation regime.

Tableau 3: Classification of water stress levels based on leaf water potential (Ψf):

Value of Ψf (MPa)	Drought stress level
–0.1 to –0.5	No stress / well-watered
–0.5 to –1.0	Mild to moderate stress
–1.0 to –1.5	Moderate to severe stress
< –1.5 to –2.5	Severe stress
< –2.5	Very severe / critical stress

Phenological Parameters
Phenological observations were conducted on each genotype to assess the impact of water stress on the duration of developmental phases. Collected data included: the date of first flowering (DAPF, in days after sowing), the date of 50% flowering (D50%F, in days after sowing), the date of 100% flowering (D100%F, in days after sowing), and the date of physiological maturity (DM, in days after sowing).

Yield Parameters
Yield components were measured after panicle drying. The following variables were recorded: - Panicle length (LP, in cm), - Panicle width (lP, in cm), - Panicle weight (PP, in g), - Grain yield per hectare (RDT, in t/ha).

Calculation of Drought Tolerance and Sensitivity Indices

a) Recovery Index after Stress (IDR):
The Recovery Index (IDR) was used to assess the physiological capacity of genotypes to recover after water stress, according to Strauss et al. (2006) and Oukarroum et al. (2007). Formula: $IDR = \log A + 2 \log B$, where A is the stressed/control ratio at the end of stress, and B is the same ratio two weeks after rewatering.

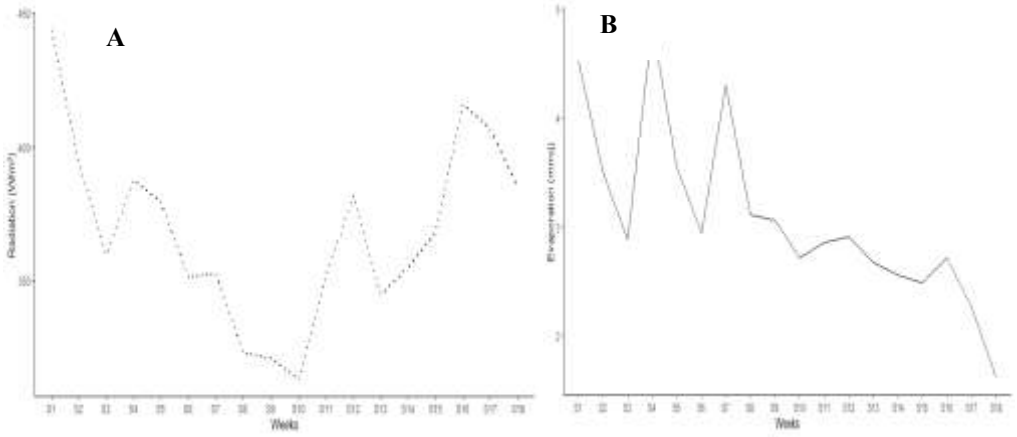
b) Stress Intensity Index (SI):
$SI = 1 - (RDT\_str / RDT\_etm)$, with RDT_str = mean yield under stress conditions and RDT_etm = mean yield under normal conditions. The closer SI is to 1, the more severe the stress.

c) Stress Susceptibility Index (SSI):
$SSI = [1 - (RDT\_str / RDT\_etm)] / SI$, where RDT_str is the yield of each genotype under water stress, RDT_etm is the yield under normal conditions, and SI is the stress intensity. Genotypes with $SSI < 1$ are considered tolerant, while those with $SSI \geq 1$ are considered sensitive.

d) Stress Tolerance Index (STI):
STI = (RDT_str × RDT_etm) / (RDT_m)², where RDT_str = yield of genotype x under water stress, RDT_etm = yield under normal conditions, and RDT_m = mean yield of the trial under normal conditions. Higher STI values indicate greater tolerance and productivity.

2.3.3. Statistical Analysis
An analysis of variance (ANOVA) was performed for each measured parameter to test statistical differences among genotypes within the same water regime, between different water regimes, and for their interactions. In addition, a combined ANOVA was conducted following the method recommended by McIntosh (1983) to assess genotype × water regime interactions across the data from both environments. The homogeneity of residual variances was verified using Bartlett's test (1937). When the data did not meet the assumptions of homogeneity or normality, a non-parametric analysis was carried out using the Kruskal-Wallis test to detect significant differences between treatments. Treatment means were compared at a probability threshold of 5% ($p < 0.05$). Furthermore, a principal component analysis (PCA) was conducted to explore multivariate relationships among the measured traits. The R packages used for these multivariate analyses were FactoMineR and factoextra. All statistical analyses were carried out using R software (version 4.x).

3. Results:-
3.1. Evolution of weather conditions during the experiment.
The evolution of climatic conditions during the experiment is presented in Figure 1. Solar radiation (Figure 1A) shows a daily variation ranging from 10 W/m²/day to about 430 W/m²/day. The highest increases in radiation were recorded at the beginning of the experiment, followed by a gradual decline reaching minimum values around the 10th week, before progressively rising again towards the end. Evaporation (Figure 1B) follows a similar trend, with values ranging from 2 mm/day to about 0.5 mm/day. The highest evaporation rates were observed between the 1st and 10th weeks of the experiment, before gradually decreasing towards the last weeks. Relative humidity (Figure 1C) fluctuated between 60% and 80% at 8 a.m., between 20% and 40% at 1 p.m., and between 40% and 60% at 6 p.m. Lower values, dropping to around 30%, were recorded between the 1st and 10th weeks of the experiment, before progressively increasing towards the end. Air temperature (Figure 1D) oscillated around 35 °C for the maximum and around 15–20 °C for the minimum.



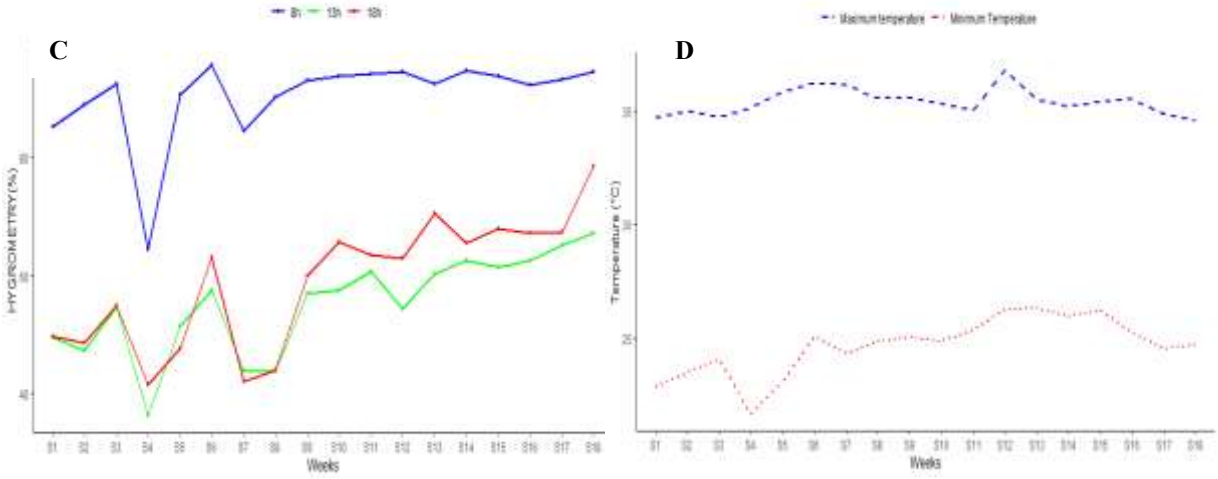


Figure 1:Evolution of solar radiation (A), evaporation (B), relative humidity (C), and air temperature (D) during the experiment

.3.2. Evolution of soil moisture, pH, and temperature during the experiment

The evolution of the edaphic parameters measured during the experiment is presented in the figure. Soil moisture, measured through piezometers placed at a depth of 1.20 m (Figure 2A), shows variations between 0 and 0.5 cm, indicating the presence or absence of moisture at this depth. The analysis of this figure reveals that in the control plot (non-stressed), water levels ranging from 0.2 to 0.5 cm were recorded throughout the entire experimental period, highlighting a permanent presence of soil moisture. In contrast, in the stressed plot, values of 0 cm were recorded between the 9th and 13th week, indicating the absence of soil moisture. This period corresponds to the stress treatment (cessation of irrigation). Soil pH (Figure 2B) ranged between 6 and 6.3 in the control plot and between 6 and 6.8 in the stressed plot during the experimental period. Soil temperature (Figure 2C) varied between 15 °C and 34 °C in both plots, except for an increase recorded between the 7th and 14th week in the stressed plot.

