Drought Tolerance in Soybean (Glycine max L. Merr.) Genotypes during the Flowering Stage of Development

---

ABSTRACT

Aims: To access the responses of 22 soybean genotypes under drought stress during the flowering stage of development.

Study design:A completely randomized experimental design (CRD) was adopted in this study. Five seeds of each of the 22 soybean genotypes were planted in 12 liter (L) plastic buckets (with holes at the bottom) containing sandy loam soil, one genotype per pot with three replications in the greenhouse. The setup was repeated to represent experimental (drought-stressed (DS) and control (well-watered (WW) groups respectively.

Place and duration of study: Teaching and Research Farm of the School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghanain 2019.

Methodology: Twenty-one exotic soybean genotypes and a local variety were assessed for their responses to drought stress at the flowering stage of development using pot experiment. One group (experimental) was exposed to drought stress by withholding water for 15 days whilst the other group (control) was watered regularly at three days intervals. Data collected were the number of leaves, plant height, stem girth, leaf area, and number of flowers, at 5, 10, and 15 days after treatment (DAT) and relative leaf water content at 15 days after treatment. The number of days to permanent wilting of the genotypes was also recorded.

Results: Drought stress reduced the number of leaves and plant height significantly,(*P*-values=0.033, 0.000) and (*P*-values=0.004, 0.000) at 10and 15 days after drought treatment respectively. Also, stem girth, leaf area, and number of flowers were significantlyreduced at all sampling dates (*P*-value=0.002, 0.000, 0.000), (*P*-values=0.004, 0.000, 0.000) and (*P*-values= 0.009, 0.000, 0.000) respectively. At 15 DAT, drought significantlyreduced relative leaf water content at $p<0.001$. Genotypes TGX-1989-11F and TGX-1987-62F were the first and last to wilt at 7 days and 16 days after rewatering respectively.

Conclusion: The pot screening method revealed that the number of leaves, plant height, stem girth, leaf area, number of flowers, relative leaf water content, and days to permanent wilting differed significantly (*P*= .05) at 15 days of drought exposure**.**

Keywords: Soybean genotypes, Drought tolerance, Flowering stage, Climate change

1. INTRODUCTION

World food security is faced with the threat posed by water scarcity, a phenomenon known as drought and the most significant among the abiotic stresses. Drought events are predicted to become more frequent and severe due to global environmental changes, and water scarcity in semi-arid areas will likely worsen [1].Everyone including men, women, boys, and girls admitted that drought was the cause of food insecurity in a survey conducted in Somalia [2]. They further reported that to cope with the ever-increasing food insecurity, they resorted to rationing of food intake [2]. To obtain good yields, an important crop such as soybean needs enough water availability during its growing cycles [3]. Drought stress, on the other hand, produces more than just harm to plants. To compensate for the damage and losses caused by drought stress, soybean plants might display progressive physico-biochemical growth compensation or overcompensation in terms of metabolism and growth and development after a particular level of dehydration and for a short period following rehydration [4] [5][6].

Drought stress can drastically reduce chlorophyll a, b, and total chlorophyll levels [7]. Drought damage is mainly ascribed to the inhibition and disruption of photosynthesis, which is the essential process for sustaining plant growth and recovering from drought [8]. This damage can occur at any stage of soybean growth.[8]. Plants employ compensation as a key self-regulation mechanism to guard against environmental shocks or damage. It is also an important physiological reference for successful water control in plants and a signal of extremely water-efficient agriculture [9][10]. For many years, researchers have screened genotypes for drought tolerance using photosynthetic-related traits, especially chlorophyll content [11]. Plant growth and development are governed by the synchronization of multiple endogenous hormones and physio-biochemical processes. Endogenous hormones are the most important regulators throughout the plant's life cycle, and they play a role in stress signal transduction when plants are challenged. These hormones control plant physio-biochemical metabolism, growth, and development by opposing endogenous hormone regulation to improve plant tolerance to a harsh environment [12][4] Plant drought resistance is characterized by osmoregulation, in which the quantity of malondialdehyde (MDA), a result of membrane lipid peroxidation that happens when plants are stressed, can reflect the degree of cell membrane damage [13][12]. The antioxidant system can actively adapt, maintain, and eliminate reactive oxygen species (ROS). When soybeans are faced with water stress, for example, the activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) frequently rise, as does the MDA level [14]. Antioxidants that accumulate in cells, such as pro). The study aimed at screening for drought tolerance in soybeans by assessing their responses to drought stress. Twenty-two (22) soybean genotypes were screened for their drought tolerance level at the flowering stage of development at 5, 10, and 15 days of drought exposure using pot experiment. Screening for drought tolerance is therefore, a necessity in the era of climate change to help alleviate the challenges posed by food insecurity.

2. MATERIAL AND METHODS

2.1 Study site

The study was carried out in a greenhouse at the School of Agriculture and Natural Sciences Technology Village, of the College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast, Ghana. The area is located on latitude 05o08' N and longitude 01o20' W and is characterized by a coastal savannah agro-ecology and Acrisol soil type [15]

2.2 Experimental materials and sources

Twenty-one out of the 22 soybean genotypes used in this study were obtained from the International Institute of Tropical Agriculture (IITA). The remaining genotype ANIDASO, is a local check from the Crop Research Institute of the Council for Scientific and Industrial Research, Ghana.

Table 1. Soybean genotypes used for the study

S/N.	Genotype	S/N	Genotype.
1	TGX-1990-114FN	12	TGX-1990-40F
2	TGX-1993-4FN	13	TGX-1988-5E
3	TGX-1989-75FN	14	ANIDASO
4	TGX-1987-62F	15	TGX-1990-52F
5	TGX-1990-78F	16	TGX-1990-95F
6	TGX-1989-48FN	17	TGX-1990-46F

7	TGX-1985-10E	18	TGX-1990-57F
8	TGX-1989-11F	19	TGX-1989-49FN
9	TGX-1990-21F	20	TGX-1990-55F
10	TGX-1990-110F	21	TGX-1989-68FN
11	TGX-1989-45F	22	TGX-1989-40F

Source: The authors

2.3 Experimental design and plant culture

A completely randomized experimental design (CRD) was adopted in this study. Five seeds for each of the 22 soybean genotypes were planted in 12 L plastic buckets (with holes at the bottom) containing sandy loam soil, one genotype per pot with three replications in the greenhouse. The setup was repeated to represent experimental (drought-stressed (DS) and control (well-watered (WW) groups respectively.

After emergence, thinning out was carried out leaving one plant per pot. Hand weeding was also done the first week after planting and subsequently when necessary. A total of one hundred and thirty-two (132) buckets were used for the drought screening at the flowering stage with its corresponding number of plants. Sixty-six (66) of the pots were watered with 1500 ml of water every three days until 48 days after planting (48 DAP) when water was withdrawn. The remaining 66 pots were watered throughout the experiment to serve as the control. The drought-stressed plants were rewatered after 15 DAT and monitored till the day of permanent wilting. The soybean genotypes were ranked based on the relative percentage of each parameter determined by the ratio of individual performance of a genotype under water stress to that of the well-watered as described by AbdouRazakou [16]. The soybean genotype which recorded the highest value of relative percentage was termed most tolerant, while the most susceptible was the one which recorded the lowest value.

