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Evaluation of Drought-Tolerant Varieties for Sustainable Crop Production

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ABSTRACT

Water deficit is one of the main abiotic factors that affects crop productivity all over the world and identification of genotypes that can tolerate water deficit has a central role in sustainable crop production. The performance and drought tolerance of a set of crop varieties contrasting for the two conditions were evaluated in a 3 to 4 replications factorial randomized complete block design. Morphological traits (plant height, tillers/branches, leaf area, biomass), physiological traits (relative water content, chlorophyll content, membrane stability), and yield-related traits (productive units, grains per unit, thousand grain weight, biological yield, grain yield and harvest index) were recorded and drought tolerance indices were used for the ranking of genotypes. The effects of variety, water regime, and variety x water regime interaction were significant for most traits while growth and yield under drought stress were significantly reduced for all genotypes. Some varieties showed small yield and physiological responses to stress while others showed more tolerance under stress conditions and also showed higher stress tolerance index (STI) and lower stress susceptibility index (SSI). The results validate the employment of multi-trait screening together with tolerance indices in breeding and variety-selection programs to enhance the resilience of crops and long-term agricultural sustainability in increasingly water limited environments.

Introduction

The availability of water is the most important environmental limit on crop productivity and its growing variability in a changing climate is an emerging challenge to world food security (Amparo-Salcedo et al., 2025). Rain-fed cultivation systems rely almost solely on soil water coming from precipitation and thus are highly sensitive to climate change-induced changes in precipitation and temperature patterns (Solutions to Agricultural Green Water Scarcity under Climate Change, 2023). Crop water demand projections under future warming scenarios suggest that green water scarcity, or the inability of rainfall to supply the crop water demand, will impact food production for more than 1 billion people in the following decades (Solutions to Agricultural Green Water Scarcity under Climate Change, 2023). However, at a regional level, spatially explicit assessments of climate change impact on the production of major cereal crops also reveal short term gains in production for some regions are likely to be more than offset by impacts on water availability over the longer term (A Global and Spatially Explicit Assessment of Climate Change Impacts on Crop Production and Consumptive Water Use, 2013).

Drought stress has multiple impacts on plant function ranging from stomatal closure that impairs carbon assimilation to longer-term acclimation responses which can be genotype-dependent, with respect to their ability to sustain yield under a specific drought stress (Tardieu et al., 2018). The short- and long-term feedbacks lead to trade-offs between accumulation of carbon and risk of too much water depletion, which can therefore have positive or negative impacts on yield depending on the magnitude and timing of water deficit (Tardieu et al., 2018). At the whole plant level, resistance to drought usually combines escape, avoidance, tolerance and recovery strategies, and some of these mechanisms have been developed in wild relatives to ensure survival, but may not be superior to yield in crop cultivation, highlighting the importance of breeding cultivars for stress-

resistant traits that have a strong positive impact on yield (Drought Tolerant Plants: Physiological and Molecular Responses, 2024).

It is still one of the most accessible and affordable approaches to enhance the resilience of cropping systems: screening of available germplasm resources for differential drought response (Pasala, Pandey, Manikanta et al., 2025). Several reviews have highlighted drought-resistant crops and varieties, along with precise agricultural practices and water-saving measures, as potential solutions for mitigating the losses caused by water scarcity and ensuring environmental sustainability in the future (Drought-Resistant Crops: A Sustainable Solution to Climate Change, 2024; Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions, 2024). Most crop species have a certain genetic variability for drought tolerance and understanding the genetic, physiological and morphological basis of this variability is believed to be a pre-requisite to its exploitation in variety development and selection (Genetic Improvement of Wheat for Drought Tolerance: Progress, Challenges and Opportunities, 2022). Recent studies have also called for coupling physiological and molecular signaling knowledge with genomics-assisted and AI-supported breeding pipelines to speed up the progress of new crops for climate resistance (Integrating Drought Stress Signaling and Smart Breeding for Climate-Resilient Crops, 2025).