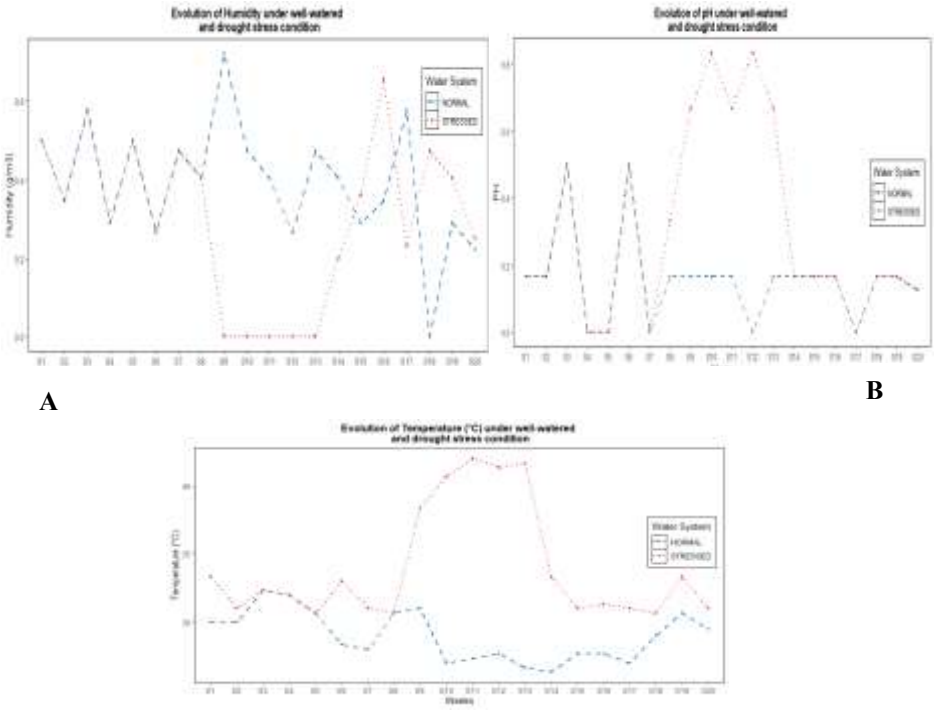


Figure 2:Evolution of soil moisture (A), pH (B), and temperature (C) during the experiment

3.4. Response of genotypes' leaf water potential under irrigation regimes.

Table 4: Response of leaf water potential of genotypes under different irrigation regimes

Genotypes	ds		ww		ΔWS
	Ψf (MPa)	Stress level	Ψf (MPa)	Stress level	ΔWS
V1	0.93	Moderate	0.16	No stress	5
V2	1.18	Moderate	0.2	No stress	4.89
V3	1.28	Severe	0.1	No stress	11.78
V4	0.91	Moderate	0.18	No stress	4.13
V5	1.01	Severe	0.17	No stress	5.07
V6	1.09	Severe	0.13	No stress	7.17
V7	1.53	Severe	0.11	No stress	12.8
V8	0.99	Moderate	0.11	No stress	7.9
V9	1.54	Severe	0.13	No stress	10.58
V10	1.28	Severe	0.1	No stress	11.78
V11	0.89	Moderate	0.11	No stress	7
V12	0.92	Moderate	0.1	No stress	8.22
V13	1.16	Severe	0.13	No stress	7.67
V14	1.79	Severe	0.19	No stress	8.47
V15	1.08	Severe	0.21	No stress	4.11
V16	0.72	Moderate	0.13	No stress	4.42
V17	1.03	Severe	0.13	No stress	6.75
V18	1.76	Severe	0.1	No stress	16.56
V19	1.78	Severe	0.13	No stress	12.33
V20	1.41	Severe	0.14	No stress	8.77
V21	1.3	Severe	0.1	No stress	12
V22	0.98	Moderate	0.1	No stress	8.78
V23	4.84	Very Severe	0.13	No stress	35.33
V24	1.14	Severe	0.17	No stress	5.87
V25	1.4	Severe	0.12	No stress	10.45
V26	1.88	Severe	0.1	No stress	17.78
V27	3.53	Very Severe	0.12	No stress	27.91
V28	0.68	Moderate	0.1	No stress	5.78
V29	0.59	Moderate	0.13	No stress	3.42
V30	2.67	Very Severe	0.13	No stress	19
V31	0.94	Moderate	0.14	No stress	5.54
V32	1.61	Severe	0.1	No stress	15.11
Overall Main	1.4325	Severe	0.13125	No stress	
Genotype	ns	-	ns	-	-
E	***	-		-	-
GxE	ns	-		-	-

Ψf: Leaf water potential; ds: Water-stress regime; ww: Well-watered regime; ΔWS: Percentage of variation due to stress; ***: significance at p = 0.001; **: significance at p = 0.01; ns: not significant, E: environment; G: genotypes.

The Table 4 presents the leaf water potential (Ψf) of the 32 evaluated sorghum genotypes. Analysis of this table indicates a highly significant difference ($p < 0.001$) in leaf water potential between the two water regimes. Under well-watered conditions (ww), all genotypes exhibited an average Ψf of −0.13125 MPa, indicating no water stress. In contrast, under water-stress conditions (ds), Ψf values ranged from −0.59 MPa to −4.84 MPa, reflecting varying levels of stress among genotypes. Specifically, genotypes V1, V2, V4, V8, V11, V12, V16, V22, V28, V29, and V31 experienced moderate stress (Ψf between −0.59 MPa and −0.99 MPa), whereas V3, V5, V6, V7, V9, V10, V13, V14, V15, V17, V19, V20, V21, V24, V25, V26, and V32 were severely affected (Ψf between −1.00 MPa and −1.88 MPa). These genotypes, although showing marked physiological responses to drought, remain within tolerance limits compared to V23, V27, and V30, which recorded the highest stress levels (Ψf below −2.00 MPa).

3.5. Effect of water stress on the agro-physiological traits of sorghum evaluated under well-watered and water-stress conditions

Table 5: Statistical parameters and mean performance of agro-physiological traits of sorghum evaluated under well-watered and water-stress conditions.

Parameters	ds	ww	ΔWS	Significatively
HP	144.18	182.60	- 21.04	***
NFA	13.21	13.21	0	ns
DAC	18.4	19.66	- 6.41	ns
NFD	5.8	2.78	108.63	***
SLA	145.90	121.71	19 87	***
DAPE	65.29	64.93	0.55	ns
DM	100.79	101.17	-0.3	ns
RDT	1610.68	3045.03	- 47.10	***
gs	0.06	0.08	- 25	***
A	12.68	14.73	- 13.91	***
E	2.53	4.24	- 40.33	***
Tleaf	42.34	39.69	6.67	***

ds: Stressed condition; ww: Well-watered condition; ΔWS: Percentage variation due to stress; *** significance at $p = 0.001$; ** significance at $p = 0.01$; ns: not significant; NFA: Number of leaves emerged; DAC: Stem diameter (mm); HP: Plant height at maturity (cm); NFD: Number of dried leaves at the end of stress; SLA: Specific leaf area of the last ligulated leaf ($cm^2 \cdot g^{-1}$); A: Photosynthetic capacity ($\mu mol \cdot m^{-2} \cdot s^{-1}$); Tleaf: Leaf temperature (°C); E: Transpiration ($mmol \cdot m^{-2} \cdot s^{-1}$); gs: Stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$); DAPF: Days to first flowering (days after sowing); DM: Days to physiological maturity (days after sowing); RDT: Grain yield (t/ha).

Comparative analysis of the agro-physiological parameters of sorghum evaluated under well-watered (ww) and water-stress (ds) conditions reveals significant effects of water stress on several traits (Table 5, Figure 3). Plant height at maturity (HP) significantly decreased under stress, with a 21 % reduction (144.18 cm vs. 182.60 cm; ***). This trend is confirmed by the height development throughout the vegetative cycle (Figure 3C), where stressed plants exhibit lower growth. In contrast, the number of leaves emerged (NFA) showed no significant difference, indicating that water stress did not affect initial leaf development (Figure 3A). Similarly, stem diameter (DAC) slightly decreased by 6 % under stress, but this reduction was not statistically significant (Figure 3B).