2.4 Ranking soybean genotypes based on the relative percentages of six growth and yield parameters

The 22 soybean genotypes were ranked according to their tolerance level to water stress. The scoring was done in such a way that genotypes with the highest total score value of relative percentage were scored number twenty-two (22), followed by subsequent scores (21, 20) to the lowest relative percentage [16].

In the greenhouse it was adopted that any genotype that recorded a total (summation) relative percentage value from 103-132 for the growth and yield parameters may be considered highly tolerant, from 73-102 may be considered moderately tolerant, and lastly susceptible if less than 73.

The scale made was as follows:

103→132: highly tolerant

73→102: moderately tolerant

<73: susceptible

2.5 Data collection and analysis

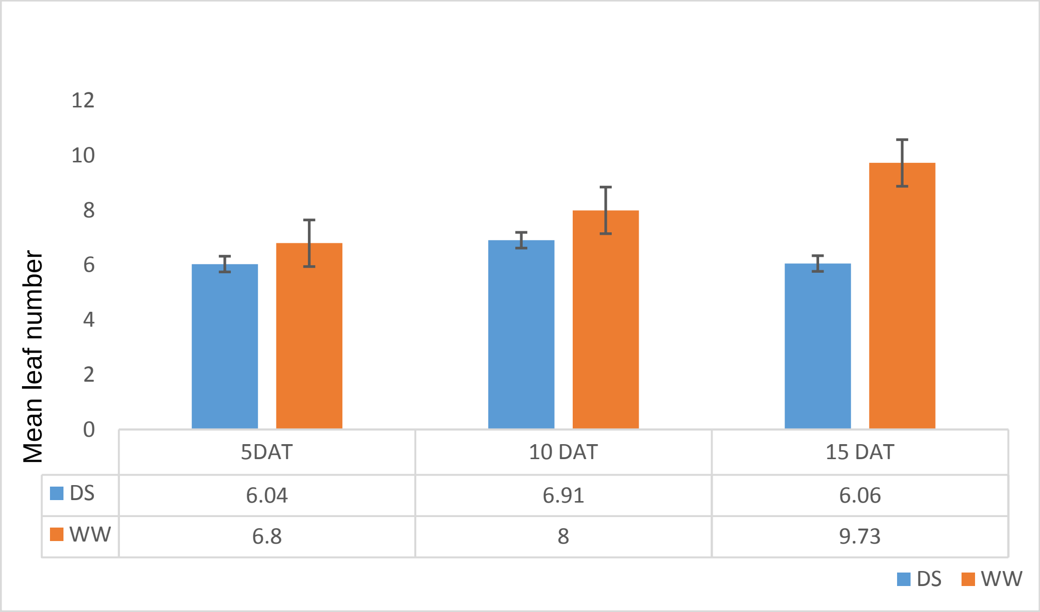
Data were collected at 5, 10, and 15 DAT, and three plants were selected from each treatment. Parameters measured were the number of leaves, plant height, stem girth, leaf area, number of flowers, relative leaf water content, and number of days to permanent wilting. The total number of leaves was counted and recorded at each sampling date. Plant height was measured from the base of the stem just above the soil surface with a meter rule. The stem girth was measured with a digital vernier caliper at 1.5 cm above the soil surface. The leaf area was estimated by measuring the widest part of the leaf as the width [17] and measuring the length of the leaf along the midrib up to the tip of the leaf with a ruler. The leaf area was then calculated as follows:

Leaf area (cm^2) = 0.75 x length (cm) x width (cm). The number of flowers was also counted and recorded. The relative leaf water content was recorded for each soybean genotype at 15 DAT. The relative leaf water content was measured by taking 0.1g fresh leaves (Wf), soaking them in distilled water for 12 h, weighing saturated (Wt), then putting them into an oven at 105^{O}C for 10-15 minutes and then drying them to a constant weight (Wd) at 80^{O}C [18]. The relative leaf water content was computed as RWC % = $(Wf - Wd)$/(Wt-Wd) x100. The number of days to permanent wilting was counted for each soybean genotype after rewatering at 15 DAT. Days to permanent wilting were recorded for each genotype and the average days to permanent wilting were calculated. Growth and yield data were analyzed using analyses of variance (ANOVA) in MINITAB software version 18. Individual means of water-stressed genotypes were compared to their corresponding well-watered in a One-way ANOVA to determine differences in treatment means.

3. RESULTS AND DISCUSSION

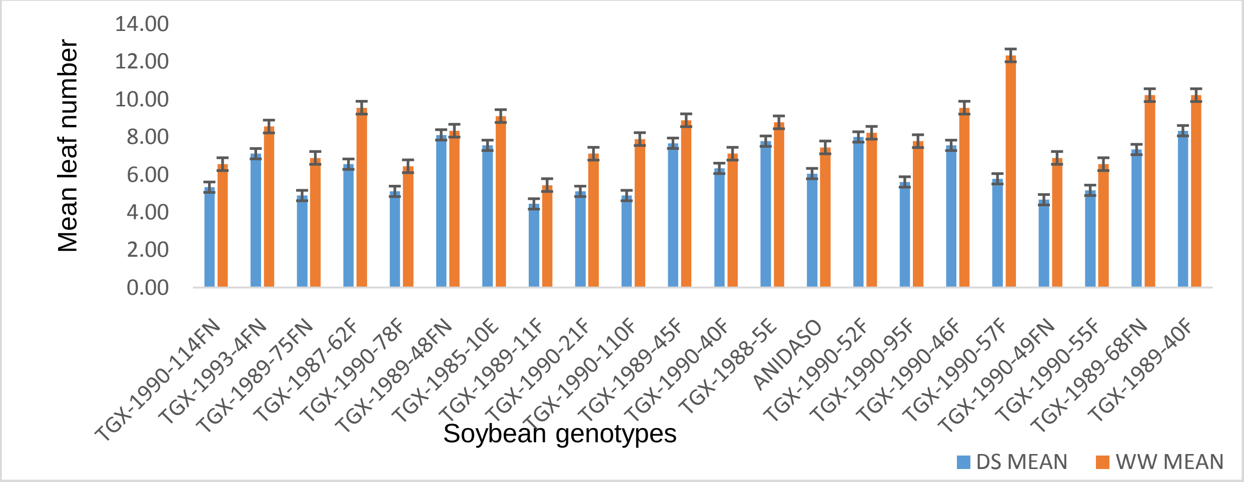
3.1 Number of leaves

Drought-stressed (DS) and control (WW) plants had similar leaf numbers of 6.04 and 6.80 respectively (Figure 1a). Drought stress reduced the number of leaves significantly (p <0.05, P-values = .033, .000) at 10 DAT and 15 DAT. The highest mean leaf numbers of 8.3 and 12.33 were recorded for TGX-1989-40F and TGX-1990-57F for the DS and WW groups respectively (Figure 1b). Drought reduced number of leaves at the flowering stage by 22.50 %.



Source:Calculated and collated according to statistical software.

Figure 1a. Mean leaf number among drought-stressed (DS) and control (WW) plants of soybean at the flowering stage at 5, 10, and 15 DAT. Values are means of three replicates.

