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Article

Evaluating Drought Recovery Responses in Sorghum: Insights into Genotypic Variation and Adaptation

Samuel Ssebulime ^{1,2,3,*}, Ephraim Nuwamanya ¹, Ronald Kakeeto ², Emmanuel Opolot ⁴, Ephraim Echodu ², Herbert Ochan Alinaitwe ^{1,2}, Loyce Migamba ^{1,2}, Moses Biruma ^{2,5} and Scovia Adikini ²

¹ Department of Crop and Horticultural Sciences, Makerere University, P. O. Box 7062, Kampala, Uganda

² National Agricultural Research Organization; National Semi-Arid Resources Research Institute (NaSARRI), P. O. Box 56, Soroti-Uganda

³ Rural Development Administration; National Institute of Agricultural Sciences, 166, Nongsaengmyeong-ro, Iseo-myeon, Wanju-gun, Jeollabuk-do 55365, Republic of Korea

⁴ Department of Soil Science and Land Use Management, Makerere University, P. O. Box 7062, Kampala, Uganda

⁵ National Agricultural Research Organization; Abi Zonal Agriculture Research and Development Institute, P.O.Box 219, Arua, Uganda

* Correspondence: ssebulimesamuel1@gmail.com

Abstract

In Uganda, rain-fed crops frequently encounter cycles of drought stress followed by rewatering. Thus, with escalating fluctuations in water supply, drought recovery has become a critical focus for future sorghum drought phenotyping, genetics, and breeding research. However, there is currently a low level of inquiry into the drought recovery potential of prospective genotypes in Uganda's National Sorghum Improvement Program. The present study aimed to assess the response of selected genotypes to rewatering after drought. Sixteen sorghum genotypes and two check lines were evaluated under two contrasting moisture regimes: well-watered and drought stress-rewatering in a split-plot layout embedded within a randomized complete block design (RCBD). Watering regimes were assigned to whole plots, while sorghum genotypes were assigned to subplots, with three replications. Results showed highly significant effects ($P < 0.05$) of drought stress on key agronomic traits, decreasing dry weight, grain weight, and biomass yield by 39%, 43% and 37%, respectively, while delaying flowering by an average of 11 days. Key genotype-specific traits associated with drought recovery included rapid rehydration, compensatory growth, and maintenance of high chlorophyll content, all of which were essential for optimizing yields after stress. Leveraging stress tolerance indices, genotypes were classified into four distinct groups (A-D) based on their yield performance and stability under the two watering regimes. Genotypes in category A demonstrated high yield stability and strong recovery potential. Conversely, genotypes in category D exhibited the poorest recovery response. Overall, the information generated from this study will support local sorghum breeding efforts for drought tolerance.

Keywords: drought; recovery; indices; sorghum; watering; regime; stress

1. Introduction

Climate models predict increasingly frequent and severe rainfall fluctuations, prompting growing interest in exploring crop recovery potential as a strategy to maintain stable agricultural productivity amid changing climatic conditions [1–3]. These unpredictable patterns of alternating drought and rainfall events create significant risks for crop productivity, especially in areas vulnerable to water scarcity [4]. In Uganda, where rain-fed agriculture predominates [5], this

vulnerability is especially acute. Staple crops such as sorghum (*Sorghum bicolor*), essential for both food and income security, face considerable challenges [6,7].

Sorghum's inherent drought tolerance has made it a resilient crop in arid and semi-arid regions of Uganda [8,9]. However, its long-term productivity under fluctuating water conditions depends not only on its drought resistance but also on its ability to recover once water becomes available. While extensive research has focused on drought tolerance, avoidance, and escape mechanisms [10–12], the physiological and growth responses of sorghum to rehydration and their implications for productivity remain comparatively understudied [13,14]. Recovery from drought involves processes such as water uptake, leaf re-expansion, photosynthetic restoration, and biomass accumulation, all of which play a crucial role in maintaining yield stability [14,15].

In Uganda, the National Sorghum Improvement Program has largely prioritized resistance mechanisms (namely, tolerance, avoidance, and escape), assessing genotype performance under random drought scenarios typical of Target Production Environments (TPEs), such as the Karamoja region. Although this approach has yielded valuable insights into drought resistance, limited attention has been given to how sorghum genotypes recover once water availability is restored [14]. Yet, understanding recovery-related traits is essential for developing more resilient sorghum varieties, particularly in the context of climate change. Evaluating genotypic variation in drought recovery responses presents a promising opportunity to enhance breeding programs. By identifying genotypes with superior recovery potential, researchers can equip breeders with reliable indicators for selecting drought-resilient crops. Traits related to post-drought growth, physiological resilience, and yield recovery can serve as critical selection criteria for developing varieties suited to variable water conditions [16].

This study aimed to evaluate the recovery responses of selected sorghum genotypes following drought stress, focusing on growth, physiological traits, and yield parameters after rehydration. We hypothesized that significant variation would exist among genotypes in these traits, providing valuable insights into genetic adaptation mechanisms. The findings will contribute to the development of sorghum varieties with enhanced drought resilience, supporting food security in vulnerable regions.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted at the National Semi-Arid Resources Research Institute (NaSARRI)-Serere. Serere is located at 1°39'N and 33°27'E and has an elevation of 1038m above sea level. The native soils are sandy, with low water holding capacity and limited organic matter content, typical of a semi-arid environment. The area experiences a bimodal type of rainfall, with an annual mean of 1427 mm and wide inter-annual fluctuations. The mean annual temperature is 24°C, with a minimum of 17.9°C and a maximum of 34.4°C. The relative humidity ranges between 72% and 84% [17].

2.2. Planting Materials

This study evaluated a diverse set of sorghum genotypes selected from the breeding program based on their prior performance under random drought conditions. A total of 16 genotypes and 2 checks were used to assess their drought recovery potential. The checks were chosen based on farmer preference and documented performance. NAROSORGH 4, known for its strong drought resistance traits [18], served as the positive check, while ETEREMA, a more susceptible local landrace, was the negative check. The selected genotypes represented a spectrum of resistance levels, ranging from highly resistant to moderately resistant and susceptible (Table 1).

Table 1. The 18 sorghum genotypes used in the study.