Moreover, the number of dried leaves (NFD) strongly increased under stress, from 2.78 to 5.8 leaves, representing a 108 % rise (***), reflecting pronounced foliar desiccation due to water deficit. Specific leaf area (SLA) increased significantly by nearly 20 % (145.90 $cm^2 \cdot g^{-1}$ vs. 121.71 $cm^2 \cdot g^{-1}$; ***), suggesting morphological adjustments of leaves in response to stress. Phenological traits, including days to first flowering (DAPE) and physiological maturity (DM), showed no significant differences between the two regimes, indicating that water stress did not affect the plant development cycle.Regarding physiological performance, water stress caused a significant decrease in stomatal conductance (gs) by 25 % (0.06 vs. 0.08 $mol \cdot m^{-2} \cdot s^{-1}$; ***), photosynthetic capacity (A) by 13 % (12.68 vs. 14.73 $\mu mol \cdot m^{-2} \cdot s^{-1}$; ***), and transpiration (E) by 40 % (2.53 vs. 4.24 $mmol \cdot m^{-2} \cdot s^{-1}$; ***). Consequently, leaf temperature (Tleaf) increased significantly by 6 % under stress (42.34 °C vs. 39.69 °C; ***), reflecting reduced cooling via transpiration. Grain yield (RDT) was drastically reduced by 47 % under water stress (1610.68 kg/ha vs. 3045.03 kg/ha; ***).

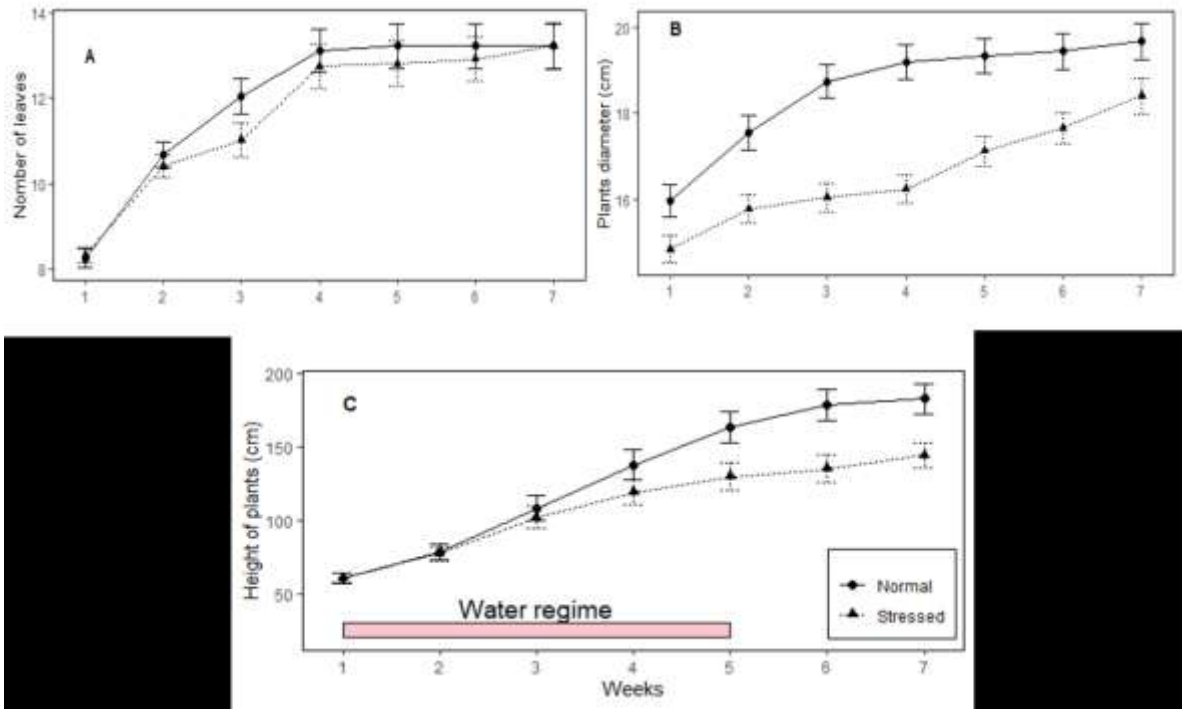


Figure 3: Changes in Number of Leaves (A), Stem Diameter (B), and Plant Height (C) under Well-Watered and Water-Stress Conditions.

Table 6: Drought Recovery Index (IDR) of Sorghum Genotypes for Plant Height, Stem Diameter, and Number of Leaves Emerged

Genotypes	IDR_ Height	IDR_ Diameter	IDR NFA	Codes	IDR_ Height	IDR_ Diameter	IDR_ NFA
V1	-0.45	-0.08	0.03	V17	-0.38	-0.09	-0.06
V2	-0.24	-0.06	0.02	V18	-0.35	-0.13	-0.05
V3	-0.40	-0.10	0.00	V19	-0.46	-0.06	-0.03
V4	-0.22	-0.18	-0.04	V20	-0.22	0.13	-0.21
V5	-0.24	-0.09	0.04	V21	-0.17	-0.14	-0.10
V6	-0.25	0.19	0.00	V22	-0.25	-0.08	0.06
V7	-0.51	-0.11	0.06	V23	-0.05	-0.28	0.04
V8	-0.29	-0.10	0.05	V24	-0.06	-0.12	-0.01
V9	-0.57	-0.23	-0.04	V25	-0.54	-0.16	-0.04
V10	-0.12	0.01	-0.13	V26	-0.25	-0.06	0.06
V11	-0.45	-0.25	0.02	V27	0.04	-0.06	-0.10
V12	-0.19	-0.20	0.00	V28	-0.81	-0.44	-0.15
V13	-0.29	-0.12	0.05	V29	-0.33	-0.07	-0.06
V14	-0.35	-0.04	0.07	V30	-0.10	-0.07	0.00
V15	-0.31	-0.15	0.05	V31	-0.38	-0.12	-0.04
V16	-0.38	-0.08	-0.12	V32	-0.36	-0.17	0.12

NFA: Number of emerged leaves; DRI: Drought Recovery Index

Table 6 presents the Drought Recovery Index (DRI), calculated according to the formula of Oukarroum et al. (2007) on plant height, stem diameter, and the number of emerged leaves of the different genotypes. DRI values close to zero indicate a good recovery capacity, whereas values near −1 indicate poor recovery. Considering plant height, DRI values range from −0.81 (V28) to 0.04 (V27), with the majority of genotypes showing

negative values, reflecting partial or limited recovery after stress. However, several genotypes exhibit relatively good recovery, notably V27 (0.04), V23 (−0.05), V24 (−0.06), and V10 (−0.12). In contrast, genotypes V28 (−0.81), V9 (−0.57), and V25 (−0.54) show very low recovery for plant height.Regarding stem diameter, DRI values are generally negative, except for V6 (0.19), V20 (0.13), and V10 (0.01), which exhibit positive recovery. The lowest values are observed in V28 (−0.44), V11 (−0.25), and V23 (−0.28), indicating poor recovery for this trait. Conversely, several genotypes show DRI values close to zero or slightly positive for the number of emerged leaves (NFA), indicating good recovery of leaf activity after stress for genotypes V32 (0.12), V14 (0.07), V22, V7, V26 (0.06), and V8, V13, V15 (0.05).

3.7. Variability of physiological adaptation performances of the different genotypes under well-watered and water-stress conditions.

Table 7: Physiological performance of the different genotypes evaluated under well-watered and water-stress conditions.