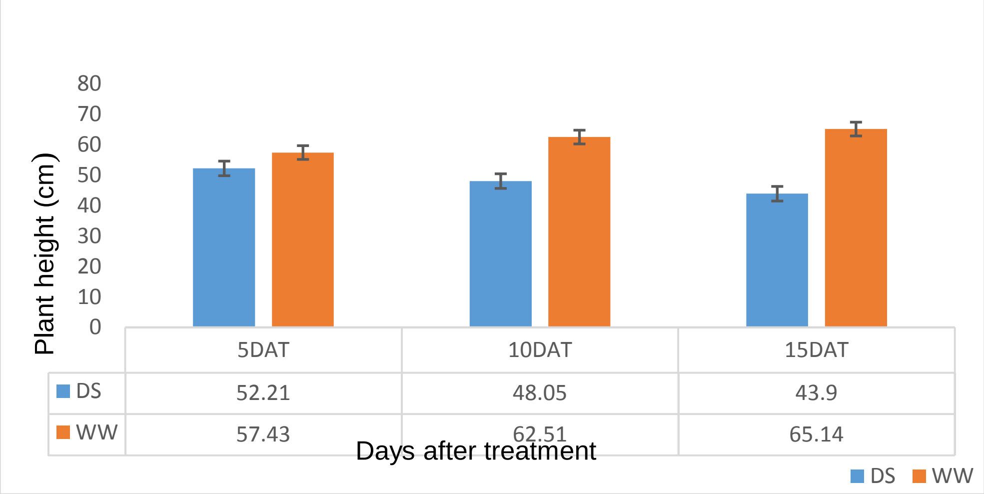


Source: Calculated and collated according to statistical software.

Figure 1b. Mean leaf number among drought-stressed (DS) and control (WW) plants of soybean

Plant height

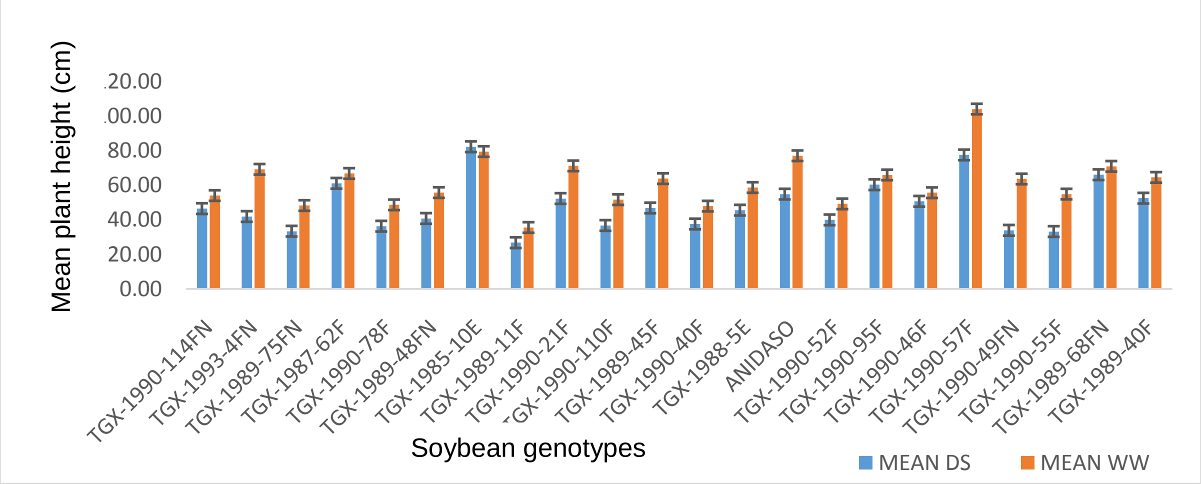
Generally, drought stress affected plant height (Figure 2a). It reduced plant height significantly *(P*-values= .004, .000) at 10 and 15 DAT. (Fig. 2a). TGX-1990-57F recorded the highest plant height of 77.54 cm and 104.11 cm for both the drought-stressed and the control groups respectively (Figure 2b). Drought stress therefore reduced plant height by approximately, 22.1 %.



	5DAT	10DAT	15DAT
■ DS	52.21	48.05	43.9
■ WW	57.43	62.51	65.14

Source: Calculated and collated according to statistical software.

Figure 2a. Mean plant height among drought-stressed (DS) and control (WW) plants of soybean at the flowering stage at 5, 10, and 15 DAT. Values are means of three replicates.

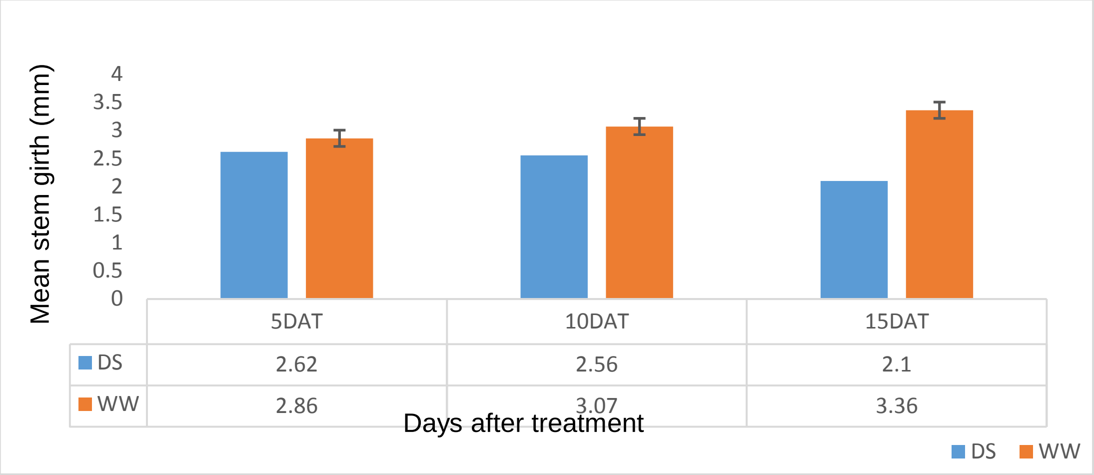


Source: Calculated and collated according to statistical software.

Figure 2b. Mean plant height among drought-stressed (DS) and control (WW) plants of soybean

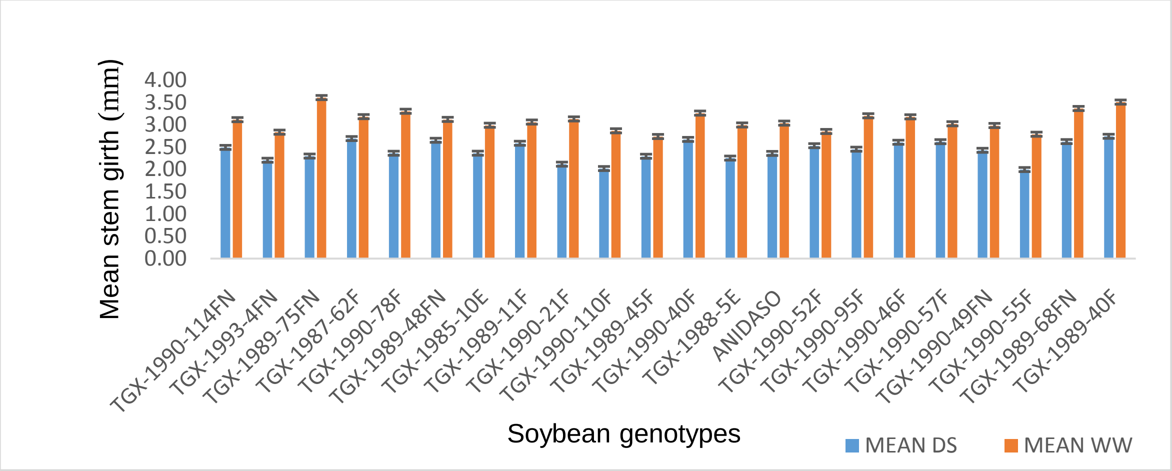
Stem girth

At 5, 10, and 15 DAT, stem girth was reduced significantly (*P*-values = .002, .000, and .000 respectively) (Figure 3a). Thus, drought stress affected stem girth negatively. The highest stem girth of 2.74 mm and 3.51 mm for the DS and WW groups respectively were recorded in genotype TGX-1989-40F (Fig. 3b). Stem girth was reduced by drought stress at approximately 21.7 %



Source: Calculated and collated according to statistical software.