	Genotype	Source & Origin	Resistance level	FLWD
1	ICSX162719-1-4-1-1-1	ICRISAT-Kenya	Resistant	64
2	ICSX152666-B-2-7-3-1-1-1	ICRISAT- Kenya	Resistant	66
3	SSGA/RAP/349	L.V (Karamoja)-Ug	Resistant	64
4	ASARECA13-1 x Framida -1-1-3-1/22B	B.L (NaSARRI)-Ug	Resistant	69
5	NAROSORGH1x NAROSORGH3-1-1-5-1/22B	B.L (NaSARRI)-Ug	Resistant	60
6	ASARECA13-1 x NAROSORGH3-1-1-1-1/22B	B.L (NaSARRI)-Ug	Resistant	63
7	ASARECA13-1x NAROSORGH3-1-1-5-1/22B	B.L (NaSARRI)-Ug	Resistant	60
8	NAROSORGH4 (positive check)	Variety-Ug	Resistant	62
9	MAZDA 105 Enyankore	L.V (Masindi)-Ug	Mod.	60
10	NAROSORGH1x FRAMIDA-1-1-5-1/22B	B.L (NaSARRI)-Ug	Mod.	61
11	NAROSORGH1xNAROSORGH1-1-1-1-1 /22B	B.L (NaSARRI)-Ug	Mod.	60
12	ICSX 152005-SB-5-3-2-1	ICRISAT- Kenya	Mod.	63
13	ETEREMA (negative check)	L.V (Teso)-Ug	Susceptible	61
14	NAROSORGH1x NAROSORGH3-1-1-1-1/22B	B.L (NaSARRI)-Ug	Susceptible	62
15	IESV 214006DL	ICRISAT- Ethiopia	Susceptible	66
16	ICSV 142001	ICRISAT- India	Susceptible	59
17	GE16/2/20B x IESV92041SH (SEA 18B#6)	B.L (NaSARRI)-Ug	Susceptible	64
18	IESV16 143-1-3-1	Ethiopia	Susceptible	60

FLWD: Days to 50% flowering, Mod: Moderately, L.V: Land race variety, B.L: Breeding line, Ug: Uganda.

2.3. Experimental Setup and Management

The experiment was conducted in a screen house at NaSARRI, following a split-plot arrangement within a completely randomized block design (RCBD). The two main treatments (whole plots) were well-watered and drought stress-rewatering treatments. Each whole plot was subdivided into 18 subplots (sorghum genotypes), with each genotype replicated three times.

The soil used in the pots was sourced from the experimental station's fields and enriched with fully decomposed organic manure. Sowing was carried out on April 13, 2024, by placing three pairs of seeds equidistantly in 5-litre pots. Two weeks later, at the 3-leaf stage, thinning was performed to retain the three most vigorous seedlings in each pot, which were maintained up to physiological maturity.

Manual weeding was performed, and irrigation was managed according to the specified watering regimes. For the well-watered regime, pots were irrigated every two days (at a rate of 1 litre per pot) until the plants reached physiological maturity. Under the drought stress-rewatering regime, plants received regular irrigation until May 23, 2024; 36 days after emergence (at the panicle development stage), after which irrigation was withheld for 10 consecutive days to impose drought stress. This duration was chosen to induce substantial drought stress in the pots without causing plant death. After this drought period, plants were fully irrigated again until they grew and reached physiological maturity (Figure 1).

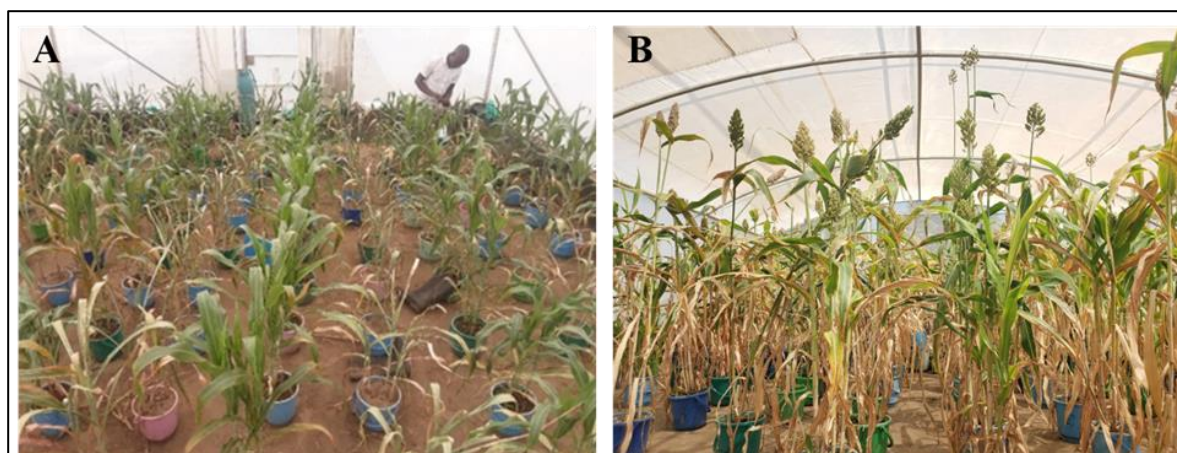


Figure 1. Visual comparison of sorghum plants under different watering treatments: (A) 7 days during drought stress; (B) 25 days after rewatering. Plants exposed to drought stress are shown alongside well-watered controls.

2.4. Data Collection

Data were collected at four-day intervals during both the drought stress period and the recovery phase, which extended up to 15 days after rewatering. Key parameters measured included: leaf length, leaf width and internode length assessed using a 30cm ruler on all three plants within each pot. Plant height was measured using a 2.5 m wooden ruler, while leaf angle was determined as the angle between the stem and the second fully expanded leaf using a geometry protractor. Meanwhile, chlorophyll content and stem diameter were measured using a SPAD chlorophyll meter and a Digital Vernier Caliper 0-150mm, respectively. Leaf rolling (1–5), wax density (1–3), and drought recovery (1–5) were assessed, with lower scores indicating more favourable traits. The drought recovery scores were assigned at two time points: 12 hours and 15 days after rewatering. This study further employed the Drought Recovery Index (DRI) [19,20] to assess agro-physiological traits, including plant height, stem diameter, internode length, and chlorophyll content. The DRI was computed using the formula $DRI = \log (A) + 2 \log (B)$ [20], where A denotes the relative trait value measured at the end of the drought period, and B represents the relative trait value measured two weeks after rewatering. The relative trait values were computed as follows:

Relative Trait Value =

$$\frac{\text{Mean trait value in drought stress-rewatering at point } i}{\text{Mean trait value in well watered conditions at point } i}$$

where i represents either measurement point A or B. At physiological maturity, panicle length, panicle width and panicle exertion were also measured using a 30cm ruler. Yield traits, including grain yield harvested from the pot, grain weight after threshing and 100-seed weight, were measured after drying using a kitchen weighing scale SF-400. To obtain the above-ground biomass yield, all three plants were cut at the soil level after harvesting the panicles, dried at 70°C in an oven for 3 days, and then weighed using the same weighing scale. The harvest index was calculated as the ratio of grain yield to total aboveground biomass, expressed as a percentage (%).