Genotypes	Tleaf			E			gs			A			SLA		
	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS
V1	41.5	40.58	-2.20	2.98	3.57	-16.66	0.06	0.07	-16.83	14.03^{abcde}	12.97	8.21	155.15	124.19	24.92
V2	41.82	40.22	-3.84	2.98	3.65	-18.39	0.07	0.07	-6.01	13.73^{abcde}	14.76	-7.02	143.00	166.45	-14.09
V3	43.08	39.28	-8.82	2.26	4.63	-51.20	0.05	0.09	-45.51	10.71^{ef}	14.73	-27.31	170.64	104.47	63.33
V4	40.19	39.12	-2.66	2.11	3.62	-41.76	0.05	0.1	-52.39	11.45^{bcdef}	14.15	-19.09	145.66	130.47	11.64
V5	43.67	40.02	-8.35	2.94	5.14	-42.82	0.07	0.1	-31.90	14.06^{abcde}	14.03	0.25	178.64	147.44	21.16
V6	42.3	40.24	-4.86	2.70	4.14	-34.84	0.06	0.08	-30.54	12.88^{abcdef}	12.15	5.98	145.27	96.38	50.72
V7	43.49	39.24	-9.78	1.83	4.00	-54.34	0.04	0.07	-38.80	9.84^{f}	14	-29.69	178.10	92.96	91.59
V8	39.96	40.24	0.69	2.22	3.68	-39.63	0.05	0.09	-49.89	11.05^{cdef}	13.65	-19.08	161.36	115.42	39.81
V9	42.16	39.39	-6.56	2.65	4.67	-43.33	0.06	0.1	-36.55	12.7^{abcdef}	16.01	-20.64	104.31	137.17	-23.96
V10	41.06	38.07	-7.28	2.65	3.92	-32.39	0.07	0.08	-12.84	14.38^{abc}	15.66	-8.21	167.28	104.63	59.88
V11	43.23	40.73	-5.80	2.78	4.64	-40.07	0.06	0.09	-33.80	12.59^{abcdef}	14.41	-12.63	135.54	99.54	36.17
V12	41.88	40.45	-3.42	2.52	3.72	-32.25	0.05	0.07	-35.21	12.23^{abcdef}	15.82	-22.73	194.92	95.69	103.71
V13	41.28	40.06	-2.94	2.36	3.21	-26.45	0.05	0.06	-23.16	12.25^{abcdef}	15.23	-19.57	186.60	148.34	25.79
V14	42.12	41.72	-0.9	2.77	4.01	-30.	0.05	0.08	-36.	11.88^{abcdef}	14.96	-20.	149.11	146.65	1.68

			4			82			69			54				
V15	42.25	39.97	-5.39	2.91	3.79	-23.43	0.07	0.07	0.85	14.47^{ab}	11.87	21.85	129.65	130.09	-0.33
V16	43.23	38.83	-10.18	2.56	5.03	-49.14	0.06	0.1	-32.56	13.6^{abcde}	16.48	-17.49	144.99	140.37	3.29
V17	42.09	36.53	-13.21	1.93	4.36	-55.68	0.06	0.09	-37.19	12.3^{abcdef}	12.76	-3.58	151.05	124.93	20.91
V18	44.16	41.39	-6.28	2.67	4.46	-40.21	0.05	0.08	-34.64	10.88^{def}	16.7	-34.83	153.54	106.87	43.67
V19	42.91	40.79	-4.95	2.99	3.71	-19.20	0.06	0.07	-3.33	12.65^{abcdef}	15.56	-18.74	139.12	143.75	-3.23
V20	42.71	37.84	-11.40	1.92	5.42	-64.60	0.05	0.11	-55.88	11.96^{abcdef}	15.59	-23.33	116.74	109.18	6.93
V21	42.72	38.42	-10.07	2.65	4.32	-38.70	0.07	0.08	-14.30	14.91^{a}	16.02	-6.94	115.00	102.94	11.72
V22	42.16	38.68	-8.27	2.22	4.31	-48.40	0.05	0.09	-41.82	11.43^{bcdef}	14.75	-22.54	153.67	115.17	33.43
V23	44.1	40.06	-9.16	2.14	4.34	-50.56	0.04	0.07	-40.43	11.61^{abcdef}	14.85	-21.87	166.24	133.24	24.77
V24	41.26	41.19	-0.18	3.01	2.59	16.15	0.06	0.05	21.15	13.76^{abcde}	12.91	6.60	109.78	102.38	7.23
V25	43.28	40.51	-6.40	2.56	5.45	-53.13	0.05	0.11	-48.16	14.6^{ab}	16.05	-9.04	140.47	137.30	2.31
V26	41.58	39.57	-4.83	2.72	3.94	-31.05	0.06	0.08	-24.58	14.16^{abcd}	14.94	-5.21	104.10	120.93	-13.92
V27	42.38	39.12	-7.68	2.43	3.31	-26.66	0.06	0.06	-3.20	11.61^{abcdef}	13.66	-15.01	123.32	96.21	28.18
V28	43.51	40.98	-5.82	2.74	6.23	-56.00	0.06	0.12	-51.93	12.9^{abcdef}	15.8	-18.34	124.95	135.86	-8.03
V29	42.53	39.95	-6.07	2.61	3.92	-33.39	0.05	0.08	-27.31	12.33^{abcdef}	15.71	-21.51	130.15	103.91	25.25
V30	41.56	39.19	-5.70	2.18	4.71	-53.72	0.05	0.1	-50.70	12.57^{abcdef}	14.66	-14.22	128.68	98.63	30.47
V31	42.17	38.33	-9.10	2.53	3.78	-33.15	0.06	0.07	-12.87	13.49^{abcde}	14.49	-6.94	169.29	133.11	27.19
V32	42.63	39.29	-7.82	2.51	5.37	-53.33	0.06	0.11	-47.20	12.76^{abcdef}	15.91	-19.76	152.46	150.11	1.56
Overall Mean	42.34	39.69	-	2.53	4.24	-	0.06	0.08		12.68	14.73		124.15	121.71	
Genotype	ns	ns		ns	ns		ns	ns		***	ns		ns	ns	

E		***		***			***			***			***		
GxE		---		----			---			***			---		

ds: stressed regime; ww: well-watered regime; ΔWS: percentage change due to stress; *** significance at p = 0.001; ** significance at p = 0.01; ns: not significant; SLA: specific leaf area of the last fully expanded leaf ($cm^2 \cdot g^{-1}$); A: photosynthetic capacity ($\mu mol \cdot m^{-2} \cdot s^{-1}$); Tleaf: leaf temperature (°C); E: transpiration ($mmol \cdot m^{-2} \cdot s^{-1}$); gs: stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$); E: environment; G: genotypes. Means sharing the same letter are not significantly different.

Table 7 presents the physiological performances of the different genotypes evaluated for drought tolerance. Analysis of this table reveals a highly significant difference between the different water regimes for the physiological parameters studied ($p < 0.001$). Under well-watered conditions, genotypes V24, V15, and V1 stand out for their high performance in terms of photosynthesis (A), stomatal conductance (gs), and transpiration (E), whereas V3, V7, and V20 exhibit lower values. Under water-stress conditions, most genotypes showed a marked reduction in photosynthesis, stomatal conductance, and transpiration. However, V1, V15, and V24 displayed an increase in photosynthetic capacity under stress, in contrast to V3, V7, V18, and V20, which showed greater reductions (up to −35%). Regarding specific leaf area (SLA), some genotypes exhibited a marked increase in response to stress: V12 (+103.7%), V7 (+91.6%), and V6 (+50.7%). Conversely, V2, V26, and V9 experienced a decrease in leaf area.