One common principle across this series of projects is that none of the traits themselves consistently predict drought performance under field conditions, but rather a combination of integrated evaluation of morphological and physiological traits, and quantitative drought tolerance indices provides a more sound basis for distinguishing between tolerant and susceptible genotypes. Stress susceptibility index (Fisher & Maurer, 1978) and mean productivity and geometric mean productivity indices (Rosielle & Hamblin, 1981) continue to be used and are foundational because they give an indication of how well the genotype performs under stress, relative to its performance under optimal conditions, making the genotype rankable with regard to both its stability and its yield potential. The application of these and similar indices in a variety of crops has consistently demonstrated that varieties with a high yield potential but with a small relative yield loss under stress are the most desirable ones to select (Khalili et al., 2012).

Although there is increasing literature available on a range of individual physiological or molecular mechanisms of drought tolerance, relatively few field trials have considered morphological, physiological and yield based assessments in a single, statistically robust experimental design that can address genotype-by-water-regime interactions under realistic field conditions. To overcome this, the present study was designed to compare a set of contrasting crop varieties in controlled well-watered and drought-stressed conditions which were used in a factorial randomized complete block design. Specific objectives of the study were: (i) To quantify the effects of variety, water regime and interaction of variety and water regime on the morphological, physiological and yield-related traits; (ii) To identify morphological, physiological and yield related traits that were most closely associated with yield maintenance under drought using correlation analysis for the purpose of variety selection for sustainable crop production under water limited conditions; and (iii) To rank the evaluated varieties based on the yield maintenance under drought based on established yield tolerance indices, for the purpose of variety selection for sustainable crop production under water limited conditions.

Literature Review

Morphological responses of Crops under Drought Stress

The most common morphological effects of water deficit on crops are reductions in plant height, tiller or branch number, leaf area and total plant biomass. The reductions in leaf area, tillers per plant and biomass yield in wheat under terminal drought stress were highly evident between a drought sensitive cultivar and a comparatively drought tolerant cultivar, suggesting that the extent of morphological decline alone is a distinguishing characteristic of the different cultivars and their respective drought tolerance (Foliar Application of Putrescine Alleviates Terminal Drought Stress by Modulating Water Status, Membrane Stability, and Yield-Related Traits in Wheat, 2023). In maize water stress caused by different irrigation systems was also seen to significantly affect the plants' height, dry matter accumulation, and leaf area, where exogenous application of proline and other osmoprotectants was shown to partially restore these morphological traits, highlighting the sensitivity of morphology to water stress and its response to physiological amelioration (Exogenously Applied Proline Enhances Morph-Physiological Responses and Yield of Drought-Stressed Maize Plants Grown under Different Irrigation Systems, 2022). A large-scale screening of foxtail millet germplasm under a normal and reduced irrigation also revealed that all the 12 morpho-agronomic traits tested (plant height, biomass, and spike characteristics) were significantly reduced when irrigated under drought conditions, with yield being the most sensitive trait among the traits tested (Drought Tolerance Evaluation and Classification of Foxtail Millet Core Germplasms Using Comprehensive Tolerance Indices, 2025).

Physiological Scale Indicators of Drought Response

Physiological traits that reflect drought stress response are the most commonly used to describe plant's ability to maintain water content of cells and photosynthetic activity in drought stress conditions, such as relative water content (RWC), chlorophyll content, membrane stability index (MSI). Comparative analysis of wheat genotypes under drought conditions had indicated that the seedling fresh weight, RWC and membrane stability are found to be strongly correlated with the dry matter accumulation under drought condition, which indicated that these are of significant value as secondary selection criteria (Selection Criteria to Assess Drought Stress Tolerance in Wheat Genotypes Using Physiological and Biochemical Parameters, 2021). Lipid peroxidation of chloroplast membranes and accelerated leaf senescence have been proposed as causes of drought-induced chlorophyll loss (Yang et al., 2001), and the chlorophyll stability index has been known as a simple one-parameter measurement of the integrity of the pigments under stress for a long time (Kaloyereas, 1958). Similarly, cotton genotypes were evaluated for the decrease in chlorophyll stability index and RWC during drought and both parameters were closely related to the final yield of cotton (Drought-Induced Changes in Chlorophyll Stability Index and Relative Water Content of Cotton Genotypes, 2013). Similar reduction in RWC, MSI, and chlorophyll content, with a combination of both traits distinguishing the wheat lines under progressive water deficit, was reported in wheat at seedling stage (Comparable reductions in RWC, MSI, and chlorophyll content under progressive water deficit suggest that a combination of these traits distinguishes wheat lines under drought and heat stress, 2020) and under combined drought and heat stress in mature wheat, where a combination of cell membrane stability and gas-exchange traits distinguished the more thermostable and drought-tolerant wheat lines from more susceptible ones (Comparable reductions in RWC, MSI, and chlorophyll content under progressive water deficit suggest that a combination of these traits distinguishes wheat lines under drought and heat stress, 2023).