2.5. Statistical Analyses

Statistical analyses were performed following the procedure described by [21]. The collected data were entered into Microsoft Excel spreadsheets, summarised, and saved as comma-delimited (CSV) files, then imported into R software (version 4.3.1) [22] for all the statistical analyses. Homogeneity of variances and normality of the residuals were tested using the Shapiro–Wilk test. The collected data were then analysed through a general analysis of variance (ANOVA) using a generalized linear model, implemented with the lmerTest package [23], to assess statistical

differences among genotypes and their interactions with the watering regime. Principal component analysis (PCA) based on the correlation matrix was performed using the `prcomp()` function from R's base stats package. The eigenvectors derived from the PCA were used to identify the variables that had a strong relationship with a specific principal component. The PC biplot was then generated using the `ggbiplot` package in R [24] to describe and group sorghum genotypes based on their response to drought and rewatering. Yield improvement and stability are the ultimate goals of any breeding program. Tolerance/Resistance indices were calculated following the methodology outlined by [25] and analysed using the `Hmisc` package [26] to assess their correlations with each other and with grain yield under both stress-recovery and well-watered conditions. Indices showing strong correlations with grain yield in both conditions were considered key predictors of genotypic drought recovery responses.

3. Results

3.1. Effect of Drought Stress and Rewatering on Biomass Yield and Yield-Related Traits

Drought stress caused notable reduction in key yield traits, with dry weight dropping by 39% and grain weight by 43% relative to well-watered plants. Additionally, biomass yield decreased by 37%, and time to reach 50% flowering was delayed by an average of 11 days (Figure 2).

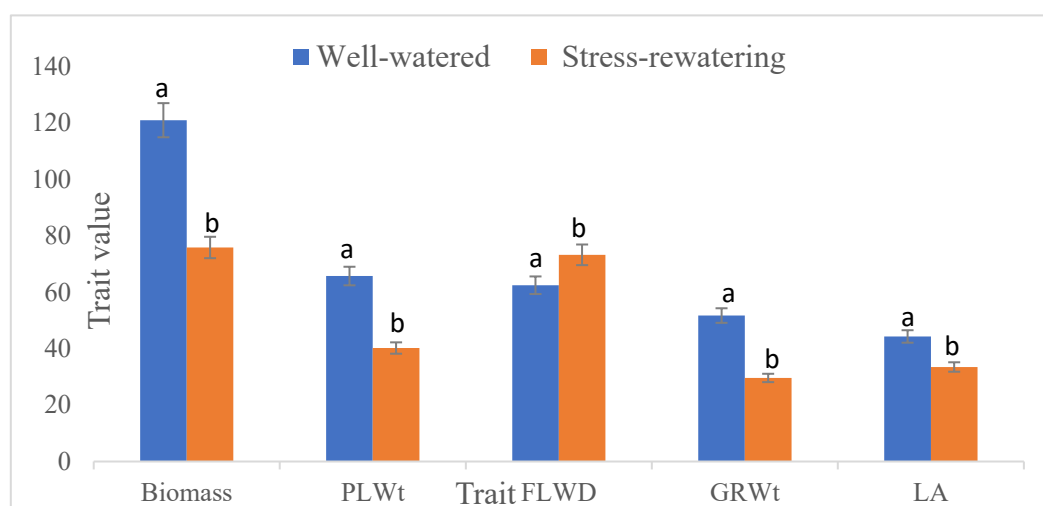


Figure 2. Average performance of selected phenological, physiological and yield traits under drought stress-rewatering and well-watered conditions. Mean values are shown for each treatment. PLWt: Dry weight harvested from a pot, FLWD: Days to 50% flowering, GRWt: Grain weight after threshing, LA: Leaf angle.

3.2. Variation in Drought Recovery Responses Among Sorghum Genotypes Based on Plant Height (PLH), Chlorophyll Content (CHL), Stem Diameter (SD) and Internode Length (INTL)

Figure 3 illustrates the variation in sorghum genotypes' responses during drought stress and recovery phases. Drought stress caused reductions in chlorophyll content and stem diameter during stages 1-4 of treatment (T), and declines in plant height and internode length during stages 1-3 (T). However, following rewatering beyond these stages, these traits exhibited greater variability among genotypes during the recovery phase compared to the stress period.

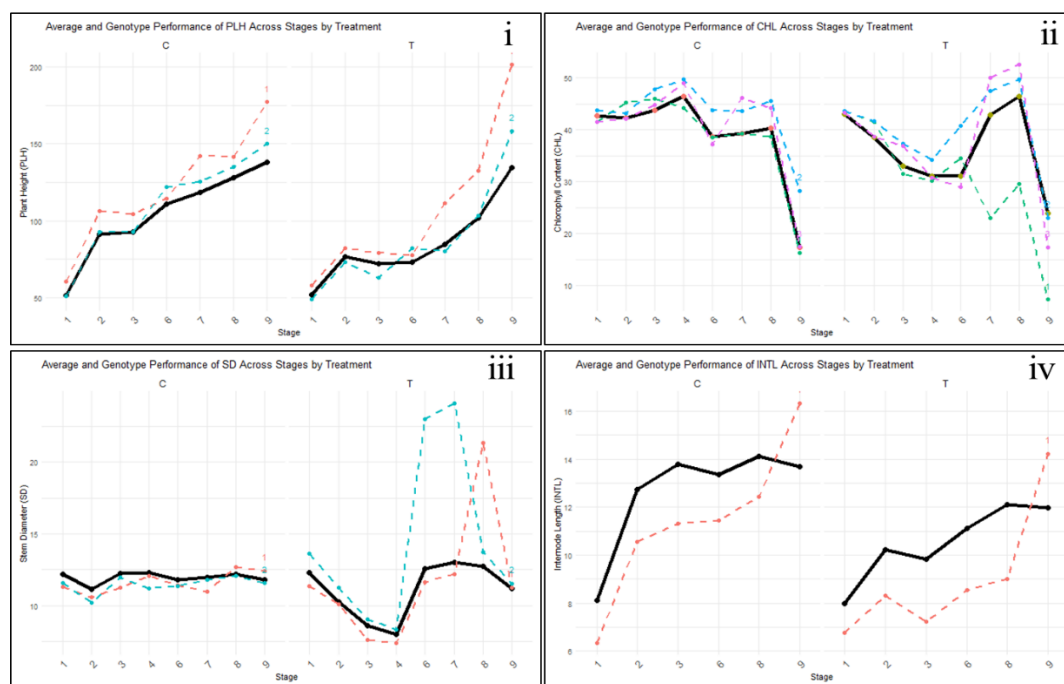


Figure 3. Performance of selected sorghum genotypes across sequential stages during drought stress and recovery phases, compared to the overall mean performance (). C = control (well-watered); T = drought stress-rewatering treatment.

