Euphytica (2025) 221:44
https://doi.org/10.1007/s10681-025-03493-9

RESEARCH

Selection of soybean genotypes exhibiting drought resistance by assessing morphological and yield traits

Muhammad Amjid · Rüstem Üstün

Received: 29 December 2024 / Accepted: 4 March 2025
© The Author(s) 2025

Abstract Drought stress significantly impacts soybean (*Glycine max* L. Merr.) productivity, making selecting drought-resistant genotypes a critical focus for breeding programs. This study aims to select drought tolerance levels in various soybean genotypes by evaluating key morphological and yield factors. In this study, four different irrigation levels were applied in 2023 and 2024: irrigation stopped at the flowering stage (T1), pod-setting stage (T2), and pod-filling stage (T3), along with a control group (T0) that received regular irrigation. Through field experiments under controlled water stress conditions, we analyzed plant growth parameters and yield such as first pod height, plant height, number of branches, number of pods, seed yield, and 1000-seed weight. The first treatment (T1) at the flowering stage showed higher drought tolerance among the genotypes, likely because the plants had more time to activate their drought response mechanisms. However, the pod-setting stage (T2) was identified as the most sensitive to drought stress, leading to more significant yield reductions. The primary effect at the pod filling (T3) stage was the reduced seed size with wrinkles on the seed surface, which led to a decrease in 1000-seed weight and seed yield per plant despite having a slight difference in seed count per plant compared to control. These highlight the critical nature of the pod-setting stage in soybean cultivation under water-limited conditions. Despite facing a shorter drought than the flowering stage, sensitivity toward drought was the highest in the pod setting stage. Plant height and the number of branches had no significant impact on yield in this study. While T1 resulted in the shortest plants, seed yield and 1000-seed weight were lowest in T2 due to the high sensitivity of plants at that critical growth phase. A comprehensive analysis of data from both years showed that the G7 variety exhibited the highest level of tolerance under water-limited conditions. These findings highlight the importance of incorporating drought-tolerant traits in breeding programs to ensure the sustainability of soybean production in water-limited environments.

Keywords Abiotic stress · Drought · Soybean · Yield · Climate change

M. Amjid · R. Üstün (✉)
Department of Field Crops, Faculty of Agriculture, Akdeniz University, 07070 Antalya, Turkey
e-mail: rustemustun@akdeniz.edu.tr

Introduction

Soybean (*Glycine max* L. Merr.) is one of the most important crops in global agriculture, providing high levels of oil and protein content. It is widely grown for its high nutritional content, valuable fatty acids and oils, protein-rich animal feed, and various food products. The soybean seeds contain approximately 36–40% protein, 18–20% oil, and 30–35% carbohydrates by dry weight (Wilson et al. 2011). Beyond its

Published online: 23 March 2025

role in livestock nutrition, soybean oil is an essential feedstock for biodiesel production and is utilized in diverse sectors such as food processing, baking, textiles, pharmaceuticals, and chemicals. Due to its multiple benefits for human nutrition and soil health, the soybean is considered a "dual-purpose crop" (Goldschein 2011), contributing to both human food security and sustainable farming practices (Kananji et al. 2013). Furthermore, when included in crop rotations, soybean's nitrogen-fixing properties improve soil fertility.

Plants are affected by many biotic and abiotic stress factors during their growth and development periods. Recently, drought has become one of the most critical stress factors that limit productivity with increasing global warming. Drought stress results in significant yield loss in soybean, with a reduction of up to 40% under moderate conditions (Marinho et al. 2022) and potentially as high as 80% depending on the severity and timing of stress (Guimarães-Dias et al. 2012). The most noticeable effects of drought are evident during the early stages of soybean growth, particularly on seedlings (Han et al. 2022). Drought negatively impacts soybean germination and all subsequent growth stages, with severe consequences during the reproductive phase, significantly affecting seed development (Igiehon et al. 2021). Soybean's sensitivity to water deficit is strongly linked to the growth stage, with moderate water shortages generally not compromising productivity or quality (Vaghar et al. 2020). However, drought stress during the developmental stage significantly impacts yield potential (Zhang et al. 2022). While drought stress during the seedling stage may stimulate root development, benefiting overall plant growth, this can also increase the plant's water demand for pod filling (Zhengbin et al. 2011). Drought episodes occurring at flowering time result in severe reductions in final yield. Researchers have identified key environmental factors associated with drought stress to achieve higher and more stable soybean yields and are developing new soybean genotypes with enhanced drought tolerance (Jogawat et al. 2021).

Studies have demonstrated that soybean plants are highly susceptible to dry periods due to their substantial water requirements and limited tolerance to water deficits (Hossaina et al. 2014). As a result, researchers have actively sought soybean varieties with enhanced drought resistance from various regions globally (Pathan et al. 2010; Fenta et al. 2012; Mabulwana 2013). Studies showed that soybean yield depends on the amount of water used (transpiration) and yield to biomass ratio (harvest index) (Passioura and Angus 2010). Since soybeans are C3 plants, they lose more water through evaporation and use water less efficiently for photosynthesis than C4 plants.

Seed yield in soybeans is linked to several factors, including the number of main-stem nodes on each plant, the number of branches bearing pods that emerge from each node, the number of seeds within each pod, and the final weight of each mature seed. The soil's water content variability is a crucial factor that significantly impacts this yield equation. Drought conditions that induce water deficits during critical growth periods dramatically reduce the seed yield. Water provides a vital dual purpose, acting as a solvent and a transport medium for essential nutrients throughout the plant. Furthermore, water has a critical role in photosynthesis, acting as an electron donor, a necessary element in converting sunlight into energy (McConnell et al. 2010). The size of the shoot at the time of flowering, measured by the height of the main stem, the length of the branches, the number of nodes, and the total leaf area, significantly influences soybean yield. Drought stress impacts the number of nodes per plant and the number of pods per node. However, this response varies among different cultivars and depends on the timing and duration of the drought stress interval (Yan et al. 2020). Another study provided the significance of physiological traits such as photosynthetic rate, leaf chlorophyll content, and yield components like pod and seed numbers, which are adversely affected by drought (Yan et al. 2020).

The number of seeds in soybeans depends on different conditions such as the duration and number of flowers on the plant, pod filling and seed formation time. Plants that experience drought stress during flowering have a shorter period and produce fewer flowers and seeds. Research showed that water stress directly affects the amount of water in the flower and how well the flower functions (Zhou et al. 2022). The timing and duration of drought stress significantly impact soybean pod and seed production (Staton 2020). The early pod formation stage is the most critical period for drought stress, as it dramatically reduces the number of pods and seeds (Aziez and Prasetyo 2022). Drought stress during flowering

and pod development also significantly decreases harvested seed number. Some studies have shown that when drought occurs during seed formation, the pod-filling time is shortened, causing the seeds to shrivel (Desclaux et al. 2000). Studies indicated significant yield reductions (13–64%) in seed size, seed number, and overall yield due to drought stress (Kisman and Sudarmawan 2002). These findings are consistent with those of researchers like Zhou et al. (2022), who highlight that drought stress increases the possibility of pod abortion and reduces pod set by hindering pod growth and metabolism.