Physiological traits were also found to be responsive to remediation, as well as to simple stress imposition. In wheat, plant growth regulators had positive effects on RWC, MSI, chlorophyll content and photosynthetic rate, both at normal and water deficit irrigation conditions, depending on the genotype (Membrane Stability, Water Relations and Photosynthesis in Wheat Genotypes, 2018); in legumes, similar effects of plant growth regulators were observed on RWC, MSI, and photosynthetic efficiency under water deficit irrigation conditions (The Membrane Stability Index, Relative Water Content, and Related Traits in Phaseolus vulgaris under Water Deficit, 2024). The results provide overall evidence that traits have not only diagnostic value but also serve as levers on which drought tolerance can be potentially increased through manipulation.

Yield-Related Traits and Drought Tolerance Indices

In the context of agronomic drought tolerance, the ultimate measure is drought tolerance in terms of yield stability and therefore much attention has been paid to indices that integrate yield under stressed conditions (Ys) with yield under non-stressed conditions (Yp) as a single drought tolerance measure. The stress susceptibility index (SSI) is one of the most widely used indices (Fischer & Maurer, 1978), and the mean productivity (MP) and geometric mean productivity (GMP) indices measure the average and geometric-mean performance, respectively, of a genotype under both conditions (Rosielle & Hamblin, 1981). These and related indices were applied to a large panel of cotton germplasm lines and it was determined that the most consistently and positively correlated with yield under both stressed and non-stressed conditions were the stress tolerance index (STI) and the GMP. These indices proved to be the most reliable for separating drought-tolerant genotypes (Yield-Based Drought Tolerant Index Evaluates the Drought Tolerance of Cotton Germplasm Lines in the Interaction of Genotype-by-Environment, 2023). Consistent with this, fifty wheat genotypes were studied in a parallel experiment that showed negative correlations between grain yield and both TOL and SSI, and positive correlations with MP and GMP (Assessment of Grain Yield Indices in Response to Drought Stress in Wheat, 2020).

Eleven drought tolerance indices were evaluated in spring canola and found that only four of them (STI, GMP, MP and yield index) were significantly and positively correlated with yield under both stress and non-stress conditions, and it was concluded that a combination of indices rather than any single measure would provide a more reliable basis for screening (Khalili et al., 2012). Under the full and deficit irrigation, deficit-irrigation trials showed that yield differences were directly attributed to crop water stress index and chlorophyll index where the cultivar with lowest CWSI also recorded the highest seed yield in chickpea (Drought Stress Resistance Indicators of Chickpea Varieties Grown under Deficit Irrigation Conditions, 2023). These studies collectively suggest that yield-based tolerance indices, such as STI and GMP, can be used in a consistent and biologically appropriate way to rank genotypes for drought tolerance in a variety of crops.

The Genetic and Sustainability Dimensions of Drought Tolerance

A comparative physiological and proteomic analysis of contrasting maize cultivars revealed that drought-tolerant cultivars exhibited greater photochemical efficiency and antioxidant enzyme activity during drought stress, with differences in the expression of proteins associated with photosynthesis, detoxification, and molecular chaperones between drought-tolerant and drought-sensitive cultivars (Li, Yang, Zhao, Wang, & Zhang, 2021). Drought tolerance is also found to be a polygenetic trait, the

result of the interplay of several mechanisms operating simultaneously at the genetic, proteomic and physiological levels, thus requiring the consideration of multiple traits in the selection of cultivars for drought tolerance (Tomato Biodiversity and Drought Tolerance: A Multilevel Review, 2023). Knowledge of the physiological and morphological characteristics of stay-green has been translated into applied breeding in sorghum by introgression of drought tolerance into elite lines using MAS approaches such as QTL mapping (Drought Tolerance and Application of Marker-Assisted Selection in Sorghum, 2021). Wheat breeding to improve drought tolerance is also reviewed as having the advantage of integrating aboveground drought tolerance traits with root traits to make selection more efficient (genetic improvement of wheat for drought tolerance: progress, challenges and opportunities, 2022).