Summary of curve parameters in Figure 3

- i. PLH ----- MAZDA105 Enyankore, ----- NAROSORGH1 x NAROSORGH3 -1-1-1-1/22B
- ii. CHL----- ICSX152005-SB-5-3-2-1, ----- NAROSORGH1 x NAROSORGH3-1-1-1-1/22B, -----MAZDA105 Enyankore
- iii. SD ----- NAROSORGH1 x NAROSORGH1-1-1-1-1/22B, -----ASARECA13-1 x NAROSORGH3-1-1-5-1/22B
- iv. INTL----- SSGA/RAP/349

The Genotypes NAROSORGH1xNAROSORGH3-1-1-1-1/22B and MAZDA105 Enyankore, from the susceptible and moderately resistant groups, respectively, consistently maintained high chlorophyll content (Figure 3 ii) throughout both the stress and recovery phases, indicating strong potential to sustain photosynthetic activity. A similar trend was observed in plant height (Figure 3i) for these genotypes. In contrast, ICSX152005-SB-5-3-2-1 exhibited a rapid decline in chlorophyll content during the stress phase, with minimal recovery after rewatering. SSGA/RAP/349 exhibited strong performance under both stress and well-watered conditions, particularly in maintaining stem diameter, but demonstrated limited internode length (Figure 3 iv) during the recovery, indicating a unique response in structural growth. Meanwhile, NAROSORGH1xNAROSORGH1-1-1-1-1/22B and ASARECA13-1x NAROSORGH3-1-1-5-1/22B showed rapid increases in stem diameter (Figure 3 iii) upon rewatering. Overall, the genotypes displayed diverse recovery mechanisms, with some genotypes like NAROSORGH1 x NAROSORGH3 -1-1-1-1/22B excelling in tissue rehydration and quickly resuming growth, while others, such as ICSX 152005-SB-5-3-2-1, showed more limited recovery capacity.

3.3. Evaluation of Drought Recovery Indices

The results of the Drought Recovery Index (DRI) for the evaluated genotypes are presented in Table 2. Genotypes with lower DRI values exhibited poor recovery potential across the assessed traits.

Table 2. Drought recovery indices for internode length, chlorophyll content, stem diameter and plant height across the different genotypes.

Genotypes	Drought Recovery Index (DRI)			
	INTL	CHL	SD	PLH
ASARECA 13-1 x Framida -1-1-3-1/22B	-0.35	0.09	0.20	-0.46
ASARECA 13-1 x NAROSORGH3-1-1-1-1/22B	-0.31	-0.09	-0.30	-0.50
ASARECA13-1 x NAROSORGH3-1-1-5-1/22B	-0.37	0.01	0.28	-0.30
ETEREMA	-0.11	-0.08	-0.22	-0.37
GE16/2/20B x IESV92041SH (SSEA 18B#6)	-0.30	0.03	-0.31	-0.35
ICSV 142001	-0.39	0.02	-0.07	-0.27
ICSV 152005-SB-5-3-2-1	-0.10	-0.40	-0.13	-0.28
ICSV 162719-1-4-1-1-1	-0.25	0.09	-0.26	-0.33
ICSV152666-B-2-7-3-1-1-1	-0.32	0.04	-0.21	-0.17
IESV 214006DL	-0.35	-0.05	-0.05	-0.11
IESV16 143-1-3-1	-0.22	0.11	-0.25	-0.20
MAZDA 105 Enyankore	-0.32	-0.03	-0.02	-0.47
NAROSORGH 1 x FRAMIDA-1-1-5-1/22B	-0.27	0.13	-0.22	-0.18
NAROSORGH 4	-0.25	0.00	-0.15	-0.33
NAROSORGH1 x NAROSORGH1-1-1-1-1 /22B	-0.15	-0.02	-0.01	-0.27
NAROSORGH1 x NAROSORGH3-1-1-5-1/22B	-0.28	0.07	-0.16	-0.43
NAROSORGH1 x NAROSORGH3 -1-1-1-1/22B	-0.29	0.07	-0.19	-0.40
SSGA/RAP/349	-0.48	-0.04	-0.12	-0.60

INTL: Internode length, CHL: Chlorophyll content, SD: Stem diameter, PLH: Plant height.

Generally, the genotypes displayed strong recovery for chlorophyll content (CHL) and stem diameter (SD), while exhibiting relatively poor recovery for internode length and plant height. Chlorophyll content recovery was most pronounced in the genotypes NAROSORGH1 x FRAMIDA-1-1-5-1/22B (0.13), IESV16 143-1-3-1 (0.11), ICSX 162719-1-4-1-1-1 (0.09), and ASARECA13-1 x FRAMIDA-1-1-3-1/22B (0.09). Conversely, ICSX 152005-SB-5-3-2-1 and ASARECA13-1 x NAROSORGH3-1-1-1-1/22B displayed the poorest recovery, with DRIs of -0.40 and -0.09, respectively. For plant height, genotypes IESV214006DL (-0.11), ICSV152666-B-2-7-3-1-1-1 (-0.17), NAROSORGH1 x FRAMIDA-1-1-5-1/22B (-0.18), and IESV16 143-1-3-1 (-0.20) exhibited relatively good recovery. However, SSGA/RAP/349 (-0.60) and ASARECA13-1 x NAROSORGH3-1-1-1-1/22B (-0.50) demonstrated the weakest recovery. Stem diameter is an indication of the potential to rehydrate the tissues after drought stress. Genotypes ASARECA13-1 x NAROSORGH3-1-1-5-1/22B (0.28) and ASARECA13-1 x FRAMIDA-1-1-3-1/22B (0.20) exhibited good rehydration capacity, while GE16/2/20B x IESV92041SH (SSEA 18B#6) (-0.31) and ASARECA13-1 x NAROSORGH3-1-1-1-1/22B (-0.30) had the poorest.