Early drought, occurring immediately after pollination, often leads to a significant loss of immature seeds (embryos), thereby reducing the total seed yield of the plant. This reduction is primarily due to the plant's inability to generate sufficient carbohydrates (sugars) through photosynthesis, which are necessary for the growth and development of immature seeds. Notably, it has been observed that both reduced light availability and supplemental watering during the pollination period can also result in premature seed drop. In contrast, drought stress during the pod-filling stage generally does not cause seed mortality. However, it results in smaller seeds due to the reduced time available for seed growth. Studies have shown that while drought during this later stage yields smaller seeds, the total seed number remains unaffected compared to plants not subjected to drought conditions (Kness 2020; Aziez and Prasetyo 2022).

Water scarcity, or drought stress, disrupts the natural developmental cycle of plants, thereby negatively affecting their overall yield (Desclaux et al. 2000). Under drought conditions, plants may prematurely transition from the vegetative stage, characterized by the growth of leaves and stems, to the reproductive stage, which involves the formation of flowers and seeds. This accelerated progression results in a reduced number of branches and a shortened duration for each growth phase. Also, drought-stressed plants may initiate seed formation earlier than usual, bypassing the developmental stage during which some seeds fail to mature fully. Consequently, the entire growth cycle is expedited, leading to premature senescence and a reduced timeframe for seed production.

The Mediterranean region frequently faces summer droughts, making developing drought-tolerant soybean varieties a significant advantage. Such varieties mature faster and possess mechanisms to endure dry conditions with minimal yield losses (Kivuva 2013; Fuganti-Pagliarini et al. 2017). This adaptation is crucial to reducing soybean import expenditures, addressing the shortage of vegetable oil production, and ensuring the availability of high-quality animal feed. To enhance soybean yield and yield components, researchers must focus on breeding soybean varieties that integrate farmers' preferred traits with high drought tolerance, ensuring their resilience in challenging climates.

This study aimed to evaluate drought tolerance levels in various soybean genotypes by assessing key morphological traits and yield components under differing irrigation regimes. By implementing controlled non-stressed (NS) and three different irrigation regimes with drought-stressed (DS). The research aimed to identify genotypes that maintain productivity under limited water availability. This study provides insights into the adaptability of soybean genotypes to drought conditions, contributing to the development of more resilient cultivars for sustainable agricultural practices in water-scarce environments.

Materials methods

Plant materials

This study utilized 10 soybean genotypes as genetic material, comprising 4 local varieties and 6 exotic genotypes sourced from the USDA (Table 1). The field experiment was conducted with a randomized

Table 1 List of local and exotic genotypes used in the experiment

Code of genotype	Genotype	Origin
G1	Agroyal	Local Variety
G2	Lider	Local Variety
G3	Arisoy	Local Variety
G4	Antsoy	Local Line
G5	PI 556687	USDA
G6	PI 603452	USDA
G7	PI 556759	USDA
G8	PI 547551	USDA
G9	PI 595645	USDA
G10	PI 471938	USDA

block design (RBD) design with three replications at the West Mediterranean Agricultural Research Institute (36–52° N,30–50° E) located in Antalya, southern Turkey, during the first week of June to the first week of October in the 2023 for 1st experiment and in 2024 for 2nd experiment. No rainfall would affect the experiment during the critical periods as average monthly rainfall was 2.7 mm during the experimental duration from June to October in 2023 (June 9.2, July 0.0, August 0.1, September 4.1, October 0.3) and for 2024 was 2.8 mm (June 8.1, July 0.2, August 0.0, September 3.8, October 1.8) according to Turkish State Meteorological Service. Temperature fluctuations were from 23 to 45 °C during the growing seasons. This low rainfall and high temperature indicated that the experimental area exhibited a semiarid climate.

Methods

In this study, a randomized block design (RBD) with three replications was conducted for 10 different genotypes and 4 different irrigation levels. Four different irrigation regimes were applied: irrigation was stopped at the flowering stage (T1), the pod-setting stage (T2), and the pod-filling stage (T3), while the control group (T0). The irrigation with a drip irrigation system twice a week throughout the growing season, approximately 30 min for each irrigation time. This short-term irrigation was done to prevent water leakage into the plants under drought stress. The genotypes were planted in 4-row plots of 1-m length, 70 cm between rows and 5 cm between plants within the rows. To minimize border effects, exterior plants served as guard plants, and data collection focused on interior plants. When sowing, 30 g of a 10:10:15 ratio garden fertilizer was mixed with drip irrigation water and applied to 150 square meters to provide good nutrition to the seedlings. Recommended agronomic and agricultural practices were carried out uniformly for all lines. Before harvest, three plants were randomly selected from each replicate and observed and analyzed.

Data collection

Plants were measured with high precision during the harvest process. While collecting data, plants in the middle were randomly selected and measured.

I. 1st Pod height

The vertical distance from the soil surface to the first pod on each plant was manually measured using a measuring tape. To ensure the accuracy of the data, three plants were randomly selected from each replication within each treatment group.

II. Plant height

The length from the soil surface to the last pod was measured with tape. As in the first pod height measurement, three plants per treatment were randomly selected.

III. Number of branches

The number of lateral branches on each of the three selected plants was also determined through manual counting.

IV. Number of pods

The pods found on the selected plants were counted and placed in envelopes. They were then placed in an oven at 40 degrees Celsius for 48 h to bring them to optimum humidity.

XXII. Seed yield

Seeds were removed from oven-dried pods by hand. Seeds from each plant sample were weighed using a precision balance to determine the yield per plant. These individual plant yields were then averaged to obtain the results.

VI. 1000-seed weight

After seed collection and yield determination, one hundred seeds were randomly selected from each sample corresponding to every treatment within each replication. The weight of these one hundred seeds was measured using a standardized analytical balance. This measurement was subsequently multiplied by ten to estimate the weight of one thousand seeds.

Analysis

This trial was set up as the main factor genotypes and the sub-factor irrigation methods. Data analysis was performed each year, and then the means of the data from each year were compared and combined using JMP statistical software, which offers advanced tools for comprehensively evaluating experimental data. The software enabled efficient data organization, exploration, and the application of a range of statistical techniques to investigate relationships and effects within the experimental design. Standardized values were utilized for direct path analysis to identify traits directly influencing yield.