3.8. Variability of morphological performance of the different genotypes under well-watered and water-stress conditions

Table 8: Morphological performance of the different genotypes evaluated under well-watered and water-stress conditions

Genotypes	HP			DAC			NFA			NFD		
	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS
V1	123.2^{fg} hijk	175.93^{d} efghi	-29.97	18.13^{bc} defgh	18.93^{d} efg	-4.23	14.67^{a} bcde	14.33 bcd	2.33	5.67^{a} bcd	2.33^{c} def	142.86
V2	122.8^{hijk}	148.4^{ijkl}	-17.25	18.65^{bc} defgh	18.83^{d} efg	-0.97	12.33^{hijklm}	12^{ghij}	2.78	6a^{bcd}	2.33^{c} def	157.14
V3	125.53 ghijk	171.43^{f} ghij	-26.77	17.47^{cd} efghi	18.57^{d} efgh	-5.92	13^{fghij}	13^{efgh}	0.00	7.33^{a}	2^{def}	266.67
V4	105.03^{jk}	127.37^{kl}	-17.54	17.02^{de} fghi	19.27^{d} efg	-11.68	13.33^{ef} ghij	13.67 cdef	-2.44	5^{cde}	2.33^{c} def	114.29
V5	117.13^{i} jk	144.36^{ij} kl	-18.86	23.47^{a}	24.3^{ab}	-3.43	15.33^{a} bc	14.67 abc	4.55	5.33^{c} de	2^{ef}	166.67
V6	127.49^{f} ghijk	155.33^{h} ijkl	-17.93	20.98^{ab} cde	17.73^{e} fgh	18.30	14^{cdefgh}	14^{cde}	0.00	7.33^{a}	3.67^{a} bc	100.00
V7	113.27^{i} jk	169.97^{g} hij	-33.36	17.53^{cd} efghi	18.7^{def} gh	-6.24	14.33^{b} cdef	13.67 cdef	4.88	6.67^{a} b	3^{abcdef}	122.22
V8	112.86^{jk}	145.92^{jkl}	-22.65	20.69^{ab} cd	22.17^{a} bcde	-6.64	15.33^{a} bc	14.67 abc	4.55	6.67^{a} b	2d^{ef}	233.33
V9	153.87^{a} bcde	228.11^{a} b	-32.	20.6^{ab}	23.83^{a} bc	-13.	15^{abc}	15^{abc}	0.00	5^{cde}	2.33^{c} def	114.29

			55			55						
V10	177.72[a] bc	195.73[b] cdefg	-9.20	16.61[hi]	16.18[f] gh	2.69	9.33[mn]	10.33 ijk	-9.68	5[de]	1.67[f]	200.00
V11	144.03 defgh	200.49[a] bcde	-28.16	16[hi]	19.02[d] efg	-15.89	12.67[g] hijkl	12.33 ghij	2.70	5[de]	2.67[b] cdef	87.50
V12	177.8[ab] cd	205.72[a] bcd	-13.57	17[ghi]	19.5[def] g	-12.82	12.33[ij] klm	12.33 fghi	0.00	7.33[a]	3.33[a] bcde	120.00
V13	158.82[a] bcde	199.43[b] cdef	-20.37	20.48[ab]	21.98[a] bcde	-6.82	15.67[a] b	14.67 abc	6.82	5.33[b] cde	2.67[b] cdef	100.00
V14	132.4[efg] hij	172.13[ef] ghij	-23.08	18.2[bcdefg] h	18.67[d] efgh	-2.50	12.67[gh] ijk	12[ghij]	5.56	6.33[a] bc	4[ab]	58.33
V15	171.8[abc] d	219.2[abc]	-21.62	19.67[abcd]	21.8[abc] de	-9.79	16.33[a]	15.67[a]	4.26	5.33[b] cde	5[a]	6.67
V16	151.47[b] cde	206.9[abcd]	-26.79	20.27[ab]	21.2[bcd] e	-4.40	13.33[de] fghi	14.67[ab] c	-9.09	5.33[c] de	3[abcde]	77.78
V17	179.27[a] bc	222.93[ab]	-19.59	20.4[ab]	21.2[bcd] e	-3.77	15.33[ab] c	15.67a	-2.13	6.33[a] bc	3[abcdef]	111.11
V18	147.07[c] def	192.1[bcde] fg	-23.44	17.87[bcde] fgh	19.27[d] efg	-7.27	11.33[jkl] mn	11.67[g] hijk	-2.86	5.67[b] cde	2[def]	183.33
V19	127.33[f] ghijk	184.45[de] fgh	-30.97	20.09[abc]	20.57[b] cdef	-2.32	14.33[bc] def	14.67abc	-2.27	5[de]	2.33[cd] ef	114.29
V20	138[efghi]	164.67[hijk]	-16.19	17.13[efghi]	15.27[g] h	12.23	9.67[lmn]	11.33hijk	-14.71	6.67[a] b	3.33[ab] cd	100.00
V21	117[ijk]	147ijkl	-20.41	21.27[abcd] ef	23[abcd]	-7.54	14[cdefg]	14.33[bc] d	-2.33	4.67[b] cde	3.33[ab] cde	40.00
V22	145.47[c] defg	173.58[de] fghij	-16.20	19.42[abcd] ef	20.23[b] cdef	-4.01	14[cdefg]	13.33[de] fg	5.00	5[bcde]	2[def]	150.00
V23	147.05[c] defg	154.13[ijk] l	-4.60	12.2i	14.67[h]	-16.82	8[n]	7.67[k]	4.35	7[a]	1.67[f]	320.00
V24	192.13[a] b	204.57[bc] defg	-6.08	16.87[fghi]	18.28[ef] gh	-7.75	14[cdefg]	14[cde]	0.00	6[abcd]	3.33[ab] cde	80.00
V25	137.75[ef] ghi	197.47[bc] de	-30.24	17.43defghi	19.07[d] efg	-8.57	14[cdefgh]	14.33[bc] d	-2.33	5[de]	2[ef]	150.00
V26	154.2[abc] de	185.69[cd] efgh	-16.96	18.8[abcdefg]	19.91[c] def	-5.58	12.67[gh] ij	12[ghij]	5.56	5.67[b] cde	2.33[cd] ef	142.86
V27	190.27[a]	185.8[defgh]	2.40	14.27i	14.6[h]	-2.28	9.33[mn]	9.67[jk]	-3.45	7.67[a]	3.67[ab] c	109.09
V2	79.61[k]	145.33[ijk]	-	18.39[bcde]	25.33[a]	-	12.33[hij]	13.67[cd]	-	3.67[d]	2.67[bc]	37.5

8		^{l}	45.22	^{fgh}		27.41	^{klm}	^{ef}	9.76	^{e}	^{def}	0
V29	146.53^{c} ^{defg}	183.6^{defgh}	-20.19	19.95^{abcd} ^{efg}	20.62^{b} ^{cdef}	-3.26	15^{abc}	15.67^{a}	-4.26	3.67^{e}	2.33^{cd} ^{ef}	57.14
V30	109.93^{jk}	118.4^{l}	-7.20	17.27^{defg} ^{hi}	17.93^{ef} ^{gh}	-3.72	10^{klmn}	10^{ijk}	0.00	6.67^{a} ^{b}	3^{abcde}	122.22
V31	143.58^{d} ^{efgh}	195.53^{bc} ^{def}	-26.57	17.07^{fghi}	18.37^{ef} ^{gh}	-7.08	15^{abc}	15.33^{ab}	-2.17	5.67^{b} ^{cde}	3.33^{ab} ^{cd}	70.00
V32	243.47^{a} ^{bcde}	321.53^{a}	-24.28	17.67^{ghi}	20.28^{b} ^{cdef}	-12.90	14^{abcd}	12.33^{g} ^{hij}	13.51	6.67^{a} ^{b}	4.33^{ab}	53.85

Overall Mean	144	182.60	-0.21	18.4	19.66	-0.06	13.21	13.21	0	5.8	2.78	1.09
Genotypes	***	***		***	***		****	***		***	***	
E	***									***		
GxE	0.99477		0.99875				1.000			0.99581		

ds: water-stress condition; ww: well-watered condition; ΔWS: percentage change due to stress; *** significance at p = 0.001; ** significance at p = 0.01; ns: not significant; NFA: number of leaves emerged at maturity; DAC: stem diameter (mm); HP: plant height at maturity (cm); NFD: number of dried leaves at the end of stress; E: Environment; G: Genotype. Means sharing the same letter are not significantly different.

Table 8 presents the morphological performance of the different genotypes evaluated under well-watered (ww) and water-stress (ds) conditions. The results show highly significant differences between the water regimes for the main morphological parameters measured: plant height, stem diameter, number of leaves emerged, and number of dried leaves ($p < 0.001$). Moreover, genotypes displayed statistically significant differences for all parameters within the same water regime ($p < 0.001$).Under well-watered conditions, genotypes V32, V24, V17, and V12 exhibited the highest plant heights: 321.53 cm, 204.57 cm, 222.93 cm, and 205.72 cm, respectively. In contrast, V28, V30, and V4 showed the lowest heights, representing small-sized genotypes (less than 1.5 m). Regarding stem diameter, V28 displayed the highest value (25.33 mm) under well-watered conditions, while several genotypes, such as V23, V10, and V27, showed lower diameters.In terms of the number of leaves emerged, V15, V5, and V13 stood out with the highest leaf counts, indicating a good foliar development capacity, whereas V10, V20, and V23 had the lowest values. Water stress caused a reduction in plant height, stem diameter, and number of leaves emerged in most genotypes. However, some genotypes showed atypical responses: for example, V27 exhibited a slight height increase (+2.40%), and V20 showed a stem diameter increase (+12.23%), suggesting possible morphological adaptation strategies.Regarding the number of dried leaves, a generalized increase was observed in nearly all genotypes under water stress. The largest increases were recorded in V23 (+320%), V3 (+266.67%), V8 (+233.33%), and V10 (+200%), indicating high sensitivity to water stress. Conversely, V15 demonstrated marked tolerance, with only +6.67% of dried leaves.