Figure 3a. Mean stem girth among drought-stressed (DS) and control (WW) plants of soybean at the flowering stage at 5, 10, and 15 DAT. Values are means of three replicates.

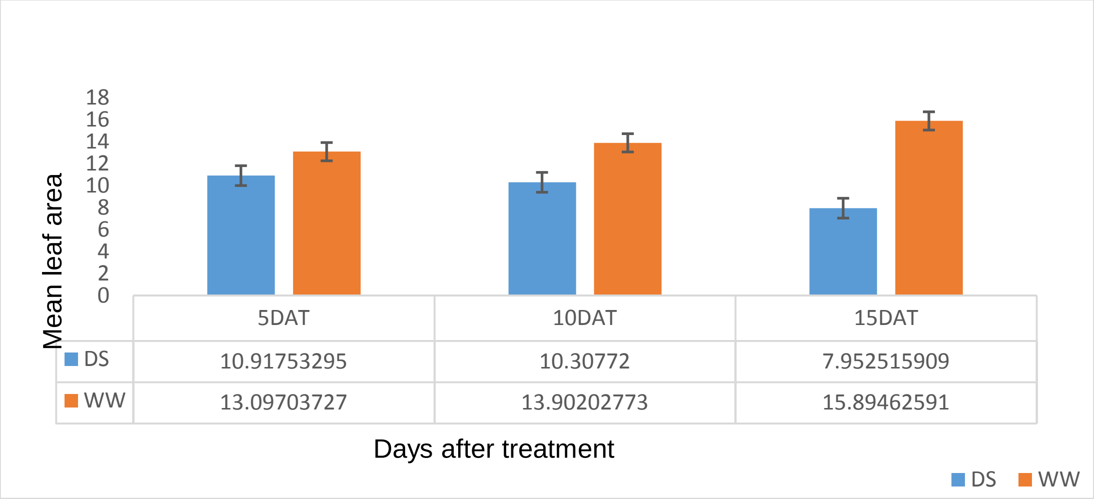


Source: Calculated and collated according to statistical software.

Figure 3b.Mean stem girth among drought-stressed (DS) and control (WW) plants of soybean

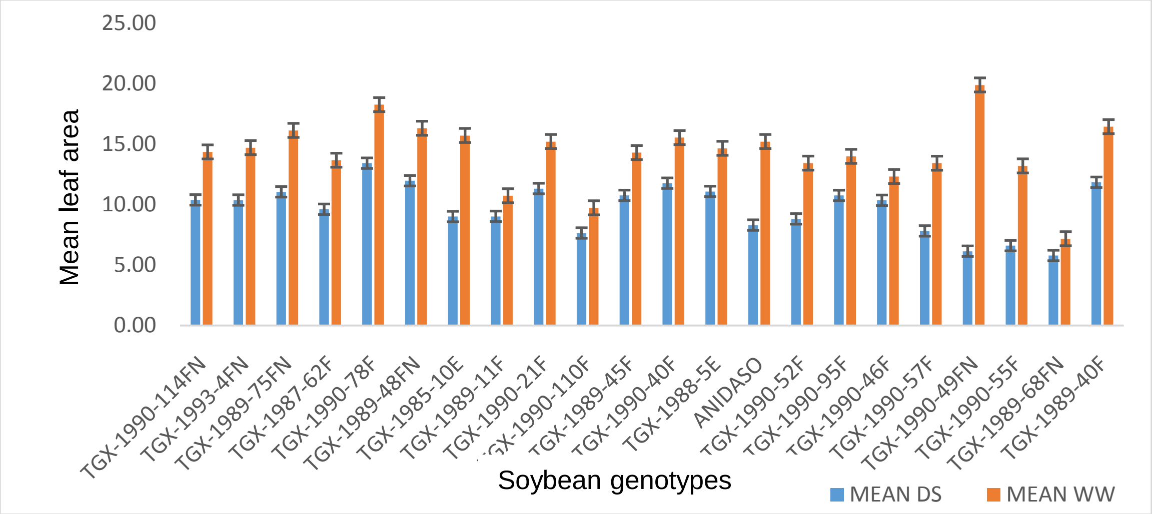
Leaf area

Leaf area was reduced significantly at all sampling dates (Figure 4a) (*P*-values = .004, .000 and .000) respectively. The mean leaf area for the DS and WW groups were 9.73 cm^2 and 14.30 cm^2 respectively. Genotypes TGX-1990-78F and TGX-1990-49FN had the highest mean leaf area of approximately 13.43 cm^2 and 18.27 cm^2 among the DS and WW groups respectively (Figure 4b). Drought reduced leaf area by approximately 31.97 %.



Source: Calculated and collated according to statistical software.

Figure 4a. Mean leaf area among drought-stressed (DS) and control (WW) plants of soybean at 5, 10, and 15 DAT. Values are means of three replicates

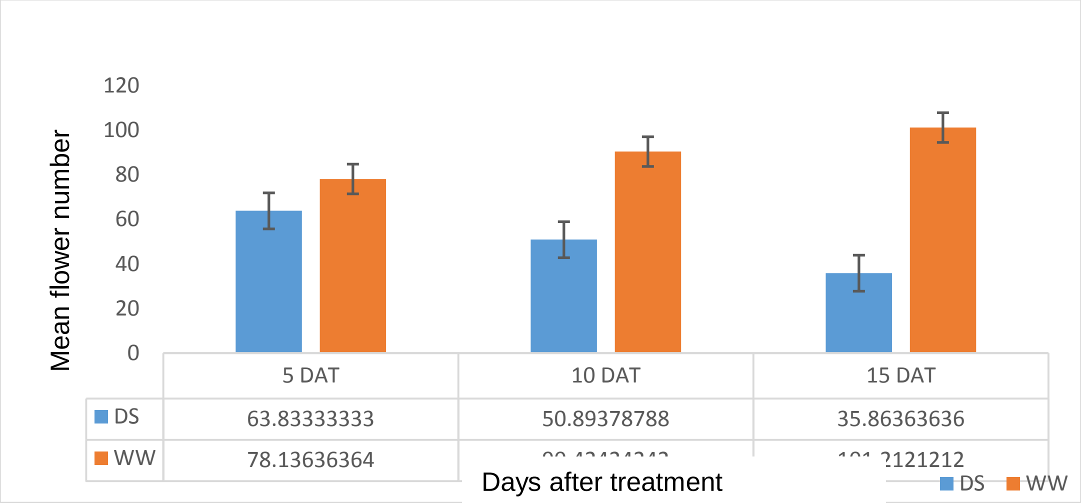


Source: Calculated and collated according to statistical software.