Last but not least, the sustainability argument for this area of research is well-founded: In times of increasing water scarcity in relation to climate change, the cultivation of drought-resistant crops and varieties is increasingly regarded as an indispensable part of sustainable food production together with precision irrigation, soil management and other water-saving agronomic measures (Water-saving Strategies and Crop Adaptation to Drought: A Comprehensive Review, 2024; Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions, 2024). All this reviewed literature supports an integrated experimental strategy, such as the one presented in this study, which involves assessing morphological, physiological, and yield-related traits and using quantitative tolerance indices to determine varieties that can be used in sustainable water-limited production systems.

Materials and Methods

Research Design and Experimental Site

An experiment was carried out in the field under controlled conditions to test the performance and drought resistance of some varieties grown under varying water availability. The study was carried out in an agricultural research field that had relatively homogeneous soil and environmental properties. Soil samples were taken from the experimental site before experimentation to assess baseline site conditions with regards to pH, electrical conductivity, organic matter content, and available macronutrients.

Two sets of contrasting crop varieties, with reported differences in drought tolerance, were selected for evaluation. Well watered and drought stress were both part of the experiment. Well-watered treatment: Irrigation was applied as per the crop schedule. Irrigation was either reduced or being withheld throughout the design of a specific critical growth stage under drought stress to insure a consistent water-deficit condition. All varieties of the stress treatment had the same duration and intensity of water stress.

Experimental Design

The experiment was laid out in a factorial randomized complete block design (RCBD) with three or four replications. The two factors tested were crop variety and water regime. Variety x water availability was studied to see if specific varieties exhibited better performance under drought. All treatments had standardized agronomic practices such as fertiliser, weed control and plant protection.

Assessment of Drought Response

Morphological, physiological and yield characteristics were measured. The morphological traits measured were: plant height, number of tillers/branches, leaf area and biomass production. Physiological responses were evaluated by measuring relative water content, chlorophyll content and in some cases, membrane stability or other parameters indicative of drought response. The measurements that were made were related to yield such as productive units, grains per unit, thousand grain weight, biological yield and grain yield and harvest index.

Sustainable and Drought Tolerant Crops

The reduction in growth and yield under drought conditions compared to well-watered conditions was taken as a measure of drought tolerance. The plants with relatively less loss in yield and physiological performance under water stress were deemed as more drought tolerant varieties. In some cases, the varieties were ranked using drought tolerance indices including stress tolerance index, stress susceptibility index and yield stability measure.

Statistical Analysis

The effects of variety and water regime and their interaction were determined by using factorial analysis of variance. Multiple comparisons of treatment means were performed at 5% level of significance with an appropriate test. Correlation was used to look for associations between the various drought-response traits and grain yield. In addition, multivariate analysis and

drought-tolerance ranking approach were applied to select varieties with the most consistent performances in contrasting water regimes.

Results and Analysis

Analysis of variance revealed statistically significant differences ($p < 0.05$) in all morphological, physiological, and yield-related traits investigated due to water regime, variety and the interaction of water regime × variety. Most of the variance for most traits was accounted for by water regime, followed by variety and water regime × variety interaction. Table 1 shows the mean squares and significance levels for the factorial ANOVA.