3.9. Variability of Agronomic Performance of the Different Genotypes under Well-Watered and Water-Stress Conditions.

Table 9: Agronomic Performance of the Different Genotypes Evaluated under Well-Watered and Water-Stress Conditions.

Genotypes	LP			lP			PP			RDT		
	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS	ds	ww	ΔWS
V1	33.89 abc	38.67 abcde	-12.36	6.17 bcdefghij	8.89 abcd	-30.63	36.11 cdefghijk	63 cdefg	-42.68	1576.39 bcdefghij	2694.44 efghijk	-41.49
V2	31.44 abcdefgh	33.17 cdefghi	-5.19	6.78 abcd	6.78 bcd	0.00	29.33 ghijk	31.94 i	-8.17	1131.94 ghijk	1281.25 m	-11.65
V3	30 abcdefgh	35.56 abcdefg	-15.63	7.17 abcd	8.06 abcd	-11.03	36.33 bcdefghijk	60.89 defgh	-40.33	1354.17 defghijk	2486.11 efghij	-45.53
V4	30.72 abcdefgh	34.89 abcdefg	-11.94	5.44 fghij	7.33 abcd	-25.76	28.06hijk	44.44 ghi	-36.88	1031.25 ijk	2097.22 ijklm	-50.83
V5	27.44 abcdefgh	33.67 cdefghi	-18.48	5.61 efghij	7.67 abcd	-26.81	26.33 ijk	63.78 bcdefg	-58.71	888.89 jk	2743.06 cdefghi	-67.59
V6	34.89 ab	40.89 ab	-14.67	6.11 cdefghij	6.94 bcd	-12.00	30.89 ghijk	49ghi	-36.96	1229.17 fghijk	1986.11 ijklm	-38.11
V7	32 abcdefg	36.56 abcdef	-12.46	6.5 abcdefgh	8.22 abcd	-20.95	30.33 ghijk	57.11 efghi	-46.89	1055.56 hijk	2631.94 fghijkl	-59.89
V8	33.33 abcde	41.89 a	-20.42	6.11 cdefghij	8.11 abcd	-24.66	28 hijk	66.78 bcdefg	-58.07	1062.5 ijk	2923.61 defghi	-63.66
V9	31.33 abcdefgh	41.44 a	-24.40	4.78 j	6.22 cd	-23.21	21.89 jk	62.33 bcdefg	-64.88	937.5 jk	3055.56 cdefghi	-69.32
V10	25.78 abcdefgh	24.44 kl	5.45	6.28 abcdefghi	6.78 bcd	-7.38	60.44 a	40.56 ghi	49.04	2694.44 abc	1590.28 cdefghi	-12.37
V11	23.67 cdefgh	27.33 hijkl	-13.41	5.61 defghij	7.39 abcd	-24.06	41.44 abcdefghi	65.44 bcdefg	-36.67	1888.89 abcdefghi	3013.89 cdefghi	-37.33
V12	33.06 abcde	34.33 bcdefgh	-3.72	7.33 abc	7.78 abcd	-5.71	46.22 abcdefgh	51.78 fghi	-10.73	1812.5 ghijk	1569.44 jklm	-23.89
V13	24.22 bcdefgh	32.44 defghij	-25.34	7.11 ab	10.22 a	-30.43	51.89 abcdef	87.78 abcd	-40.89	2201.39 abcd	3854.17 abcdefg	-42.88
V14	22.78 cdefgh	24.44 kl	-6.82	5.22 ghij	5.78 d	-9.62	31.72 efghijk	38.78 hi	-18.19	1447.92 cdefghij	1520.83 klm	-4.79
V15	32.56 abcdef	40 abc	-18.61	7.56 a	8.78 abcd	-13.92	56.89 abc	93.22 abcd	-38.97	2381.94 ab	4555.56 abc	-47.71
V16	29.11 j abcdefgh	33.33 cdefghi	-12.67	7.44ab	8.67abcd	-14.10	57.44 ab	78.78 abcdef	-27.08	1993.06 abcdefghi	3736.11 abcdefgh	-46.65
V17	33.67 abcd	39.33 abcd	-14.41	7 abc	10 ab	-30.00	53.11 abcde	94.22 abcd	-43.63	2145.83 abcdef	4451.39 abcd	-51.79
V18	23.11 cdefgh	26.11 ijkl	-11.49	6.22 bcdefghij	7.39 abcd	-15.79	48.67 abcdefghi	82.89 abcde	-41.29	2187.5 abcdefgh	3284.72 bcdefghi	-33.40
V19	25.11 abcdefgh	29.11 ghijkl	-13.74	7.06abc	8.44 abcd	-16.45	42.89 abcdefghi	93.11 ab	-53.94	1833.33 abcdefghi	4861.11 ab	-62.29

ds: Water-stress regime; ww: Well-watered regime; ΔWS: Percentage change due to stress; ***: significance at p = 0.001; **: significance at p = 0.01; ns: not significant; LP: panicle length (cm); - lP: panicle width (cm); PP: panicle

V20	26.78 cabcdefgh	25.39 jkl	5.47	6.5 abcdefg	6.83 bcd	-4.88	52.56 abcde	54.11 efghi	-2.87	2347.22 abcde	2201.39 ghijklm	-6.21
V21	22.22 iefgh	26.33 ijkl	-15.61	5.5 efghij	6.89 bcd	-20.16	35.33 efghijk	53.44 ghi	-33.89	902.78 jk	2465.28 ijklm	-63.38
V22	25.44 abcdefgh	33 cdefghi	-22.90	6.56 abcdef	8.33 abcd	-21.33	42.67 abcdefghi	109.11 a	-60.90	2118.06 abcde	5625 a	-62.35
V23	25.67 abcdefgh	26.33 ijkl	-2.53	5.83 defghij	6.78 bcd	-13.93	32.44 fghijk	51.44 ghi	-36.93	1312.5 efghijk	2423.61 ijklm	-45.85
V24	35.56 a	38.56 abcde	-7.78	6.78 abcdef	7.67 abcd	-11.59	35.78 defghijk	56.33 efghi	-36.49	1305.56 efghijk	2131.94 ijklm	-38.76
V25	24.67 abcdefgh	30.56 fghijk	-19.27	6.17 bcdefghij	8.22 abcd	-25.00	38.78 abcdefghij	91.67 abcd	-57.70	1756.94 abcdefghi	4625 abcd	-62.01
V26	23.61 cdefgh	24.11 kl	-2.07	6.33 bcdefghij	7.22 abcd	-12.31	55.44 abcd	82.33 abcde	-32.66	2611.11 a	4166.67 abcde	-37.33
V27	21.78 fgh	21.94 l	-0.76	5ij	5.61 d	-10.89	27.56 hijk	34.22 i	-19.48	1118.06 hijk	1236.11 m	-9.55
V28	22.5 idefgh	31.61 efghij	-28.82	5.06 hij	9.17 abc	-44.85	19.17 k	88.78 abc	-78.41	611.11 k	3916.67 abcdef	-84.40
V29	20.33 h	26.67 ijkl	-23.75	7 abcde	8.67 abcd	-19.23	55.44 abcdefg	100.89 a	-45.04	2562.5 abcde	4951.39 ab	-48.25
V30	21.78 fgh	21.89 l	-0.51	6 cdefghij	6.06 cd	-0.92	44.44 abcdefghi	53.56 fghi	-17.01	2097.22abcdef	2361.11 hijklm	-11.18
V31	20.89 gh	27.33 hijkl	-23.58	6.39 abcdefgh	8.44 abcd	-24.34	41.89 abcdefghi	86.11 abcd	-51.35	2090.28 abcdefg	4305.56 abcd	-51.45
V32	30.67 defgh	32.22 defghij	-4.83	6.67 abcd	7.78a bcd	-14.29	23.44 cdefghijk	35.67 i	-34.27	902.78 jk	1388.89 lm	-35.00
Overall Mean	27.50	31.67	-0.13	6.29	7.72	-0.19	39.47	66.36	-0.41	1643.45	3004.23	-0.45
Genotypes	***	***		***	***		***	***		***	***	
E										***		
GxE	0.00479***			0.118			0.000322***			3.84e-5***		

weight (g); RDT: grain yield (t/ha); E: Environment; G: Genotype. Means sharing the same letter are not significantly different.