Results

A combined ANOVA was performed to assess the impact of drought stress levels on ten soybean genotypes. The results indicated that drought was the primary factor contributing to variation across most measured traits, as reflected by significant values. The drought treatments significantly impacted key characteristics such as plant height, pod number, biomass, seed number, seed weight, and water use efficiency, highlighting the critical role of water availability in determining soybean performance. The overall seed yield per plant in the 2024 trial was lower than in 2023. The reason for this is approximately one week of extreme heat and hot and dry winds during flowering, which reduced the number of pods and the number of seeds in the pods and consequently reduced the final seed yield per plant.

There was no significant difference in the height of the first pod between different treatments for most of the genotypes, except for G8, which showed a slight but notable considerable difference for the results of 2023 but showed no significant difference for 2024. This study showed that drought treatment effects on first pod height were minimal for varieties (Table 2). Over the years, significant differences were observed among genotypes across all treatments (Fig. 1). In 2023 and 2024, genotype G10 had the highest first pod height, measuring 24.5 cm and 24.6 cm, respectively. G4 followed it in 2023 (24.1 cm) and G1 in 2024 (23.1 cm). In contrast, G5 consistently showed the lowest values, with 13.6 cm in 2023 and 14.5 cm in 2024, followed by G6 with 17.9 cm in 2023 and 17.0 cm in 2024 (Table 3). These findings highlight the key role of genetic variation in determining the first pod height. When all varieties were considered collectively, there was no significant difference between treatments in either year. For instance, T2 recorded 20.1 cm in 2023 and 19.9 cm in 2024, while T1 measured 20.7 cm in 2023 and 20.4 cm in 2024. This indicates that drought treatments had a very low impact on first pod height across the studied genotypes (Table 4).

Over consecutive years, significant differences in plant height were observed among treatments for most varieties. However, G6 and G10 showed no significant differences in 2023, G7 and G9 showed no differences across both years, and G8 showed no differences in 2024 (Fig. 1, Table 2). A greater significance level was observed when treatments were analyzed collectively across all varieties. In 2023, genotype G6 had the tallest plants at 126.5 cm, followed by G8 at 118.1 cm. In 2024, G8 had the tallest plants at 126.2 cm, followed by G9 at 112.0 cm. Conversely, G2 recorded the shortest plant heights for both years at 86.8 cm and 93.2 cm, followed by G1 in 2023 (99.7 cm) and G4 in 2024 (95.8 cm) (Table 3). Across all varieties, there was a significant difference between treatments. T1 recorded the shortest plant heights for both years (89.9 cm in 2023 and 90.5 cm in 2024), while T0 had the tallest plants (122.8 cm in 2023 and 122.2 cm in 2024) (Table 4). These results indicate that treatment effects were more influential than genotypic differences under specific conditions.

The number of branches per plant is not typically considered a critical trait for quality, yield, or biochemical characteristics. However, it can affect per-plant yield and the number of pods per plant. The branch number is generally affected by genotype and field conditions, such as plant spacing and row distances, and in this study, there are no significant differences between treatments within individual genotypes for either year (Table 2). However, all varieties

Table 2 Analysis of variance of genotypes according to applied drought stress levels and comparison of results for 2023 and 2024