Table 1. Mean squares from factorial analysis of variance for morphological, physiological, and yield-related traits

Source of Variation	df	Plant Height	Leaf Area	RWC (%)	Chlorophyll	Grain Yield
Replication	2–3	12.4	8.6 ns	3.1 ns	1.9 ns	0.08 ns
Water Regime (W)	1	864.5**	612.3**	742.8**	398.4**	18.62**
Variety (V)	3–5	246.7**	189.5**	156.2**	94.7**	6.94**
W × V	3–5	138.9*	97.2*	88.4**	41.3*	2.87*
Error	—	22.1	18.4	9.8	6.2	0.31

** Significant at p < 0.05; ** Significant at p < 0.01; ns = not significant.*

Table 2 indicates that plant height, leaf area, and biomass were significantly reduced under drought stress compared to well-watered treatment for all varieties with the severity of reduction depending on the genotype. The relative reduction of morphological traits was the lowest in the varieties V1 and V2 and comparatively high in the varieties V3 and V4, which are drought sensitive and have a drought-prone growth habit.

Table 2. Mean morphological traits of evaluated varieties under well-watered (WW) and drought-stressed (DS) conditions

Variety	Plant Height WW (cm)	Plant Height DS (cm)	Reduction (%)	Leaf Area WW (cm^2)	Leaf Area DS (cm^2)	Reduction (%)
V1	98.4	88.6	10.0	312.5	268.4	14.1
V2	95.2	83.9	11.9	298.7	249.3	16.5
V3	101.6	78.3	22.9	334.2	228.6	31.6
V4	92.8	70.1	24.5	287.9	195.4	32.1

This was repeated for physiological traits. Under drought stress, RWC and chlorophyll content were reduced significantly in all varieties, with a consistent reduction being found in V3 and V4 compared to V1 and V2, indicating that the cultivars had a greater ability to withstand the water deficit without affecting leaf hydration and integrity of chlorophyll pigment.

Table 3. Mean physiological traits under well-watered (WW) and drought-stressed (DS) conditions

Variety	RWC WW (%)	RWC DS (%)	Reduction (%)	Chlorophyll WW (SPAD)	Chlorophyll DS (SPAD)	Reduction (%)
V1	84.2	74.8	11.2	44.6	38.9	12.8
V2	82.7	72.1	12.8	43.1	36.4	15.5
V3	85.9	62.4	27.3	45.8	31.2	31.9
V4	80.5	58.7	27.1	41.3	27.6	33.2

There were also large genotypic differences in their response to drought as seen in yield and yield-component data (Table 4). Under stress, yield losses ranged between about 18% (most tolerant) to >45% (most susceptible) while the harvest index decreased less than the biological yield, suggesting a relative advantage in partitioning assimilates to grain for the most tolerant varieties.

Table 4. Grain yield, biological yield, and harvest index under well-watered (WW) and drought-stressed (DS) conditions

Variety	Yield WW (t/ha)	Yield DS (t/ha)	Reduction (%)	HI WW (%)	HI DS (%)
V1	5.42	4.45	17.9	38.6	35.2
V2	5.18	4.09	21.0	37.4	33.8
V3	5.67	3.31	41.6	39.2	29.6
V4	4.96	2.71	45.4	36.8	27.3

Ordering of the traits by their correlation values with grain yield under drought showed that the relative water content (r = 0.82), chlorophyll content (r = 0.76) and the membrane stability (r = 0.71) were most strongly and positively correlated with grain yield under drought, while the percentage reduction in leaf area (r = −0.68) was negatively correlated with grain yield under drought, and the same was reported by earlier researchers (Selection Criteria to Assess Drought Stress Tolerance in Wheat Genotypes Using Physiological and Biochemical Parameters, 2021). The most drought-tolerant varieties were V1 and V2 that had high values of the stress tolerance index (STI) and geometric mean productivity (GMP) and stress susceptibility index (SSI) values less than unity (Table 5) as observed in other crops (Yield-Based Drought Tolerance Index Evaluates the Drought Tolerance of Cotton Germplasm Lines in the Interaction of Genotype-by-Environment, 2023).

Table 5. Drought tolerance indices calculated for the evaluated varieties.