Figure 4b. Mean leaf area among drought-stressed (DS) and control (WW) plants of soybean.

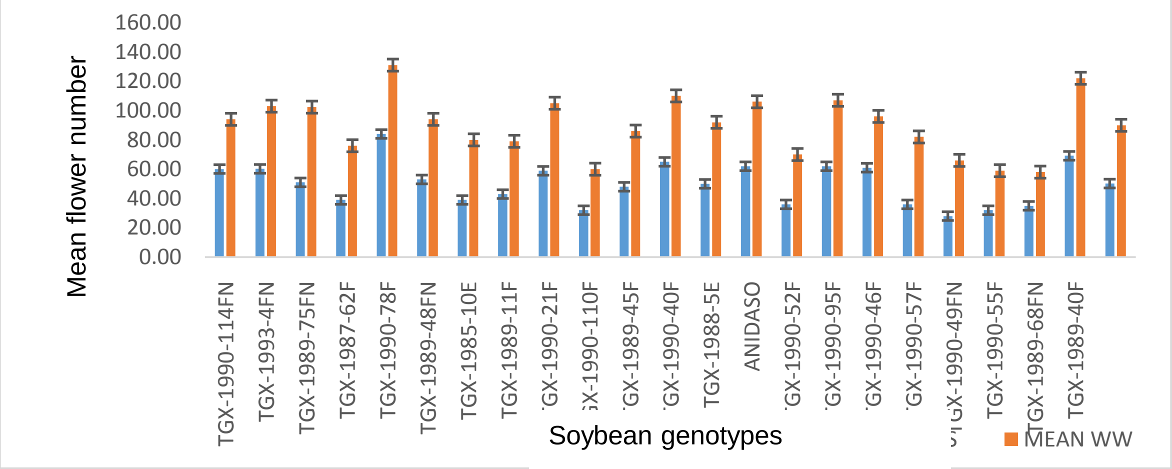
Number of flowers

The number of flowers experienced a significant (*P*-values= .009, .000, .000) reduction by drought stress at all sampling dates (5, 10, and 15 DAT) (Figure 5a). Among the DS group, genotype TGX-1990-78F recorded the highest mean flower number of 84.00 (Figure 5b). Genotype TGX-1990-78F again had the highest mean flower number (131.00) among the WW group. Drought stress therefore reduced flower number by approximately 44.1%.



Source: Calculated and collated according to statistical software.

Figure 5a. Mean flower number among drought-stressed (DS) and control (WW) plants of soybean at 5, 10, and 15 DAT. Values are means of three replicates.

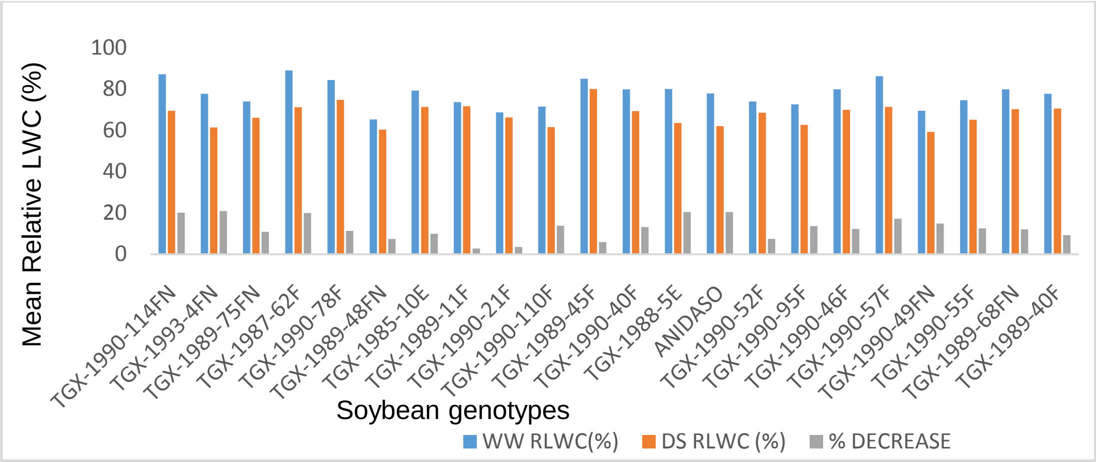


Source: Calculated and collated according to statistical software.

Figure 5b. Mean flower number among drought-stressed (DS) and control (WW) plants of soybean

Relative Leaf Water Content (RLWC)

The relative leaf water content was highly significantly ($p < 0.001$) reduced by drought stress at 15 DAT (Figure 6). The mean RLWC of the DS and WW plants were 70.5 % and 77.6 % respectively (Figure 6). Among the genotypes under drought stress conditions (DS), TGX-1989-45F had the highest relative leaf water content of 80.0 % (Figure 6). However, TGX-1987-62F had the highest relative leaf water content of 89.0 % among the WW (Figure 6). The percentage decrease in RLWC caused by drought in TGX-1989-45F was 5.89 % as compared to 20 % in TGX-1987-62F. TGX-1990-49FN and TGX-1989-48FN had the lowest RLWC among the DS and the WW respectively. On average, drought stress reduced relative leaf water content by 9.1 %.

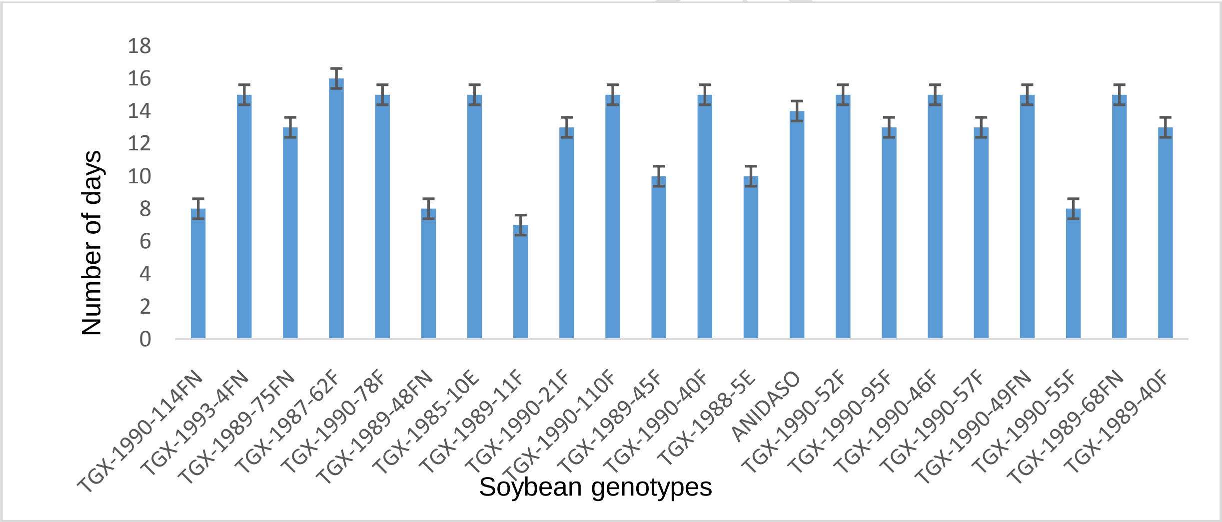


Source: Calculated and collated according to statistical software.