Genotype	Treatment	1st Pod height		Plant height		Number of branches		Number of pods		Plant yield		1000 Seed weight	
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
G1	T1	19.1 ± 0.9a	22.3 ± 0.6a	70.9 ± 8.8a	82.5 ± 10.0a	5.2 ± 0.4a	4.6 ± 1.0a	83.4 ± 8.3a	53.3 ± 2.1c	11.9 ± 2.9b	6.5 ± 0.2a	68.5 ± 3.4b	69.8 ± 7.3c
	T2	18.4 ± 1.4a	23.3 ± 2.1a	98.3 ± 8.5a	101.1 ± 4.2a	5.2 ± 0.2a	4.1 ± 0.1a	97.8 ± 18.2a	72.7 ± 5.8bc	8.5 ± 2.5b	8.5 ± 0.8b	58.6 ± 3.6b	80.8 ± 2.6b
	T3	20.1 ± 1.5a	23.1 ± 2.1a	112.6 ± 8.1ab	121.7 ± 4.8ab	4.7 ± 0.4a	5.1 ± 0.2a	153.2 ± 19.7a	79.2 ± 9.2b	21.4 ± 6.9ab	9.1 ± 0.3b	68.0 ± 7.3b	89.0 ± 3.6ab
	T0	18.8 ± 0.4a	24.0 ± 1.3a	117.2 ± 2.8b	131.0 ± 11.3b	5.2 ± 0.2a	5.3 ± 0.6a	169.0 ± 28.0a	90.2 ± 11.1a	36.6 ± 3.4a	12.9 ± 0.7c	93.5 ± 2.6a	98.9 ± 3.4a
	P	0.776	0.918	0.009*	0.011*	0.735	0.187	0.042*	0.030*	0.008*	0.0163*	0.004*	0.001*
G2	T1	20.6 ± 3.0a	23.2 ± 2.5a	69.6 ± 7.0a	79.8 ± 5.3a	6.2 ± 0.1a	5.0 ± 0.1a	61.0 ± 1.1b	42.1 ± 6.6c	10.4 ± 4.1b	7.6 ± 0.5a	80.7 ± 10.5b	95.3 ± 2.6c
	T2	21.8 ± 1.1a	20.3 ± 1.6a	87.2 ± 7.1a	85.4 ± 5.7a	6.6 ± 0.3a	5.2 ± 0.4a	93.7 ± 3.1ab	95.1 ± 17.8a	8.7 ± 2.2b	9.6 ± 0.7ab	59.0 ± 6.0b	105.8 ± 3.6bc
	T3	23.7 ± 2.5a	23.3 ± 0.8a	95.3 ± 5.9a	98.5 ± 3.4ab	7.0 ± 0.1a	5.1 ± 0.4a	132.4 ± 15.6ab	52.5 ± 10.9bc	18.0 ± 4.4b	12.0 ± 1.1b	70.3 ± 3.5b	134.1 ± 10.5b
	T0	21.2 ± 1.8a	22.2 ± 2.1a	95.3 ± 1.1a	109.4 ± 6.5b	7.4 ± 0.4a	5.2 ± 1.0a	230.2 ± 56.6a	67.1 ± 16.2b	64.1 ± 15.9a	17.5 ± 1.5c	122.7 ± 2.6a	146.6 ± 6.0a
	P	0.784	0.674	0.044*	< 0.0001*	0.095	0.694	0.022*	0.002*	0.006*	0.0095*	< 0.0001*	< 0.0001*
G3	T1	24.2 ± 2.5a	20.1 ± 0.9a	73.6 ± 3.8a	71.9 ± 8.8a	6.4 ± 0.4a	5.2 ± 0.8a	51.7 ± 8.4b	34.3 ± 9.8b	7.6 ± 1.1b	6.2 ± 0.9a	62.5 ± 12.1b	75.5 ± 1.8d
	T2	21.3 ± 1.6a	19.4 ± 1.4a	105.2 ± 2.8ab	92.3 ± 8.5a	5.2 ± 0.7a	5.8 ± 1.1a	68.5 ± 18.9b	49.8 ± 20.2ab	6.4 ± 1.3b	7.7 ± 1.1ab	59.9 ± 2.1b	93.3 ± 3.6c
	T3	24.3 ± 0.8a	21.1 ± 1.5a	122.3 ± 5.6b	112.6 ± 8.1ab	6.0 ± 0.3a	6.1 ± 0.8a	112.8 ± 16.3ab	50.8 ± 14.7ab	19.2 ± 4.1ab	9.9 ± 0.5ab	79.6 ± 3.6b	103.4 ± 10.1b
	T0	23.2 ± 2.1a	19.8 ± 0.4a	132.1 ± 3.0c	117.2 ± 2.8b	5.5 ± 0.1a	4.8 ± 0.4a	177.6 ± 14.1a	65.3 ± 11.2a	39.1 ± 8.1a	12.6 ± 1.2b	111.0 ± 0.8a	115.4 ± 9.2a
	P	0.674	0.776	< 0.0001*	0.009*	0.347	0.745	< 0.0001*	0.044*	0.005*	0.0015*	< 0.0001*	< 0.0001*
G4	T1	23.3 ± 0.6a	21.6 ± 3.0a	92.8 ± 5.3a	74.6 ± 7.0a	5.0 ± 0.8a	5.2 ± 1.7a	75.1 ± 14.1a	47.0 ± 12.4b	14.7 ± 2.8b	6.7 ± 0.03a	88.5 ± 3.6ab	73.8 ± 4.6c
	T2	24.3 ± 2.1a	22.8 ± 1.1a	115.4 ± 5.7a	92.2 ± 7.1a	4.4 ± 0.1a	5.1 ± 1.2a	85.8 ± 7.9a	43.5 ± 17.9ab	16.3 ± 2.1ab	8.4 ± 0.6b	83.0 ± 7.6b	89.6 ± 3.2b
	T3	24.1 ± 2.1a	24.7 ± 2.5a	133.5 ± 3.4ab	99.3 ± 5.9a	5.2 ± 0.3a	6.2 ± 1.2a	147.7 ± 22.3a	62.3 ± 21.3ab	30.6 ± 5.9ab	9.0 ± 0.7b	91.8 ± 9.4ab	95.8 ± 7.6ab
	T0	25.0 ± 1.3a	22.2 ± 1.8a	135.4 ± 6.5b	117.3 ± 1.1a	4.7 ± 0.4a	6.2 ± 1.7a	159.0 ± 32.1a	76.1 ± 20.9a	39.7 ± 5.9a	13.9 ± 1.1c	118.0 ± 3.8a	104.4 ± 9.1a
	P	0.918	0.784	< 0.0001*	0.044*	0.719	0.906	0.051	0.031*	0.034*	0.013*	0.024*	0.002*
G5	T1	11.6 ± 3.0a	14.3 ± 5.3a	86.5 ± 10.0a	83.6 ± 3.8a	4.6 ± 1.2a	5.8 ± 1.281a	67.0 ± 35.1a	30.0 ± 5.1d	15.0 ± 2.0b	5.1 ± 0.2a	85.7 ± 3.0b	79.7 ± 3.3b
	T2	15.1 ± 1.8a	13.0 ± 0.1a	103.1 ± 4.2a	105.2 ± 2.8ab	3.7 ± 0.1a	4.0 ± 2.2a	81.1 ± 13.1a	46.6 ± 9.3c	12.6 ± 3.7b	5.7 ± 0.8a	75.3 ± 4.5b	96.2 ± 4.2ab
	T3	16.5 ± 4.1a	16.5 ± 2.2a	126.7 ± 4.8ab	120.3 ± 5.6b	5.5 ± 0.5a	6.5 ± 1.0a	147.6 ± 11.9a	51.7 ± 14.4b	27.7 ± 3.8ab	8.3 ± 1.2b	91.9 ± 4.5b	100.2 ± 3.7ab
	T0	11.3 ± 5.9a	14.5 ± 2.7a	135.0 ± 11.3b	133.1 ± 3.0c	4.8 ± 0.1a	6.2 ± 1.3a	171.1 ± 24.4a	69.8 ± 21.5a	40.5 ± 9.4a	11.3 ± 1.5c	116.3 ± 7.8a	105.8 ± 5.7a
	P	0.755	0.635	0.011*	0.002*	0.439	0.752	0.034*	< .0.0001*	0.019*	0.0032*	0.026*	0.021*
G6	T1	18.2 ± 1.8a	19.0 ± 1.8a	124.0 ± 8.5a	92.3 ± 4.0b	3.6 ± 1.0a	5.2 ± 0.4a	111.3 ± 24.3a	43.4 ± 8.3c	13.1 ± 2.9b	6.7 ± 1.5a	61.4 ± 9.0b	73.6 ± 2.6bc
	T2	15.4 ± 1.2a	16.6 ± 1.4a	130.5 ± 7.0a	109.0 ± 5.0ab	5.1 ± 0.1a	4.2 ± 0.2a	119.7 ± 15.8a	57.8 ± 14.2b	11.1 ± 1.9b	8.5 ± 0.9b	59.3 ± 0.0b	78.2 ± 3.4b
	T3	20.9 ± 2.9a	18.5 ± 2.9a	122.3 ± 8.3a	112.7 ± 7.1a	5.7 ± 0.2a	4.7 ± 0.4a	231.2 ± 44.2a	63.2 ± 13.7b	26.2 ± 3.1a	9.5 ± 0.7b	72.0 ± 3.6ab	86.6 ± 4.1ab
	T0	17.1 ± 0.4a	14.0 ± 1.0a	129.3 ± 4.5a	111.3 ± 6.5a	5.2 ± 0.6a	5.8 ± 0.2a	174.2 ± 16.1a	79.0 ± 18.0a	32.1 ± 2.7a	14.9 ± 0.9c	95.7 ± 5.6a	103.5 ± 5.3a
	P	0.290	0.287	0.823	0.004*	0.187	0.735	0.050	0.012*	0.007*	0.0008*	0.013*	0.015*
G7	T1	17.5 ± 2.0a	23.4 ± 1.1a	98.0 ± 3.9a	101.0 ± 9.8a	5.3 ± 0.1a	6.2 ± 0.1a	79.1 ± 23.6a	41.0 ± 1.1b	16.1 ± 2.2b	7.2 ± 0.2a	102.6 ± 5.1ab	95.5 ± 0.9b
	T2	22.5 ± 2.1a	20.3 ± 2.1ab	110.1 ± 6.4a	104.6 ± 6.9a	6.1 ± 0.4a	5.6 ± 0.3a	95.1 ± 32.8a	53.7 ± 3.1ab	15.4 ± 2.5b	8.0 ± 0.4a	86.8 ± 4.7b	109.7 ± 4.3ab
	T3	21.1 ± 3.8a	20.4 ± 0.4b	102.7 ± 9.8a	111.2 ± 6.9a	5.1 ± 0.4a	6.0 ± 0.1a	50.5 ± 10.9a	62.4 ± 15.6ab	19.8 ± 3.3ab	10.9 ± 0.6ab	101.2 ± 6.1ab	115.6 ± 2.1ab
	T0	19.6 ± 0.1a	18.2 ± 0.8b	127.5 ± 6.7a	115.0 ± 9.8a	5.5 ± 1.0a	5.4 ± 0.4a	143.1 ± 56.2a	79.2 ± 56.6a	28.6 ± 4.2a	14.0 ± 0.9b	121.7 ± 6.9a	121.4 ± 3.5a
	P	0.554	0.030*	0.076	0.610	0.694	0.095	0.362	0.022*	0.009*	0.010*	0.024*	0.034*