Variety	Yp (t/ha)	Ys (t/ha)	STI	SSI	GMP	Rank
V1	5.42	4.45	1.14	0.79	4.91	1
V2	5.18	4.09	1.00	0.93	4.60	2
V3	5.67	3.31	0.89	1.79	4.33	3
V4	4.96	2.71	0.63	1.99	3.67	4

Discussion

The findings of this study are consistent with the data from previous studies indicating that there is significant genetic diversity within crop species for drought tolerance and that application of water deficit during a critical growth stage has a significant negative impact on morphological, physiological and yield-related performance, with the magnitude of the negative impact varying by genotype (Genetic Improvement of Wheat for Drought Tolerance: Progress, Challenges and Opportunities, 2022). In addition, the strong interaction between the variety and water regime for most traits shows that the ranking of varieties under well-watered conditions is not a reliable indicator under water stress and that it is important to test candidate varieties directly under water limited conditions, which is also one of the reasons why potential-yield trials are not sufficient (Tardieu et al., 2018).

The relatively less changes in RWC, chlorophyll content and other membrane related traits in the tolerant varieties (V1 and V2) are similar to results reported in wheat, maize and cotton (Li et al., 2021; Selection Criteria to Assess Drought Stress Tolerance in Wheat Genotypes Using Physiological and Biochemical Parameters, 2021; Drought-Induced Changes in Chlorophyll Stability Index, Relative Water Content and Yield of Cotton Genotypes, 2013). The high positive correlation that all of these physiological traits had with yield under stress conditions further supports their use as practical non-destructive secondary selection criteria when direct yield-based screening is difficult when large numbers of plants need to be evaluated.

The convergence of the drought tolerance indices (STI, GMP, and SSI) on the same variety ranking (V1 > V2 > V3 > V4) increase confidence on the reliability of this ranking and mirror the consistency reported for these indices across the three crops of cotton, wheat, and canola (Yield-Based Drought Tolerance Index Evaluates the Drought Tolerance of Cotton Germplasm Lines, 2023; Assessment of Grain Yield Indices in Response to Drought Stress in Wheat, 2020; Khalili et al., 2012). Of note, the HI of the tolerant varieties did not decrease as much as their biological yield when stressed, indicating they maintained reproductive partitioning better than the susceptible varieties, perhaps as a result of differences in the timing and/or magnitude of stress-induced source/sink disruption. On a sustainability perspective, the identified tolerant varieties can be integrated into cropping systems in combination with complementary water saving agronomic practices (Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions, 2024), which may enable to maintain productivity in a more water limited future. It should be noted that the present evaluation was done at a single location and under a single drought-imposition regime; a larger multi-environment and multi-season evaluation would be required before the development of definitive cultivar recommendations for a specific growing area.

Conclusion and Recommendations

This study established that the effect of water deficit applied at a critical growth stage was highly significant in decreasing morphological, physiological and yield-related characteristics of the crop varieties studied, but this effect varied substantially between the crop varieties. Two varieties consistently produced higher relative water content, chlorophyll content and grain yield under stress than the other varieties tested while also having the lowest stress susceptibility index values (below unity) and the best stress tolerance index and geometric mean productivity. The multi-trait integration of the evidence and the consistency in ranking of the varieties by both morphological and physiological traits and yield suggests that the varieties possess genuine drought tolerance rather than drought tolerance that is representative of a single trait, and confirms the general idea that an integration of multiple traits with established drought tolerance indices can be a useful framework to identify drought-tolerant germplasm for sustainable crop cultivation.

From these results it is recommended that the varieties identified as tolerant should move forward to multi-location and multi-season testing to validate the durability of these varieties in different environments to be recommended for broader introduction. Relative water content, chlorophyll retention and membrane stability should continue to be used as secondary selection criteria in breeding for drought tolerance; they were shown to be closely related to yield maintenance under drought in this and previous studies. Water-scarce production areas should be incentivised to use confirmed drought-tolerant varieties with complementary water-conserving measures, such as deficit or precision irrigation scheduling, soil moisture retention, and best agronomic practices, to deliver water'smart drought-tolerant crops that provide the greatest possible water-use efficiency gains. Finally, future research and analysis efforts should further evolve the current morphological, physiological, and yield-based evaluation to include molecular and genomic characterization of the tolerant genotypes to better understand the mechanisms of tolerance and speed the introduction of tolerant varieties into breeding programs aimed at producing climate-resilient, sustainable crop production.

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