Table 9 presents the agronomic performance results of the different sorghum genotypes evaluated under both well-watered and water-stress conditions. Statistical tests revealed highly significant differences ($p < 0.001$) between the two water regimes for all traits studied. Additionally, a significant interaction was observed between genotypes and water regimes for most parameters, reflecting a wide diversity of responses to stress. Under well-watered conditions, several genotypes exhibited excellent performance, such as V22 (yield: 5625 kg/ha), V25 (4625 kg/ha), V15 (4555.56 kg/ha), V17 (4451.39 kg/ha), and V31 (4305.56 kg/ha). In contrast, some genotypes like V27, V30, and V1 showed yields below 2500 kg/ha.Under drought condition, agronomic performance dropped markedly. On average, grain yield decreased from 3004.23 to 1643.45 kg/ha, representing a loss of over 45%. Similarly, panicle

weight declined by nearly half (−40% on average). However, genotypic responses were not uniform. Some genotypes, such as V10, V20, and V30, showed minimal variation due to drought, maintaining yields close to the control even under stress. Their panicle weights, well above average, further confirm their resilience under stressful conditions. Conversely, other genotypes, including V9, V8, V5, and V21, experienced substantial yield reductions, in some cases exceeding 60%.

3.10. Drought Stress Tolerance Analysis Based on STI and SSI Indices in the Evaluated Sorghum Genotypes

Table10: Drought Stress Tolerance and Susceptibility Indices of the Studied Genotypes

Codes	SSI	STI	Codes	SSI	STI
V1	0.881	0.458	V17	1.100	1.030
V2	0.247	0.156	V18	0.709	0.775
V3	0.967	0.363	V19	1.322	0.961
V4	1.079	0.233	V20	0.132	0.557
V5	1.435	0.263	V21	1.346	0.240
V6	0.809	0.263	V22	1.324	1.285
V7	1.272	0.300	V23	0.973	0.343
V8	1.351	0.335	V24	0.823	0.300
V9	1.472	0.309	V25	1.316	0.876
V10	0.263	0.715	V26	0.793	1.173
V11	0.792	0.614	V27	0.203	0.149
V12	0.507	0.202	V28	1.792	0.258
V13	0.910	0.915	V29	1.024	1.368
V14	0.102	0.237	V30	0.237	0.534
V15	1.013	1.170	V31	1.092	0.971
V16	0.990	0.803	V32	0.743	0.135

STI (Stress Tolerance Index).SSI (Stress Susceptibility Index)

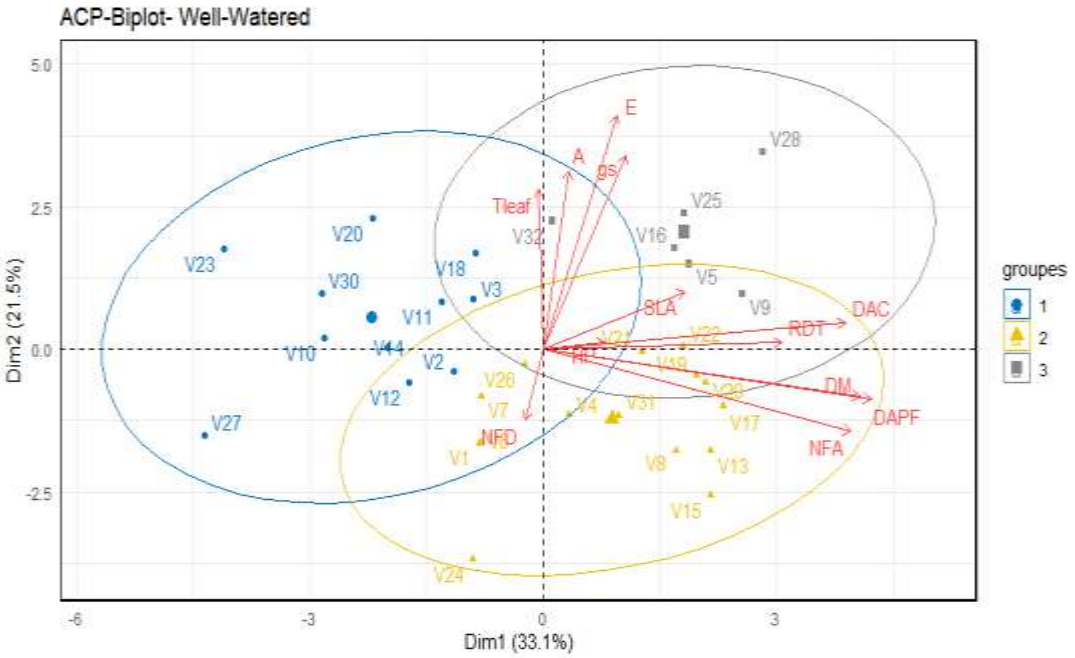
Table 10 presents drought tolerance indices, specifically the Stress Susceptibility Index (SSI) and the Stress Tolerance Index (STI) for the 32 evaluated genotypes. The joint analysis of these two indices allowed the discrimination of genotypes based on their performance under water-stress conditions.The SSI measures a genotype's sensitivity to stress: a value below 1 indicates good tolerance, whereas a value above 1 indicates high sensitivity. The STI evaluates the ability of a genotype to maintain high productivity under stress: a value above 1 reflects good performance under both normal and stressed conditions.Cross-interpretation of these two indices allows the classification of genotypes as follows: only genotype V26 (SSI = 0.793; STI = 1.173) combines both drought tolerance (SSI < 1) and excellent agronomic performance (STI > 1). This genotype stands out as the most promising in the study, capable of maintaining high yield under drought, and is thus a prime candidate for breeding programs in arid environments.In contrast, genotypes V2, V6, V10, V11, V12, V14, V16, V18, V24, V30, and V32, although drought-tolerant (SSI < 1), exhibit low production potential (STI ≤ 1). This limits their direct value for production, but they can still serve as valuable genetic resources for improving crop resilience.Additionally, the group comprising genotypes V22, V29, and V15 shows drought sensitivity (SSI > 1) but demonstrates good productive capacity (STI > 1). These genotypes, while sensitive to drought, possess high potential yield, making them suitable for environments with low water constraints or for crosses aiming to combine yield and tolerance.Finally, genotypes V5, V7, V8, V9, V21, V23, V25, and V28 are the most negatively affected by drought, showing both high SSI and low STI values. These genotypes are unsuitable for environments with high water stress.

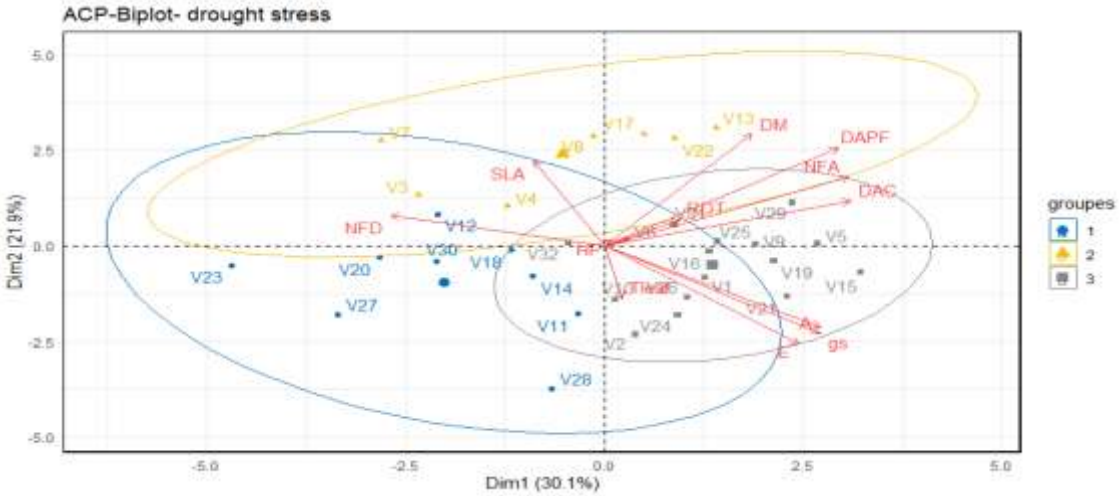
3.12. Principal Component Analysis of Agro-Physiological Traits Revealing Sorghum Genotype Grouping Under Well-Watered and drought Conditions.