3.4. Clustering of Genotypes and Traits Under Well-Watered and Drought Stress-Rewatering Conditions

Figure 4 presents biplots that cluster genotypes according to their responses under both well-watered and drought stress-rewatering treatments. The two principal components explained 48% of the total variation in the drought stress-rewatering treatment and 42% under well-watered conditions.

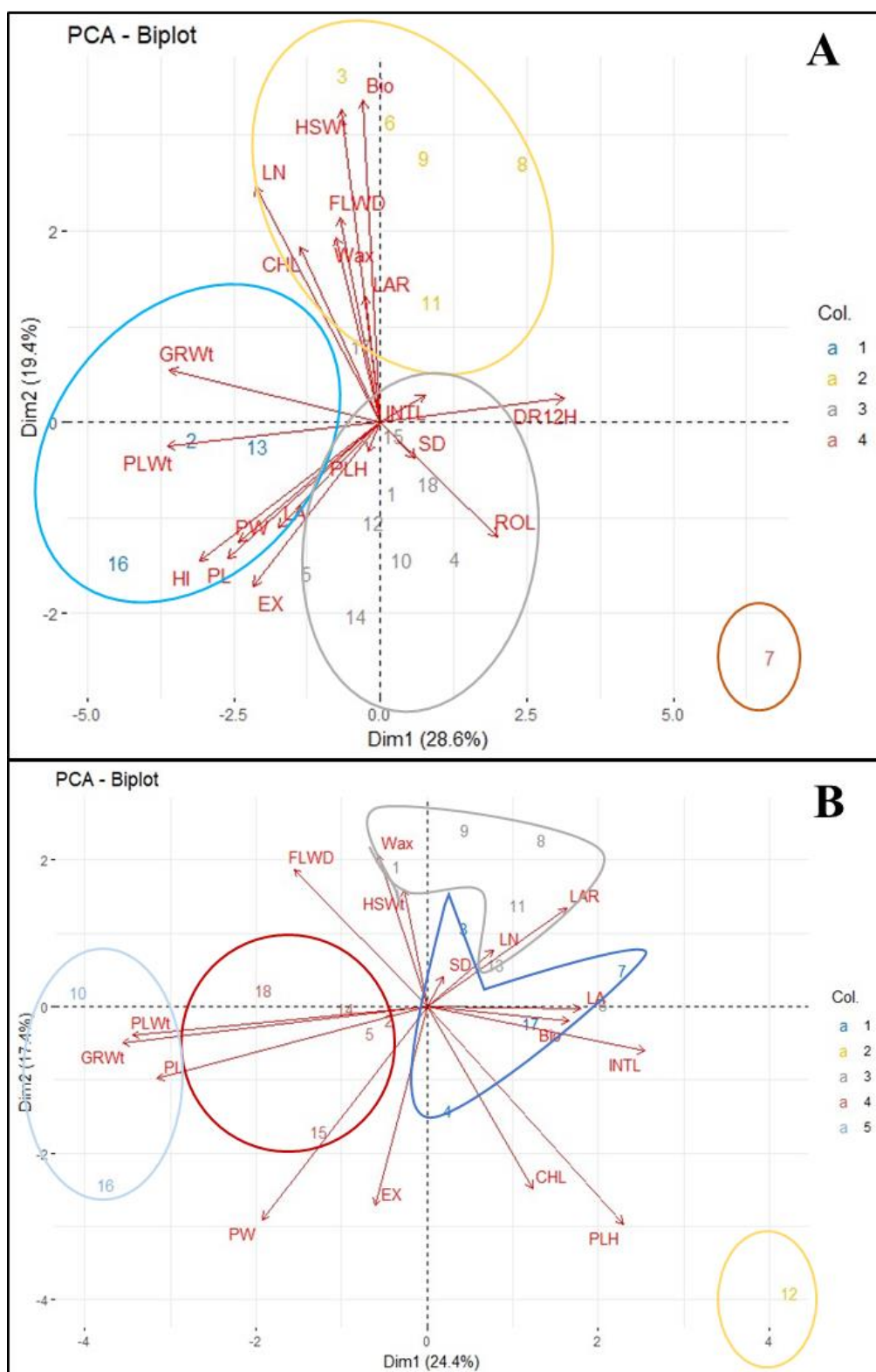


Figure 4. Clustered biplots illustrating the grouping of traits and sorghum genotypes in A: stress-rewatering conditions and B: well-watered conditions. GRWt: Grain weight after threshing, PLWt: Dry weight of harvest from a pot, HSW: 100-seed weight, SD: Stem diameter, LAR: Leaf Area, LN: Leaf numbers, INTL: Internode length, CHL: Chlorophyll content, PLH: Plant height, FLWD: Days to 50% flowering, EX: Panicle Exertion, PL: Panicle length, PW: Panicle Width, HI: Harvest index.

In the drought stress-rewatering regime, the genotypes were categorized into four distinct clusters (Figure 4A). Genotypes ASARECA13-1xNAROSORGH3-1-1-1-1/22B (2), NAROSORGH1 x

FRAMIDA-1-1-5-1/22B (13), and NAROSORGH1 × NAROSORGH3-1-1-5-1/22B (16) exhibited the highest values for key yield traits such as dry weight, grain weight, harvest index, panicle length, and panicle width, and were grouped in Cluster 1. These genotypes also demonstrated a rapid rewatering response, achieving the lowest average recovery scores (2.00) within just 12 hours after rehydration. Cluster 2 included genotypes ASARECA13-1 × NAROSORGH3-1-1-5-1/22B (3), ICSV 142001 (6), ICSX 162719-1-4-1-1-1 (8), ICSX152666-B-2-7-3-1-1-1 (9), and IESV16 143-1-3-1 (11). These genotypes were characterized by high biomass yield, 100-seed weight, and generally greater leaf numbers, but they exhibited a lower harvest index. Cluster 4, represented solely by genotype ICSX 152005-SB-5-3-2-1, exhibited distinct and unfavourable traits. It recorded the lowest grain yield, harvest index, 100-seed weight, and biomass yield, along with the poorest recovery 12 hours post-rewatering. Additionally, this genotype had the highest degree of leaf rolling, a manifestation of drought susceptibility, the lowest chlorophyll content, and the smallest number of green leaves. ICSX 152005-SB-5-3-2-1, therefore, stood out as the most susceptible genotype, displaying the weakest recovery potential.