Table 2 (continued)

Genotype	Treatment	1st Pod height		Plant height		Number of branches		Number of pods		Plant yield		1000 Seed weight	
		2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
G8	T1	24.4 ± 1.1a	19.2 ± 1.8a	99.1 ± 6.2b	123.0 ± 8.5a	4.2 ± 0.8a	6.1 ± 0.4a	64.3 ± 9.8a	31.7 ± 8.4b	13.2 ± 1.8b	5.4 ± 0.5a	90.7 ± 3.0b	99.1 ± 4.5c
	T2	19.3 ± 2.1ab	16.4 ± 1.2a	116.6 ± 2.1ab	131.5 ± 7.0a	5.2 ± 1.1a	5.0 ± 0.7a	99.8 ± 20.2a	38.5 ± 18.9b	15.6 ± 3.5b	6.8 ± 0.6ab	84.2 ± 4.4b	127.2 ± 3.1b
	T3	22.4 ± 0.4b	21.9 ± 2.9a	125.1 ± 5.6a	122.3 ± 8.3a	5.1 ± 0.8a	6.2 ± 0.3a	100.8 ± 14.7a	52.8 ± 16.3ab	19.4 ± 3.6ab	8.7 ± 0.9b	97.2 ± 2.1b	140.3 ± 4.2ab
	T0	19.2 ± 0.8b	18.1 ± 0.4a	131.6 ± 5.5a	128.3 ± 4.5a	4.2 ± 0.4a	5.8 ± 0.1a	115.3 ± 11.2a	77.6 ± 14.1a	29.8 ± 2.7a	11.8 ± 1.1c	131.4 ± 4.6a	150.3 ± 6.7a
	P	0.030*	0.290	0.010*	0.823	0.745	0.275	0.164	< .0.0001*	0.021*	0.0024*	< .0.0001*	< .0.0001*
G9	T1	20.0 ± 1.8a	18.5 ± 2.0a	120.0 ± 9.8a	108.0 ± 3.9a	5.0 ± 1.7a	5.2 ± 0.8a	67.0 ± 12.4b	35.1 ± 10.1a	13.1 ± 0.4bc	4.8 ± 0.1a	88.0 ± 2.6b	78.7 ± 3.3b
	T2	17.6 ± 1.4a	21.5 ± 2.1a	104.6 ± 6.9a	110.1 ± 6.4a	6.1 ± 1.2a	5.4 ± 0.1a	183.5 ± 17.9ab	55.8 ± 7.9a	10.2 ± 0.5c	6.9 ± 0.3b	77.9 ± 1.2b	97.2 ± 4.2ab
	T3	19.5 ± 2.9a	21.1 ± 3.8a	113.2 ± 6.9a	101.7 ± 9.8a	6.5 ± 1.2a	5.0 ± 0.3a	190.3 ± 21.3ab	67.7 ± 6.3a	16.0 ± 1.2b	8.4 ± 0.4bc	87.6 ± 5.9b	101.2 ± 3.7ab
	T0	15.0 ± 1.0a	18.6 ± 0.1a	116.0 ± 9.8a	128.5 ± 6.7a	6.0 ± 1.7a	5.7 ± 0.4a	242.1 ± 20.9a	89.0 ± 12.1a	24.0 ± 1.1a	10.4 ± 0.9c	113.5 ± 2.2a	106.8 ± 5.7a
	P	0.287	0.554	0.610	0.076	0.906	0.719	0.031*	0.051	< .0.0001*	0.002*	< .0.0001*	0.021*
G10	T1	26.3 ± 5.3a	22.6 ± 3.0a	84.3 ± 4.0a	89.1 ± 6.2b	7.8 ± 1.2a	5.6 ± 1.2a	30.0 ± 5.1d	47.0 ± 11.1a	16.8 ± 1.1b	6.7 ± 0.9a	101.2 ± 6.7b	122.1 ± 2.1b
	T2	31.0 ± 0.1a	26.1 ± 1.8a	103.0 ± 5.0a	90.6 ± 2.1ab	6.0 ± 2.2a	4.7 ± 0.1a	56.6 ± 9.3c	61.1 ± 9.1a	14.4 ± 0.9b	9.0 ± 0.4b	99.3 ± 6.7b	136.5 ± 5.1ab
	T3	22.5 ± 2.2a	27.5 ± 4.1a	104.7 ± 7.1a	125.1 ± 5.6a	7.5 ± 1.0a	5.5 ± 0.5a	111.7 ± 14.4b	77.6 ± 11.9a	21.6 ± 1.7ab	12.3 ± 1.0c	106.6 ± 5.5b	145.7 ± 5.4ab
	T0	22.5 ± 2.7a	22.3 ± 5.9a	108.3 ± 6.5a	131.6 ± 5.5a	6.1 ± 1.3a	5.8 ± 0.1a	199.8 ± 21.5a	87.1 ± 17.4a	28.8 ± 3.0a	15.7 ± 0.9d	139.9 ± 2.4a	158.6 ± 6.7a
	P	0.635	0.524	0.084	0.010*	0.752	0.439	< 0.0001*	0.034*	0.003*	< 0.0001*	0.012*	0.022*

were analyzed collectively across treatments, and a high significance level was detected, indicating considerable variation in branching among varieties. In 2023, G10 had the highest number of branches per plant (7.0), followed by G2 (6.8), while G5 and G8 recorded the lowest (4.6 each). In contrast, no significant differences were observed in 2024, with G7 recording the highest number of branches (5.8) and G1 the lowest (4.7) (Table 3). When treatments were analyzed collectively across all varieties, no significant differences were found in 2023, with T1 recording 5.3 branches per plant and T4 at 5.4. However, a slight significance was noted in 2024, with T2 showing the lowest number of branches (4.9) and T3 and T0 the highest (5.6 each) (Table 4). These results showed that genetic variation among varieties significantly influences branch number more than treatment effects.