Figure 6. Mean RLWC of drought-stressed and control plants of soybean at the flowering stage at 15 DAT. Values are means of three replicates

Days to permanent wilting

Genotype TGX-1989-11F was the first to wilt permanently at 7 days after re-watering whilst it took genotype TGX-1987-62F, 16 days (the highest number of days) to permanent wilting (Figure 7). TGX-1990-114FN, TGX-1989-48FN, TGX-1989-11F, and TGX-1990-55F wilted permanently before 10 days whilst TGX-1989-45F and TGX-1988-5E wilted permanently at 10 days after rewatering. There was an approximately 56.3 % decrease in number of days to permanent wilting between the longest day and shortest day to permanent wilting.

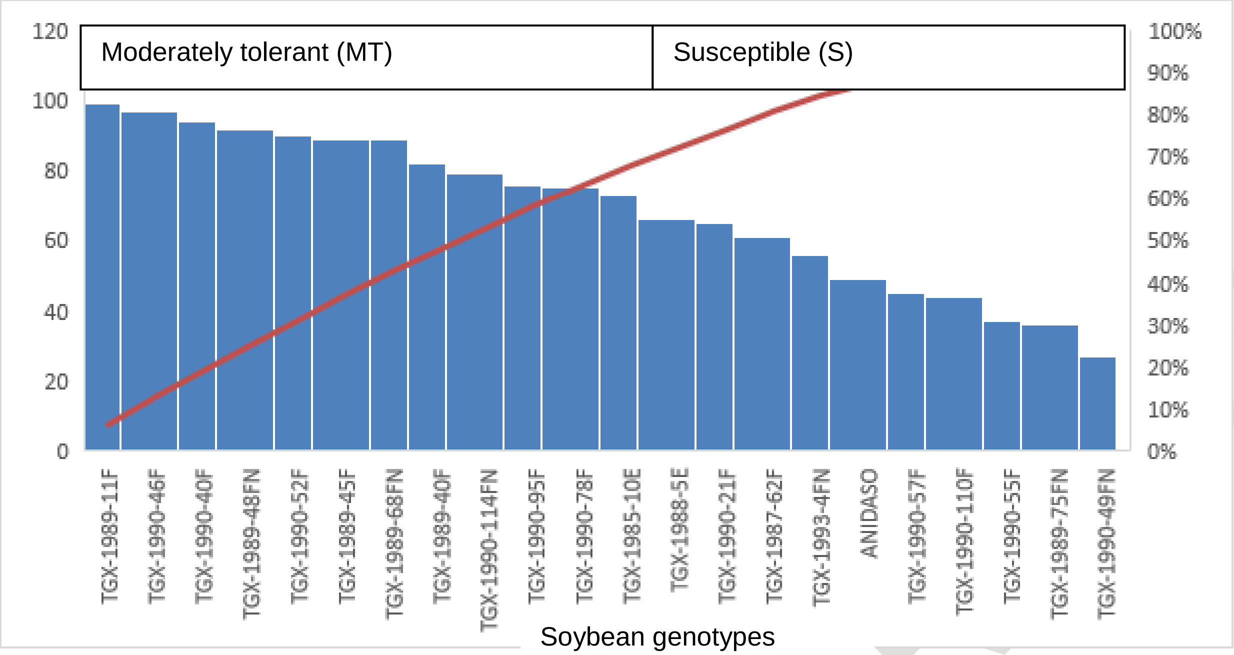


Source: Calculated and collated according to statistical software.

Figure 7. The mean number of days to permanent wilting after rewatering of 22 soybean genotypes at the flowering stage exposed to 15 days of drought stress.

Scores and rankings of soybean genotypes based on their relative performance in the five growth and yield parameters

The scores and rankings of soybean genotypes at the flowering stage have been indicated in Figure 8. Ten (10) genotypes scored between 0 and 72 and were therefore labeled as drought-susceptible. Twelve (12) genotypes had total scores between 72 and 102 and were also ranked as moderately tolerant to drought stress (Figure 8). None of the soybean genotypes were found to be highly tolerant to drought stress at the flowering stage. In descending order, the first three best performers were TGX-1989-11F, TGX-1990-46F, and TGX-1990-40F. The first three medium performers in descending order were TGX-1990-52F, TGX=1989-68FN, and TGX-1989-45F. However, genotypes TGX-1988-5E, TGX-1990-21F, and TGX-1987-62F were the top three worst performers in descending order.



Source: Calculated and collated according to statistical software.

Figure 8. Scores and rankings of soybean genotypes based on their relative performance in the five growth and yield parameters at the flowering stage; MT: Moderately tolerant (12), S: Susceptible (10)

4. Discussion

Plant morphological characteristics directly reflect the growth and development of crops [19]. Plant height is one of the most important indicators of plant growth and development, and it reflects the growth rate. The leaf area is also an important parameter related to the amount of light energy captured by crops, and therefore it directly affects photosynthesis, transpiration, and the final yield.

4.1 Number of Leaves and Leaf Area

The results obtained for the number of leaves and leaf area imply that the drought effect on leaf initiation and expansion was very critical. Therefore, TGX-1989-40F, TGX-1990- 57F, and TGX-1990-78F which performed well even under drought conditions, possessed the characteristics for adaptation to a water-limited environment. Other scientists have reported similar results to the current study.Basal and Szabo confirmed in their studies that comparing the partially and fully-irrigated groups, respectively, to the nonirrigated counterpart, irrigation increased the Leaf area index (LAI) by 8.3 and 14.9% of the soybean plants [20]. This was due to the decreased production of new leaves, increased leaf shedding, and decreased average leaf size. Leaf production and leaf expansion were therefore the two phenomena most sensitive to water stress [19]. Sun et al. have also reported that continuous drought stress had a greater effect on the leaf area of winter wheat reducing it by 30 % when compared to the control [21] They also emphasized that different levels of water stress applied on chickpea and soybean plants showed that stress conditions have a more devastating effect in soybean as compared to chickpea.

4.2 Plant Height

The drought effect on plant height in this study aligned with an observation made by Elsalahy and Reckling. They reported a decrease in soybean plant height caused by drought stress both at the vegetative and flowering stages[22]. That being said, it is possible that, regardless of the stage of plant growth, the processes of cell division and expansion were significantly impacted by dry conditions, resulting in shorter plants [23][24]. From Licht and Archontoulis's perspective, soybean plants have shorter plant height and smaller leaves as a result of lack of water, nutrient availability, and nutrient uptake [25].

4.3 Stem girth

Statistically drought stress significantly (*P*= .05) reduced stem girth at all sampling dates. The present result is in agreement with the findings of Du and his colleagues. Their research revealed that soybean stem, root, and seed biomass was reduced by drought stress during the reproductive stages [26]and a lower biomass allocation to the seed as compared to the control, which ultimately resulted in a decrease in seed weight [26]. Under drought stress, plants lose a significant amount of their yield and their ability to produce and mobilize assimilates to develop seeds.In another study by Gallardo et al, stem growth rate (SGR) was found to be most sensitive to drought during the early growth stages whilst maximum daily stem shrinkage (MDS) was at the late growth stage [27]. Shrinking expansion of the stem occurs in response to changing water potential in the xylem [28] [29][30]. More daily shrinkage of the stem under water-stressed conditions hinders the growth of the stem [31].