In the well-watered scenario, there was a limited tendency for traits to cluster (Figure 4B). However, genotypes IESV 214006DL (10) and NAROSORGH1 × NAROSORGH3-1-1-1-1/22B (16) were grouped in Cluster 1, showing generally high values for panicle length, grain yield, and dry weight. Notably, genotype MAZDA105 Enyankore (12) exhibited a unique response, forming a distinct Cluster 2. This genotype demonstrated the highest values for chlorophyll content, plant height, biomass yield, and panicle exertion, standing out from all other genotypes.

3.5. Screening Genotypes with Strong Drought Recovery Based on Resistance/Tolerance Indices

The recovery levels of the different genotypes were assessed by calculating drought selection indices, following the methodology outlined by [25].

Correlation of Drought Tolerance Indices and Genotype Ranking

The tolerance or resistance indices calculated were analysed to explore their inter-correlations as well as with grain yield under both drought stress-rewatering and well-watered treatments [25,27] (Table 3).

Table 3. Correlation coefficients between the different drought tolerance and susceptibility indices.

	Ys	Yp	SSI	GM	TOL	MP1	YSI	HM	STI	YI	MB	GMB	BI	BSI
Ys	1													
Yp	0.58*	1												
SSI	-0.68**	0.16	1											
GM	0.92***	0.85***	-0.37	1										
TOL	-0.12	0.74***	0.75***	0.28	1									
MP1	0.84***	0.93***	-0.2	0.98***	0.44	1								
YSI	0.68**	-0.16	-1***	0.37	-0.75***	0.2	1							
HM	0.96***	0.77***	-0.48*	0.99***	0.14	0.95***	0.48*	1						
STI	0.96***	0.77***	-0.48*	0.99***	0.14	0.95***	0.48*	1***	1					
YI	1***	0.58*	-0.68**	0.92***	-0.12	0.84***	0.68**	0.96***	0.96***	1				
MB	0.29	-0.23	-0.6**	0.1	-0.53*	-0.02	0.6**	0.18	0.18	0.29	1			
GMB	0.27	-0.24	-0.58*	0.08	-0.52*	-0.04	0.58*	0.15	0.15	0.27	0.98***	1		
BI	0.18	-0.2	-0.42	0.04	-0.39	-0.05	0.42	0.1	0.1	0.18	0.79***	0.88***	1	
BSI	0.08	-0.08	-0.16	0.02	-0.16	-0.02	0.16	0.05	0.05	0.08	0.4	0.53*	0.87***	1

Ys: Grain yield under stress, Yp: Grain yield under well watering, GM: Geometric mean, SSI: Stress Susceptibility index, TOL: Tolerance, MPI: Mean productivity Index, YSI: Yield Stability Index, HM: Harmonic Mean, STI: Stress tolerance Index, YI: Yield Index, MB: Mean biomass, GMB: Geometric mean biomass, BI: Biomass index, BSI: Biomass stability index.

As indicated in Table 3, yield under stress-rewatering (Y_s) was strongly and positively associated with yield under well-watered conditions (Y_p), with a correlation coefficient of 0.58. Several indices, including Geometric Mean (GM), Mean Productivity Index (MPI), Harmonic Mean (HM), Stress Tolerance Index (STI), and Yield Index (YI), showed strong positive correlations with grain yield in both watering regimes. In contrast, the Stress Susceptibility Index (SSI) and Yield Stability Index (YSI) were significantly linked only to yield under stress, with correlation values of -0.68 and 0.68, respectively. While biomass-related indices such as Mean Biomass (MB), Geometric Mean Biomass (GMB), Biomass Index (BI), and Biomass Stability Index (BSI) did not have statistical significance, they tended to correlate positively with yield under stress and negatively with grain yield in well-watered conditions. Each genotype was ranked according to its performance across the different drought tolerance indices. The mean rank, standard deviation of ranks, and rank sum (RS) were calculated for all indices to identify the most desirable genotypes with the lowest rank sum as described by [29]. Using this approach, genotypes were ranked from the most tolerant, showing the best recovery, to the least tolerant, with the poorest recovery. The initial ranking considered only grain yield-related indices (Table 4), followed by a final ranking that included both grain yield and biomass-related indices (Table 5)

Table 4. Ranking of sorghum genotypes based on grain yield-related indices.

DESIGNATION	Genotype's rank (R) for each index									\bar{R}	σ	ΣR	F. R
	GM	SSI	TOL	LYSI	HM	STI	YI	\bar{R}	σ				
GE16/2/20B X IESV92041SH (SSEA 18B#6)	3	5	9	5	5	3	3	3	4.50	2.0 7	6.57	1	
NAROSORGH1 X NAROSORGH3 -1-1-1-1/22B	6	7	7	6	7	5	5	5	6.00	0.9 3	6.93	2	
ICSX152666-B-2-7-3-1-1-1	8	6	6	8	6	7	7	6	6.75	0.8 9	7.64	3	
NAROSORGH 1 X FRAMIDA-1-1-5-1/22B	7	2	2	11	2	6	6	4	5.00	3.1 6	8.16	4	
ASARECA 13-1 X NAROSORGH3-1-1-1-1/22B	2	8	12	3	8	2	2	2	4.88	3.9 1	8.78	5	
ASARECA 13-1 X Framida -1-1-3-1/22B	10	10	10	9.5	10	8	8	9	9.31	0.8 8	10.2 0	6	
ICSV 142001	11	9	8	12	9	11	11	10.5	10.1 9	1.3 6	11.5 5	7	
NAROSORGH1 X NAROSORGH3-1-1-5-1/22B1	11	16	1	11	1	1	1	1	5.38	6.2 3	11.6 1	8	
NAROSORGH 4 (Resistant check)	9	12	13	7	12	9	9	10.5	10.1 9	2.0 3	12.2 2	9	
ASARECA13-1 X NAROSORGH3-1-1-5-1/22B	13	4	4	13	4	12	12	8	8.75	4.2 3	12.9 8	10	
IESV16 143-1-3-1	14	3	3	14	3	13	13	7	8.75	5.2 6	14.0 1	11	
SSGA/RAP/349	12	15	15	9.5	15	14	14	15	13.6 9	1.9 8	15.6 7	12	
IESV 214006DL	4	16	18	2	16	4	4	12	9.50	6.6 5	16.1 5	13	
ICSX 162719-1-4-1-1-1	16	14	11	15	14	16	16	17	14.8 8	1.8 9	16.7 6	14	