The number of pods per plant varied significantly across treatments, with a high statistical significance observed in all genotypes. Genotypes G10 and G3 exhibited the most significant responses to different treatments, while G1 showed the lowest significance. In 2023, genotypes G4, G6, and G7 showed no significant differences in pod count across treatments, whereas in 2024, G5 and G8 showed the highest significance levels, and G9 displayed no significant differences (Table 2). When analyzed cumulatively by genotype, G7 had the lowest average pod count in 2023 (92.0 pods per plant), while G10 had the highest (174.2 pods per plant). In 2024, G5 recorded the lowest pod count (49.5 pods per plant), and G1 was the highest (73.8 pods per plant) (Fig. 1). However, there was no significant difference in pod count between varieties across both years, suggesting that treatment effects were more impactful than genetic differences in this context (Table 3). A cumulative analysis of treatments across all genotypes revealed substantial differences. Treatment T2 resulted in an average of 94.7 pods per plant in 2023, and T1 produced 40.4 pods per plant in 2024. The control group (T0) achieved the highest averages, with 163.7 pods per plant in 2023 and 78.0 pods per plant in 2024 (Table 4).

Seed yield is closely linked to pod count, as pod production directly impacts overall yield (Fig. 1). Significant differences were observed between treatments across all varieties in this experiment. Genotype G9 exhibited the highest significance level in



Fig. 1 The values of the characters examined according to the applied drought stress levels in 2023 and 2024



Fig. 1 (continued)



Fig. 1 (continued)

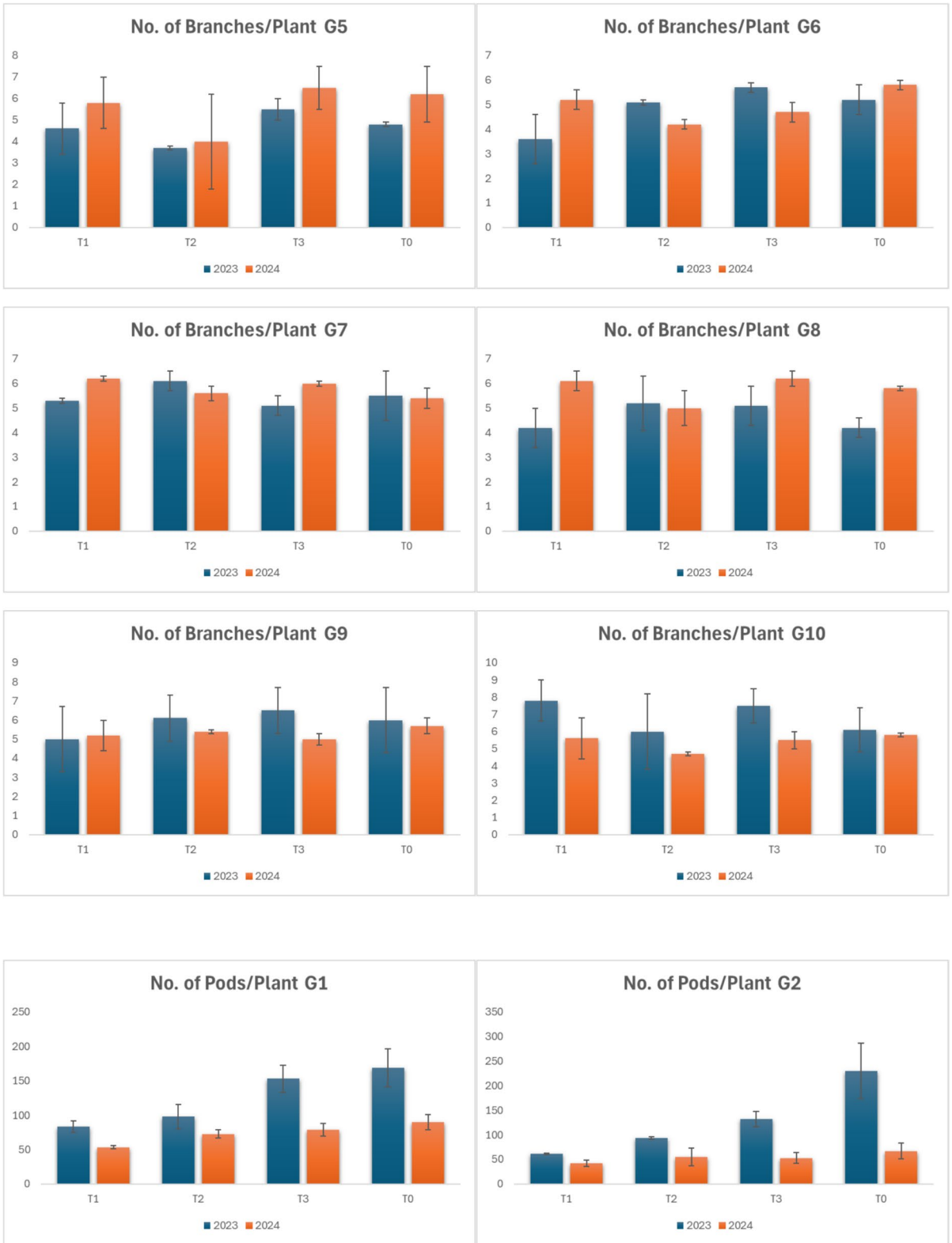


Fig. 1 (continued)



Fig. 1 (continued)



Fig. 1 (continued)



Fig. 1 (continued)