4.4. Number of flowers

The reduction in flower number was apparent and significant (*P*= .05) at all sampling dates (5, 10, and 15 DAT). The result of the present study was in support of work done by other scientists. Lenssen also observed that soybean plants were most sensitive to intense drought and prolonged stress during the flowering and early pod-fill growth stage [32]. He also mentioned that drought can cause floral abortion, reduced pod number, fewer seeds per pod, and reduced seed size. Moderate drought stress can significantly reduce or stop nitrogen fixation, disrupting seed development [32].

4.5 Relative Leaf Water Content (RLWC).

Statistically, drought stress significantly ($p < 0.05$) reduced the RLWC of the genotypes after 15 days of drought exposure. This was in agreement with results from Chowdhury et al. They reported that water stress significantly reduced the relative leaf water content of three soybean genotypes at different growth stages due to higher evaporation resulting from increased temperature and light intensity [33]. They concluded that plants grown under water-stress conditions showed a lower RWC than those grown under non-stress conditions [33]. According to Lugojan and Ciulca, leaf relative water content is an important indicator of water status in plants. It shows whether the water supply to the leaf tissue is balanced to the rate of transpiration [34].

4.6 Days to Permanent Wilting

TGX-1987-62F and TGX-1989-11F recorded the highest (16) and lowest (7) number of days to wilting respectively. (Fig. 7). TGX-1987-62F probably had an inherent adaption to wilting compared to other genotypes. The mean number of days to permanent wilting after 15 DAT was 12.77 (Fig. 7). Eleven of the genotypes wilted permanently by the end of two weeks (14 days) after 15 DAT. (Fig. 7). The remaining seven genotypes wilted permanently by the end of day 16. Six of those seven genotypes wilted at day 15 with the earlier mentioned genotype TGX-1987-62F wilting permanently at day 16 after 15 DAT. Statistically, drought significantly reduced the number of days to wilting. Novak and Lipiec reported that plantsresponded to water stress in the form of hydraulic signaling, that is, decreased root growth, water uptake, water potential, turgidity, and leaf expansion [35]. Water stress reduces water potential and transpiration rate thereby reducing cell turgor and relative water content damaging the plant cell (wilting). This condition was seen after a few days in the susceptible genotypes especially, TGX-1989-40F, TGX-1989-11F, and TGX-1990-114FN. According to Ribas-Carbo and other researchers, drought stress decreases the photosynthesis rate in soybean plants by 40 % and 70 % in mild and severe stress conditions respectively [36]. Flexas and colleagues also reiterated that plant growth, plant survival, and yield are determined by the downregulation and inhibition of photosynthesis under water stress [37].

4.7 Scoring and Ranking of Soybean Genotypes

The 15 days drought treatment at the flowering stage scored and ranked the soybean genotypes as highly drought tolerant (T), moderately drought tolerant (MT) and drought susceptible (S) (Fig. 8). After the drought screening, none of the 22 soybean genotypes was ranked as T. Twelve (54.5 %) were MT and the remaining 10 (45.5) were S (Fig. 8). The MT group had a total relative percentage score ranging from 73 to 99. The genotype with the highest total score TGX-1989-11F scored 97.1 % of the maximum total score of 102. On the other hand, the genotype with the lowest total score among the MT group was TGX-1985-10E. It scored 91.7 % of the maximum total score of 102. The Soybean genotypes had a total score ranging from 27 to 66. The genotype with the highest total score TGX-1988-5E scored 91.7 % of the maximum total score of 72. However, TGX-1990-49FN recorded the lowest total score of 27 and 37.5 % of the maximum total score. The soybean genotypes that were ranked MT probably experienced a moderately damaging effect from the drought stress on their growth and yield parameters. Drought-susceptible (S) genotypes however may have been faced with a highly damaging effect from the drought stress on their growth and yield parameters.

CONCLUSION

Drought stress reduced the number of leaves, plant height, stem girth, leaf area, number of flowers, relative leaf water content, and days to permanent wilting among the soybean genotypes. The number of leaves, stem girth, leaf area, and number of flowers were the most sensitive to drought stress. The drought effect was dependent on the period of exposure, the longer the period, the more intense the deleterious effect. The pot experiment revealed 12 (54.5 %) of the soybean genotypes to be moderately drought tolerant (MT)(TGX-1989-11F, TGX-1990-46F, TGX-1990-40F, TGX-1989-48FN, TGX-1990-52F, TGX-1989-45F, TGX-1989-68FN, TGX-1990-114FN, TGX-1990-95F, TGX-1990-78F, TGX-1985-10E, TGX-1989-40F) and 10 (45.5 %) to be drought susceptible after 15 days of drought exposure.

REFERENCES

References must be listed at the end of the manuscript and numbered in the order that they appear in the text. Every reference referred to in the text must also be present in the reference list and vice versa. In the text, citations should be indicated by the reference number in brackets [3].

1. Hoegh-Guldberg O, Jacob D, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi K, Engelbrecht F, Guiot J, Hijioka Y. Impacts of 1.5 C global warming on natural and human systems. Global warming of 1.5° C. 2018. https://helda.helsinki.fi/bitstream/handle/10138/311749/SR15_Approval_Chapter_3.pdf?seque=
2. IPC C, Pilot RG. Gender, Food Insecurity & Drought. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=food+security+and+drought%2B2023pdf&btnG=
3. Buezo J, Sanz-Saez Á, Moran JF, Soba D, Aranjuelo I, Esteban R. Drought tolerance response of high-yielding soybean varieties to mild drought: physiological and photochemical adjustments. Physiologiaplantarum. 2019 May;166(1):88-104.https://onlinelibrary.wiley.com/doi/pdf/10.1111/ppl.12864?casa_token=_PVSlsR3oCkAAAAA:RwqaDxLkrvhprdyL3jwbIds6hLK7kks7whLCFkOf6AH44YxlYAJ7QGRjOntl3_MS4kW6klDnDIjGqtS-
4. Hao S, Guo X, Wang W. Aftereffects of water stress on corn growth at different stages. Transactions of the Chinese Society of Agricultural Engineering. 2010 Jul 1;26(7):71-5. https://www.ingentaconnect.com/content/tcsae/tcsae/2010/00000026/00000007/art00012?crawler=true&mimetype=application/pdf
5. Liu H, Zheng W, Zheng F, Wang L. Influence of rewatering on the compensatory effect of maize seedling roots with diluted seawater irrigation. Transactions of the Chinese Society of Agricultural Engineering. 2012 Mar 1;28(3):101-6. https://www.ingentaconnect.com/content/tcsae/tcsae/2012/00000028/00000003/art00018?crawler=true&mimetype=application/pdf
6. Xue H Y. et al. Responses of spectral reflectance, photosynthesis, and chlorophyll fluorescence in cotton during drought stress and rewatering. ScientiaAgriculturaSinica. 2013; 46.1: 2386-2393.
7. Wu ZL, Zhang YZ. Effects of exogenous auxin on physiological and biochemical characteristics of soybean under PEG simulated drought stress. Hubei Agricultural Sciences. 2019 Mar 25;58(6):16.
8. Sakoda K, Taniyoshi K, Yamori W, Tanaka Y. Drought stress reduces crop carbon gain due to delayed photosynthetic induction under fluctuating light conditions. PhysiologiaPlantarum. 2022 Jan;174(1): e13603. https://onlinelibrary.wiley.com/doi/am-pdf/10.1111/ppl.13603
9. Luo Y, Bi T, Su Z, Cui X, Lan Q. Physiological response of Kalanchoetubiflora leaves to drought stress and rewatering. Journal of Tropical and Subtropical Botany. 2014;22(4):391-8.
10. LI GH, WAN YS, LIU FZ, ZHANG K. Photosynthetic characteristics in different peanut cultivars under conditions of drought and re-watering at the seedling stage. Chinese Journal of Plant Ecology. 2014;38(7):729. https://www.plant-ecology.com/EN/10.3724/SP.J.1258.2014.00068
11. Monteoliva MI, Guzzo MC, Posada GA. Breeding for drought tolerance by monitoring chlorophyll content. 2021 https://m.23michael.com/open-access/breeding-for-drought-tolerance-by-monitoring-chlorophyll-content.pdf
12. Wang N, Yuan M, Chen H, Li Z, Zhang M. Effects of drought stress and rewatering on growth and physiological characteristics of invasive Aegilopstauschii seedlings. ActaPrataculturaeSinica. 2019;28(1):70-8.