MAZDA 105 Enyankore	15	1	1	16	1	15	15	13	9.63	7.1	16.8	15
NAROSORGH1 X NAROSORGH1-1-1-1-1/22B	5	17	17	4	17	10	10	14	11.7	5.3	17.0	16
ETEREMA (Susceptible Check)	17	13	5	17	13	17	17	16	14.3	4.1	18.5	17
ICSX 152005-SB-5-3-2-1	18	18	14	18	18	18	18	18	17.5	1.4	18.9	18

GM: Geometric mean, SSI: Stress Susceptibility index, TOL: Tolerance, MPI: Mean productivity Index, YSI: Yield Stability Index, HM: Harmonic Mean, STI: Stress Tolerance Index, YI: Yield Index, \bar{R} : Mean Rank, σR : Standard deviation of Rank, ΣR : Rank sum, F.R: Final /overall ranking of the genotype.

Table 5. Ranking of sorghum genotypes based on both grain and biomass yield-related indices.

DESIGNATION	Genotype's rank (R) for each index													F.R			
	G M	SS I	TO L	MP I	YS I	H M I	ST I	YI	M B	GM B	B S I	\bar{R}	σR		ΣR		
ICSX152666-B-2-7-3-1-1-1	8	6	6	8	6	7	7	6	3	3	3	3	5.50	1.9	7.48	1	
NAROSORGH1X NAROSORGH3 -1-1-1-1/22B	6	7	7	6	7	5	5	5	10	10	1	1	16	7.92	3.2	11.2	2
ASARECA13-1 X NAROSORGH3-1-1-5-1/22B	13	4	4	13	4	12	12	8	1	1	1	1	6.17	5.1	11.2	3	
NAROSORGH 1 X FRAMIDA-1-1-5-1/22B	7	2	2	11	2	6	6	4	7	9	1	0	17	6.92	4.4	11.3	4
ASARECA 13-1 X Framida -1-1-3-1/22B	10	10	10	9.5	10	8	8	9	11	11	9	14	9.96	1.6	11.5	5	
ICSV 142001	11	9	8	12	9	11	11	10.5	6	4	2	2	7.96	3.6	11.5	6	
GE16/2/20B X IESV92041SH (SSEA 18B#6)	3	5	9	5	5	3	3	3	15	15	1	3	9	7.33	4.7	12.0	7
ASARECA 13-1 X NAROSORGH3-1-1-1-1/22B	2	8	12	3	8	2	2	2	5	6	1	4	18	6.83	5.3	12.2	8
NAROSORGH1 X NAROSORGH3-1-1-5-1/22B	1	11	16	1	11	1	1	1	13	12	7	5	6.67	5.6	12.3	9	
IESV16 143-1-3-1	14	3	3	14	3	13	13	7	9	7	6	4	8.00	4.4	12.4	10	
NAROSORGH 4 (Resistant check)	9	12	13	7	12	9	9	10.5	14	14	1	5	12	11.3	2.4	13.8	11
MAZDA 105 Enyankore	15	1	1	16	1	15	15	13	4	5	5	11	8.50	6.2	14.7	12	
NAROSORGH1X NAROSORGH1-1-1-1-1/22B	5	17	17	4	17	10	10	14	8	8	8	10	7	10.6	4.5	15.2	13
SSGA/RAP/349	12	15	15	9.5	15	14	14	15	16	16	1	6	8	13.7	2.6	16.4	14
ICSX 162719-1-4-1-1-1	16	14	11	15	14	16	16	17	2	2	4	6	8	11.0	5.8	16.9	15
ETEREMA (Susceptible check)	17	13	5	17	13	17	17	16	12	13	1	2	13	13.7	3.4	17.2	16
IESV 214006DL	4	16	18	2	16	4	4	12	17	17	1	7	7	11.1	6.4	17.5	17

weight. These reductions, observed in genotypes ICSX152005-SB-5-3-2-1, ICSX 162719-1-4-1-1-1 and ETEREMA, may be ascribed to poor panicle emergence, panicle blasting, ovary abortion and decreases in panicle size and grain number, traits that directly impact grain yield [32,33]. Despite post-stress growth recovery, biomass yield remained lower in drought-stressed plants compared to the control plants, consistent with the responses observed in many plant species subjected to drought stress [34–36]. As noted by [37], this discrepancy reflects pre-drought limitations that constrain the capacity for full recovery. Notably, drought stress delayed flowering by an average of 11 days, contrasting with previous reports of accelerated flowering under drought stress in other plant species [32,38].

Plant growth slowed under drought stress but recovered across all genotypes during the rewatering phase, reflecting the high plasticity of sorghum's growth. Growth reduction during stress was mainly attributed to a decrease in cell expansion and elongation [39,40]. Typically, this growth retardation reflects a shift in the energy budget, where maintenance processes take priority, leaving less energy available for growth. The genotypes NAROSORGH1 × NAROSORGH3-1-1-1-1/22B and MAZDA105 Enyankore were particularly notable for sustaining relatively high chlorophyll content during both the stress and recovery periods, underscoring their drought tolerance characteristics. This observation is supported by prior studies showing that drought-tolerant genotypes tend to maintain higher chlorophyll levels under stress compared to susceptible ones [41–43]. The rapid drought-induced reduction in chlorophyll content across genotypes suggests a significant loss in photosynthetic functionality at PSI and PSII reaction centres [34]. However, the rapid recovery of plants after rewatering, especially genotypes NAROSORGH1 × NAROSORGH3-1-1-1-1/22B, ASARECA13-1 × Framida -1-1-3-1/22B, NAROSORGH1 × FRAMIDA-1-1-5-1/22B and IESV16 143-1-3-1, indicates that this loss may serve a regulatory rather than a purely damaging function [34,44].

Dehydration is a reversible process [44], consistent with our findings that stem diameter decreased significantly during drought stress but increased across all genotypes during the recovery phase. The heightened variability in responses during the recovery phase, compared to the stress period, highlights the diverse recovery patterns and capacities across the different genotypes.