Under well-watered conditions (Figure4 :PCA–Well-Watered), the first two principal components (PCs) explained 54.6% of the total observed variability and allowed the classification of genotypes into three distinct groups. Group 1 (blue cluster) comprised genotypes V2, V3, V10, V11, V12, V14, V18, V20, V23, and V30. These genotypes were characterized by high leaf temperature but a relatively low number of dried leaves. Group 2 (green cluster), including genotypes V1, V4, V7, V8, V13, V15, V17, V19, V21, V22, V24, V26, and V29, was associated with

fewer dried leaves and better agronomic performance (grain yield and stem diameter). In contrast, Group 3 (red cluster) gathered the best-performing genotypes in terms of physiological traits (V5, V9, V16, V25, V28, and V32).

Under drought conditions(Figure4 :PCA–drought-stress), the first two axes (Dim1 and Dim2) explained 52% of the total variance, also allowing the identification of three groups. Group 1 (blue cluster) consisted of genotypes V11, V12, V14, V18, V20, V23, V27, V28, and V30, distinguished by a high number of dried leaves and high specific leaf area. Group 2 (green cluster) included genotypes V3, V4, V7, V8, V13, V17, and V22, characterized by long vegetative cycles (days to first flowering and physiological maturity). Conversely, Group 3 (red cluster) represented the most productive genotypes in terms of grain yield, panicle width, plant height, stem diameter, and number of leaves (V1, V5, V9, V10, V15, V16, V19, V21, V24, V26, and V29).Regarding correlations among variables, under well-watered conditions, physiological parameters (stomatal conductance, photosynthetic capacity, transpiration, and specific leaf area) were positively associated with grain yield, whereas the number of dried leaves was negatively correlated with yield. By contrast, under water-stress conditions, grain yield was negatively correlated with leaf temperature.





NFA: Number of leaves emerged; **DAC:** Stem base diameter (mm); **HP:** Plant height at maturity (cm); **NFD:** Number of dried leaves at the end of stress; **SLA:** Specific leaf area of the last ligulated leaf ($cm^2 \cdot g^{-1}$); **A:** Photosynthetic capacity ($\mu mol \cdot m^{-2} \cdot s^{-1}$); **Tleaf:** Leaf temperature (°C); **E:** Transpiration ($mmol \cdot m^{-2} \cdot s^{-1}$); **gs:** Stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$); **DAPF:** Days to first flowering (days after sowing); **DM:** Days to physiological maturity (days after sowing); **RDT:** Grain yield (t/ha).

Discussion:-

The increasing climatic constraints in the Sahelian and Sudanian-Sahelian zones, characterized by early droughts and shortened rainy seasons, deeply affect sorghum cultivation. This climatic instability highlights the need to adapt breeding systems, particularly by targeting sensitive stages such as panicle initiation, a key moment for yield formation (Abreha et al., 2022; Tovignan et al., 2016). The study showed that genotypes differ markedly in their ability to cope with water stress at such a critical stage. These differences are not only reflected in yield losses but also in fine physiological responses that may serve as a basis for breeding. For instance, some tested genotypes were able to maintain a relatively high leaf water status despite moderate to severe stress conditions. This maintenance suggests the activation of mechanisms such as early stomatal closure, reduced transpiration, or deeper rooting. These mechanisms are well described in the literature as classical strategies to limit water losses (Blum, 2010; Lehrer et al., 2025). In the present study, these responses translated into better leaf integrity, with fewer dried leaves in certain genotypes (e.g., V1, V2, or V28). These observations confirm that the ability to maintain leaf water potential is a relevant marker for varietal screening, as also demonstrated by Chen et al. (2020).

In parallel, the analysis of gas exchange highlighted differentiated behaviors among genotypes. Some, despite water

Figure 4:Principal Component Analysis of the Agro-Physiological Parameters of 32 Genotypes Evaluated under Normal Conditions (PCA–Well-Watered) and Water-Stress Conditions (PCA–drought-stress)

constraints, maintained relatively stable photosynthesis and transpiration rates. This could be explained by partial rather than complete stomatal closure, allowing a compromise between water conservation and carbon assimilation. This phenomenon is consistent with the findings of Lopez et al. (2017), who showed that moderate reduction in transpiration without excessive impairment of photosynthesis can enhance tolerance. For example, genotypes V1 and V24 exhibited good photosynthetic stability, suggesting fine stomatal regulation and potentially a leaf architecture favorable to water-use efficiency. Conversely, other genotypes (such as V18 or V20) showed a sharp decline in photosynthesis and transpiration, indicating greater sensitivity.From a morphological standpoint, the observed reduction in plant height under stress represents a well-known adaptive response aimed at limiting transpiring surface area.

This reduction, around 21% in the present study, is consistent with the findings of Somfalvi-Tóth et al. (2024), who reported that severe water stress induces a halt in cell elongation. However, stem diameter was relatively unaffected, which could indicate a redistribution of resources toward maintaining the basic structural integrity of the plant. This suggests that some genotypes adopt “prioritization” strategies, reducing certain functions (vertical growth) to preserve others (structural stability), as noted by Tovignan et al. (2023).In terms of leaf growth, several genotypes (V32, V14, V22, V7, V26, and V8, V13, V15) showed an ability to continue or resume leaf production immediately after the stress period. This behavior, reflected by a slightly positive leaf recovery index in some genotypes, corresponds to a form of resilience already identified by Gano et al. (2021) as a key selection criterion. They showed that, despite constraints, certain varieties can restart their vegetative apparatus and potentially sustain the recovery of photosynthesis. However, it should be noted that these adaptive responses were not sufficient to offset yield losses. The present study reported an average grain yield reduction of nearly 47%, consistent with declines ranging from 36 to 87% reported by de Souza et al. (2021) and Sanjari et al. (2021) under similar conditions.

This significant loss indicates that, although tolerance mechanisms contribute to survival and vegetative recovery, they do not necessarily safeguard reproductive function. This finding is particularly relevant for late-maturing varieties, whose delayed development exposes them to the premature end of the rainy season (Guan et al., 2015; Sultan et al., 2013). Late genotypes, although physiologically more robust, no longer benefit from the climatic window required for their full cycle.These results underline the need for a new integrated breeding strategy. Relying solely on classical physiological criteria (such as transpiration or stomatal conductance) is no longer sufficient; it is imperative to incorporate specific reproductive traits such as flowering stability, effective panicle number, and grain

filling. Sabadin et al. (2012b) and Kapanigowda et al. (2013b) also emphasize the importance of these traits in ensuring stable yields under drought conditions. Therefore, combining morpho-physiological and reproductive data, coupled with genetic and molecular analysis, represents a promising pathway toward the identification of new, more resilient sorghum genotypes.

5. Conclusion:-

The study revealed marked inter-genotypic variability in sorghum responses to water stress, both in agro-morphological and physiological traits. Genotype V26, in particular, stood out for its ability to maintain high yield under water deficit conditions, combining a low stress susceptibility index (SSI < 1) with a high stress tolerance index (STI > 1). This profile positions it as a priority candidate for breeding programs targeting areas with severe water constraints. Principal component analysis also identified distinct groups of genotypes according to their adaptive profiles, confirming the relevance of an integrated approach that considers the diversity of adaptation strategies: avoidance, tolerance, or a combination of both. These findings emphasize the importance of integrating agro-physiological traits, tolerance indices (SSI, STI), and multivariate analyses for the selection of genotypes adapted to water stress conditions.

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Data Availability Statement: All the data used to support the findings of the study are available within the research article.

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