13. Li J, Nong Y. Effects of drought stress on growth, physiological and biochemicalcharacteristics of two sugarcane varieties. Anhui Agric. Sci. Bull 24.21 (2018): 25-28. http://www.hbnykx.cn/EN/article/downloadArticleFile.do?attachType=PDF&id=627
14. Wu R, Yang J, Wang L, Xiujuan G. Physiological response of flax seedlings with different drought-resistances to drought stress. ActaAgricBoreali-Sinica. 2019; 34:145-53.
15. Mensah P, Locatelli M, Pugliese E, Poggi P, Bassuah PK, Meucci R. Scanning digital holography at 10.6 μm for large scene reconstruction. Journal of Physics Communications. 2018 May 18;2(5):055018. https://iopscience.iop.org/article/10.1088/2399-6528/aac395/pdf
16. Abdou RI. *Using morphological and physiological factors to evaluate six cowpea varieties for drought tolerance* (Doctoral dissertation).
17. Doggett H. Sorghum, 2nd edn. Tropical agricultural series. Longman Scientific & Technical, Essex, England (1988). https://www.scirp.org/(S(vtj3fa45qm1ean45vvffcz55))/reference/ReferencesPapers.aspx?ReferenceID=1739822
18. Lee HS. Principles and experimental techniques of plant physiology and biochemistry. Higher Education Press, Beijing (in Chinese). 2000. https://www.scirp.org/(S(vtj3fa45qm1ean45vvffcz55))/reference/ReferencesPapers.aspx?ReferenceID=847393
19. Dong S, Jiang Y, Dong Y, Wang L, Wang W, Ma Z, Yan C, Ma C, Liu L. A study on soybean responses to drought stress and rehydration. Saudi journal of biological sciences. 2019 Dec 1;26(8):2006-17.Crossref, https://doi.org/10.1016/j.sjbs.2019.08.005
20. Basal O, Szabo A. Physiomorphology of soybean as affected by drought stress and nitrogen application. Scientifica. 2020 Apr 10;2020. https://www.hindawi.com/journals/scientifica/2020/6093836/
21. Sun X, Henderson G, Cox F, Molano G, Harrison SJ, Luo D, Janssen PH, Pacheco D. Lambs fed fresh winter forage rape (Brassica napus L.) emit less methane than those fed perennial ryegrass (Loliumperenne L.), and possible mechanisms behind the difference. PloS one. 2015 Mar 24;10(3):e0119697.
22. Elsalahy HH, Reckling M. Soybean resilience to drought is supported by partial recovery of photosynthetic traits. Frontiers in Plant Science. 2022 Oct 20;13:971893. https://www.frontiersin.org/articles/10.3389/fpls.2022.971893/full
23. Saleem A, Aper J, Muylle H, Borra-Serrano I, Quataert P, Lootens P, De Swaef T, Roldán-Ruiz I. Response of a diverse European soybean collection to “short duration” and “long duration” drought stress. Frontiers in Plant Science. 2022 Feb 17;13:818766. https://www.frontiersin.org/articles/10.3389/fpls.2022.818766/full
24. Wei Y, Jin J, Jiang S, Ning S, Liu L. Quantitative response of soybean development and yield to drought stress during different growth stages in the Huaibei Plain, China. Agronomy. 2018 Jun 21;8(7):97. https://www.mdpi.com/2073-4395/8/7/97/pdf
25. Licht M, Archontoulis S. Influence of drought on corn and soybean. 2017
26. Du Y, Zhao Q, Li S, Yao X, Xie F, Zhao M. Shoot/root interactions affect soybean photosynthetic traits and yield formation: a case study of grafting with record-yield cultivars. Frontiers in plant science. 2019 Apr 9; 10:445. https://www.frontiersin.org/articles/10.3389/fpls.2019.00445/full
27. Gallardo M, Thompson RB, Valdez LC, Fernández MD. Use of stem diameter variations to detect plant water stress in tomato. Irrigation Science. 2006 May; 24:241-55.
28. Molz FJ, Klepper B. On the Mechanism of Water-Stress-Induced Stem Deformation 1. Agronomy Journal. 1973 Mar;65(2):304-6.
29. Dobbs RC, Scott DR. Distribution of diurnal fluctuations in stem circumference of Douglas-fir. Canadian Journal of Forest Research. 1971 Jun 1;1(2):80-3. Crossref, https://doi.org/10.1139/x71-010.
30. JARVIS PG. Water transfer in plants. Heat and mass transfer in the biosphere. 1975:369-94.
31. Goldhamer DA, Fereres E. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrigation Science. 2001 Jul; 20:115-25. Crossref, https://doi.org/10.1007/s002710000034.
32. Lenssen A. Soybean response to drought. Iowa State University Extension. (2012). https://crops.extension.iastate.edu/
33. Chowdhury SP, Hartmann A, Gao X, Borriss R. Biocontrol mechanism by root-associated Bacillus amyloliquefaciens FZB42–a review. Frontiers in microbiology. 2015 Jul 28; 6:780. https://www.frontiersin.org › fmicb.2015.00780›full.
34. Lugojan C, Ciulca S. Evaluation of relative water content in winter wheat. Journal of Horticulture, Forestry and Biotechnology. 2011;15(2):173-7. https://www.usabtm.ro/JournalHFB/romana/2011/Lista%20lucrari_2011%20PDF/JHFB_15(2)PDF/32Lugojan%20Cristian.pdf

35. Novák V, Lipiec J. Water extraction by roots under environmental stresses. InPollution and Water Resources, Columbia University Seminar Proceedings: Impact of Anthropogenic Activity and Climate Changes on the Environment of Central Europe and USA 2012. New York, NY, USA: Columbia University Press.
36. Ribas-Carbo M, Taylor NL, Giles L, Busquets S, Finnegan PM, Day DA, Lambers H, Medrano H, Berry JA, Flexas J. Effects of water stress on respiration in soybean leaves. Plant Physiology. 2005 Sep 1;139(1):466-73.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1203395/
37. Flexas J, Bota J, Cifre J, Mariano Escalona J, Galmés J, Gulías J, LEFI EK, FLORINDA MARTÍNEZ-CAÑELLAS SA, TERESA MORENO MA, RIBAS-CARBÓ MI, Riera D. Understanding down-regulation of photosynthesis under water stress: future prospects and searching for physiological tools for irrigation management. Annals of Applied Biology. 2004 Jun;144(3):273-83.
Crossref, https://doi.org/10.1111/j.1744-7348.2004.tb00343.x.