4.1. Shifts in Traits' Significance as Adaptive Responses to Drought Stress and Recovery

Plants activate a suite of adaptive mechanisms in response to drought stress and rewatering, encompassing molecular and biochemical changes as well as complex physiological and morphological adjustments [37,45]. However, the extent of plant growth recovery following rewatering may depend on the intensity and duration of the preceding drought [37]. Grain weight, dry weight, harvest index, and panicle size-key yield-contributing traits were the main contributors to Cluster 1, which comprised genotypes ASARECA13-1 × NAROSORGH3-1-1-1-1/22B, NAROSORGH1×FRAMIDA-1-1-5-1/22B and NAROSORGH1× NAROSORGH3-1-1-5-1/22B. The rapid rehydration response observed in these genotypes, likely reflecting faster recovery of the photosynthetic apparatus and thus higher photosynthetic rates, may explain their higher yields post-rewatering. While leaf rolling is known to reduce transpiration and protect the photosynthetic machinery from photodamage [39,46], our findings indicated that a high degree of leaf rolling was linked to the high susceptibility of genotype ICSX152005-SB-5-3-2-1. As leaf rolling reduces the effective leaf area for photosynthesis[10,46], this susceptibility may be linked to reduced carbon dioxide assimilation, a tradeoff for water conservation in plants [47–49]. Biomass yield, on the other hand, showed stronger correlations with leaf number, leaf area, chlorophyll content, 100-seed weight, and days to 50% flowering. These traits were associated with genotypes ASARECA13-1 × NAROSORGH3-1-1-5-1/22, ICSV142001, ICSX162719-1-4-1-1-1, ICSX152666-B-2-7-3-1-1-1, and IESV16 143-1-3-1, which were grouped in Cluster 2. 100-seed weight is a key yield component that reflects the source-sink relationship of photo-assimilates during the grain filling stage [50]. The strong positive correlation between 100-seed weight and biomass yield was similarly observed by [51]. Previous studies have reported a strong positive correlation between 100-seed weight and other yield components, such as dry weight, grain weight, and harvest index [52–54]. However, no such

correlation was observed in this study. Despite the lower productivity of genotypes MAZDA105 Enyankore and ICSX162719-1-4-1-1-1, their ability to maintain high biomass yield and chlorophyll content under both stress and well-watered conditions makes them particularly promising for forage breeding. Therefore, the grouping of traits under drought stress into distinct drought recovery patterns, as shown in the biplots, highlights the varying capacities of genotypes to recover after a drought event.

4.2. Strategy for Selecting Desirable Genotypes Using Drought Tolerance/Resistance Indices

Genotypes exhibit varied responses to drought stress [27,55]. Given this, various selection criteria have been proposed to identify genotypes based on their performance in both stress and non-stress conditions [25,27,28,32]. Tolerant genotypes are characterized by low SSI and TOL values, along with high MP, HM, GMP, STI, YI, and YSI values [25,28,55]. Considering the rank sum, genotypes GE16/2/20B x IESV92041SH (SSEA 18B#6), NAROSORGH1 x NAROSORGH3-1-1-1-1/22B, ICSX152666-B-2-7-3-1-1-1, NAROSORGH1 x FRAMIDA-1-1-5-1/22B, ASARECA13-1 x NAROSORGH3-1-1-1-1/22B, ASARECA13-1 x Framida-1-1-3-1/22B, ICSV142001 and NAROSORGH1 x NAROSORGH3-1-1-5-1/22B demonstrated the best recovery potential, outperforming the positive check NAROSORGH 4. This was further supported by the biplot analysis, highlighting their high grain yield under stress and non-stress conditions. Conversely, genotype ICSX152005-SB-5-3-2-1 emerged as the most susceptible, exhibiting the poorest recovery potential and performing below ETEREMA, the negative check. Based on both grain and biomass indices, the genotypes assumed new ranks. Two additional genotypes, ASARECA13-1 x NAROSORGH3-1-1-5-1/22B and IESV16 143-1-3-1, emerged among the previously high-performing genotypes, surpassing the positive check. Meanwhile, genotype IESV214006DL, alongside ICSX152005-SB-5-3-2-1, ranked below ETEREMA. Comparable to the findings of [56], we observed a highly significant positive correlation between grain yield under both stress and non-stress conditions. This suggests that during recovery, grain yield performance in optimal conditions serves as a reliable predictor for yield under stress, as also supported by [28] [57].

An effective selection index should have a significant relationship with grain yield in both stress and non-stress conditions [58,59]. The correlation matrix indicated a strong positive association between grain yield in stress conditions (Y_s) and in non-stress conditions (Y_p), along with indices such as the Geometric Mean (GM), Mean Productivity Index (MPI), Harmonic Mean (HM), Stress Tolerance Index (STI), and Yield Index (YI). This indicates that these criteria were effective in distinguishing drought-tolerant genotypes that maintained high grain yield across both watering regimes. Consequently, these indices were deemed suitable for selecting genotypes with strong recovery potential. Conversely, biomass indices appeared to have limited relevance to grain yield performance.

5. Conclusions

This study evaluated the responses of 18 sorghum genotypes to drought stress and subsequent rewatering to determine their drought recovery potential. Our findings confirmed genotype-specific recovery patterns and the traits that are key to achieving high yields under intermittent water supply. Genotypes such as NAROSORGH1 x NAROSORGH3-1-1-5-1/22B, ASARECA13-1 x NAROSORGH3-1-1-1-1/22B, and NAROSORGH1 x FRAMIDA-1-1-5-1/22B demonstrated rapid rehydration and compensatory growth, to recover from drought stress and maximize yield. Such a good plasticity suggests that these genotypes are particularly well-suited for agroecologies like North-eastern Uganda, which experience intense drought stress followed by short periods of heavy rainfall. Conversely, genotypes such as NAROSORGH1 x NAROSORGH3-1-1-1-1/22B, GE16/2/20B x IESV92041SH (SSEA 18B#6), and ICSX152666-B-2-7-3-1-1-1 achieved higher yields by maintaining higher chlorophyll content, which extended their photosynthetic activity during stress and recovery. Based on stress tolerance indices, genotypes suitable for various moisture conditions were identified, with those in category A proving particularly valuable under fluctuating water conditions due to

their yield stability and adaptability. These genotypes show strong potential as parents for drought resilience breeding efforts. In contrast, genotype ICSX152005-SB-5-3-2-1 exhibited the poorest recovery response, while IESV214006DL experienced drastic reductions in performance during drought stress. These two genotypes could serve as reliable negative drought checks in the breeding program. Going forward, understanding the genetic control of the observed recovery responses in selected genotypes will be essential in facilitating the precise introgression of desirable recovery traits in elite breeding materials.

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