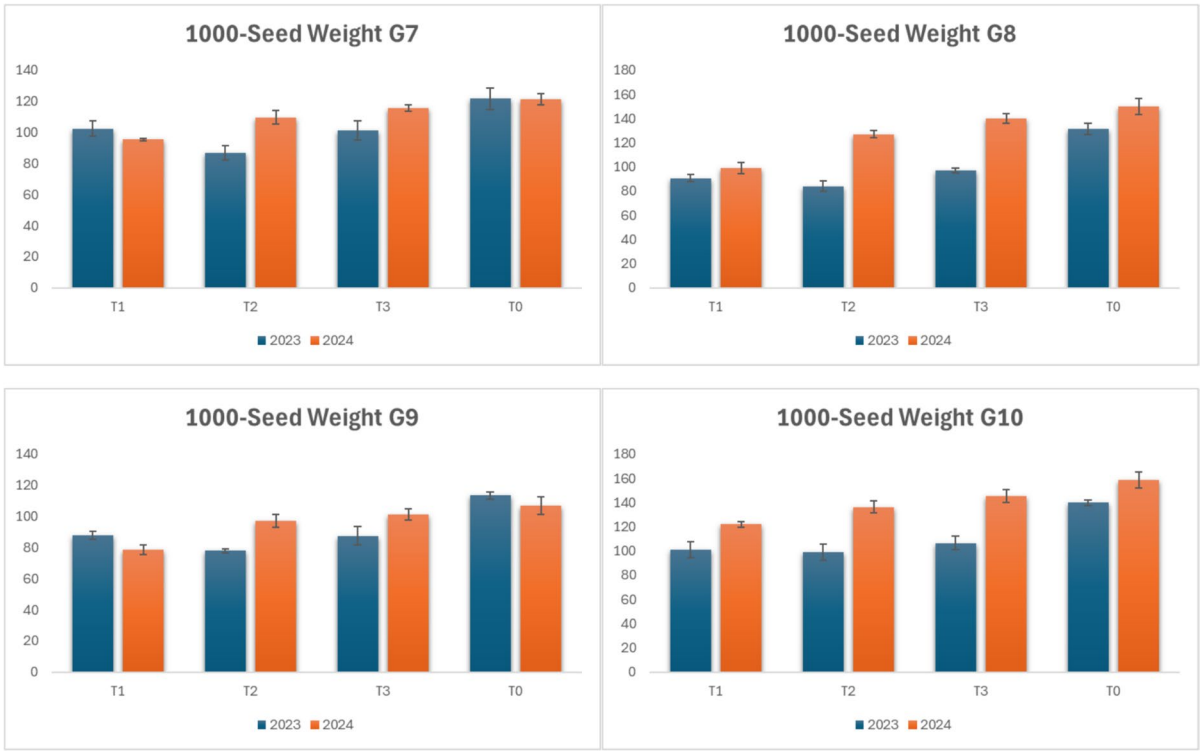


Fig. 1 (continued)

2023, while G10 showed the highest significance in 2024 (Table 2). Under cumulative treatment conditions, genotypes G2 and G4 recorded the highest yield in 2023, averaging 25.3 g. In 2024, G2 had the highest yield (11.6 g), followed by G10 (10.9 g). The lowest yields in 2023 were observed in G9 (15.8 g) and G7 (16.7 g), while in 2024, G5 and G9 had the lowest values, both at 7.6 g (Table 3). Treatment effects on yield were also significant across all genotypes. In 2023, treatment T0 yielded the highest yield (35.9 g), while T2 had the lowest (12.0 g). In 2024, T0 again showed the highest yield (13.5 g), while T1 recorded the lowest (6.2 g) (Table 4). Comparing seed yield averages in T1 and T2 conditions to those in T0 conditions can determines the drought tolerance level of each genotype. The genotype with the highest ratio exhibits the greatest tolerance. Comprehensive analysis indicated that G7 is the most tolerant, followed by G10. These findings emphasize the combined influence of genotype and treatment on seed yield, highlighting the variability in yield potential under different growing conditions and genetic backgrounds.

The weight of one thousand seeds is an essential parameter for assessing the final yield potential of a genotype, as it reflects seed size and density—key productivity indicators. Our findings revealed significant differences in seed weight across treatments among all varieties, highlighting the impact of treatments on this trait (Fig. 1). In 2023, genotypes G2, G3, G8, and G9 showed exceptionally high significance levels, while in 2024, G2, G3, and G8 exhibited the highest significance, suggesting these varieties had a strong response to treatments (Table 2). Cumulative analysis based on genotypes showed notable differences in seed weight. The highest 1000-seed weight in 2023 was observed in G10 (111.7 g), followed by G7 (103.1 g). In 2024, G10 (140.7 g) and G8 (129.2 g) recorded the highest values. In contrast, G6 and G1 had the lowest seed weights in 2023 (72.1 g), and in 2024, G1 (84.6 g) and G6 (85.4 g) again recorded the lowest values (Table 3). These results emphasize the variability in seed weight across genotypes and highlight the combined effects of genetics and treatments on this critical yield-determining parameter. Significant

Table 3 Averages and variance analysis of all genotypes regarding the traits examined in 2023 and 2024

Genotypes	1st Pod height		Plant height		Number of branches		Number of pods		Plant yield		1000 Seed weight	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
G1	19.1 ± 1.9ab	23.1 ± 0.3ab	99.7 ± 6.3bc	109.0 ± 10.8a	5.1 ± 0.1b	4.7 ± 0.2a	125.8 ± 13.7a	73.8 ± 7.7a	19.6 ± 3.7a	9.2 ± 1.3a	72.1 ± 4.3c	84.6 ± 6.1c
G2	21.8 ± 1.0ab	22.2 ± 0.6abc	86.8 ± 3.9c	93.2 ± 6.6a	6.8 ± 0.1a	5.1 ± 0.1a	129.3 ± 23.1a	64.2 ± 11.5a	25.3 ± 7.7a	11.6 ± 2.1a	83.2 ± 7.7bc	120.4 ± 11.9abc
G3	23.2 ± 0.8a	20.1 ± 0.3bcd	108.3 ± 4.0abc	98.5 ± 10.3a	5.8 ± 0.2ab	5.4 ± 0.3a	102.7 ± 0a	50.0 ± 6.3a	18.1 ± 4.4a	9.1 ± 1.3a	78.2 ± 6.7bc	96.9 ± 8.4bc
G4	24.1 ± 0.7a	22.8 ± 0.6abc	119.3 ± 6.9ab	95.8 ± 4.8a	4.8 ± 0.2b	5.6 ± 0.3a	116.9 ± 3.0a	57.2 ± 7.5a	25.3 ± 3.9a	9.5 ± 1.5a	95.3 ± 4.9abc	90.9 ± 6.4c
G5	13.6 ± 1.5c	14.5 ± 0.7e	110.8 ± 5.1ab	110.5 ± 10.6a	4.6 ± 0.3b	5.6 ± 0.6a	116.7 ± 4.1a	49.5 ± 8.1a	23.9 ± 4.6a	7.6 ± 1.4a	92.3 ± 6.6abc	95.4 ± 5.6bc
G6	17.9 ± 1.0bc	17.0 ± 1.1de	126.5 ± 6.7a	106.3 ± 4.7a	4.9 ± 0.3b	4.9 ± 0.3a	159.1 ± 8.2a	60.8 ± 7.3a	20.6 ± 3.4a	9.9 ± 1.7a	72.1 ± 5.1c	85.4 ± 6.5c
G7	20.2 ± 1.1ab	20.5 ± 1.0abcd	109.6 ± 3.2abc	107.9 ± 3.1a	5.5 ± 0.2ab	5.8 ± 0.2a	92.0 ± 0.5a	59.0 ± 8.0a	16.7 ± 3.2a	10.0 ± 1.5a	103.1 ± 6.0ab	110.5 ± 5.5abc
G8	21.6 ± 0.9ab	18.9 ± 1.1 cd	118.1 ± 4.5ab	126.2 ± 2.1a	4.6 ± 0.3b	5.7 ± 0.3a	95.1 ± 4.8a	50.1 ± 10.1a	19.5 ± 2.3a	8.1 ± 1.3a	100.9 ± 5.7ab	129.2 ± 11.1ab
G9	18.0 ± 1.1abc	19.9 ± 0.7bcd	111.9 ± 4.2abc	112.0 ± 5.7a	6.0 ± 0.4ab	5.3 ± 0.2a	173.1 ± 3.8a	61.9 ± 11.2a	15.8 ± 1.6a	7.6 ± 1.1a	91.7 ± 4.2abc	95.9 ± 6.0bc
G10	24.5 ± 0.5a	24.6 ± 1.2a	99.8 ± 3.9bc	109.1 ± 11.1a	7.0 ± 0.6a	5.4 ± 0.2a	174.2 ± 54.4a	68.2 ± 8.8a	20.4 ± 1.8a	10.9 ± 1.9a	111.7 ± 6.3a	140.7 ± 7.6a
Significance	< 0.0001*	< 0.0001*	< 0.0001*	0.2485	< 0.0001*	0.2391	0.1212	0.2152	0.7183	0.6971	< 0.0001*	< 0.0001*

Table 4 Averages and variance analysis of all treatments regarding the traits examined in 2023 and 2024

Treatment	1st Pod height		Plant height		Number of branches		Number of pods		Plant yield		1000 Seed weight	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
T1	20.7 ± 1.0a	20.4 ± 0.8a	89.9 ± 3.7c	90.5 ± 5.0	5.3 ± 0.3a	5.4 ± 0.1ab	94.7 ± 17.7b	40.4 ± 2.3c	13.3 ± 1.3c	6.2 ± 0.2c	83.0 ± 3.5bc	86.3 ± 5.1b
T2	20.1 ± 0.8a	19.9 ± 1.2a	107.6 ± 2.6b	102.2 ± 4.2	5.3 ± 0.2a	4.9 ± 0.2b	89.3 ± 6.2b	57.4 ± 5.1b	12.0 ± 1.1c	7.9 ± 0.3c	74.3 ± 3.0c	101.4 ± 5.9ab
T3	21.6 ± 0.8a	21.8 ± 0.9a	115.9 ± 2.8ab	112.5 ± 3.1	5.8 ± 0.2a	5.6 ± 0.2a	147.0 ± 12.7a	62.0 ± 3.2b	20.9 ± 1.6b	9.8 ± 0.4b	86.6 ± 3.1b	111.1 ± 6.8a
T0	19.6 ± 0.9a	19.3 ± 1.0a	122.8 ± 2.9a	122.2 ± 2.8	5.4 ± 0.2a	5.6 ± 0.1a	163.7 ± 11.5a	78.0 ± 2.8a	35.9 ± 2.8a	13.5 ± 0.6a	116.4 ± 2.9a	121.1 ± 7.0a
Significance	0.4591	0.4145	< 0.0001*	< 0.0001*	0.5014	0.0211*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	0.0031*

differences were observed when analyzing treatment effects across all genotypes. In 2023, T2 showed the lowest seed weight, followed by T1. In 2024, T1 had the lowest value, followed by T2. The control group (T0) recorded the highest seed weight for both years (Table 4).

Discussion

Despite its agricultural importance, soybean production is highly susceptible to abiotic stress factors, especially drought. The increasing prevalence of drought due to global warming has become a critical challenge, significantly limiting soybean yields. Drought tolerance is a positive trait for improving soybean productivity, particularly in regions prone to water scarcity. This study assessed the drought tolerance levels of soybean genotypes by analyzing morphological and yield-related factors, offering valuable insights into the variability of drought responses among different genotypes.

Drought stress significantly influences the soybean's morphological traits, including plant height, branch number, and pod count. Wei et al. (2018) found that drought stress significantly reduced all aspects of soybean growth and yield, particularly during the reproductive growth phases. Understanding how soybeans respond to drought stress at different growth stages is crucial for optimizing yields in drought-prone regions. The initial signs of drought stress, such as leaf wilting and scorching, are consistent with previous observations (Islam et al. 2022). Drought stress accelerates leaf senescence in soybeans, where plants shed older leaves to conserve water and energy under stressful conditions (Munne-Bosch and Alegre 2004). This is a natural response to reduce water loss and improve the plant's overall survival. This leaf senescence in soybeans starts with older leaves and progresses to younger ones. This process helps redirect resources from senescing leaves to developing fruits and seeds, speeding up the plant's life cycle under stressful conditions (Munne-Bosch and Alegre 2004). Initiation of drought at an early stage causes the activation of the drought response mechanism and leads to a considerable recovery in the loss from drought because early-stage plants activate their drought response mechanism better. The plants activate specific mechanisms to reduce water loss under stress conditions (Cattivelli et al. 2008). Some of the mechanisms include partial closure of stomata to reduce water loss through transpiration (Flexas et al. 2006). Plants may reduce shoot growth to conserve energy and focus on root development to access deeper water sources (Cattivelli et al. 2008; Cerezini et al.2019).

Drought at the flowering and pod-filling stage affects yield most (Engels et al. 2017). Seed yield was strongly linked to pod count, with genotype and treatment effects playing a pivotal role. This study recorded the highest seed yields and weights in the control group, while drought-stressed treatments showed substantial reductions. Pod development is a crucial stage in determining soybean yield, which is heavily influenced by water availability. The number of pods per plant is a major contributor to overall yield. Water stress shortens the flowering period, leading to fewer flowers per plant (Siebers et al. 2015; Nadeem et al. 2019; Soba et al. 2022). In this study, all soybean varieties experience a reduction in pod numbers under varying levels of drought stress, similar to previous studies (Mwenye 2018; Fenta et al. 2014). Drought stress, particularly during early pod formation, significantly diminishes pod numbers, resulting in notable yield losses or, in severe cases, complete crop failure (Liu et al. 2004; Lobato et al. 2009).

Drought stress adversely affects flower development in soybeans, including flower opening and the maintenance of turgor pressure (Yee-Shan et al. 2013). These effects result in increased flower abortion and reduced pollination success (Basal and Szabo 2019). Premature drying of flowers under drought conditions further diminishes pollination and pod formation (ICM 2017), leading to decreased pod set and overall yield. Desclaux et al. (2000) observed that early-season drought reduces the number of seeds per pod, whereas late-season drought predominantly impacts seed weight. Similarly, Brevedan and Egli (2003) showed that even brief periods of drought during seed filling cause significant yield reductions, highlighting the high sensitivity of this stage to water stress. Rudy and Coto (2003) identified reduced pod number as a primary factor in initial soybean yield losses, particularly during critical phases such as pod formation and seed filling. Likewise, studies by Rotundo and Westgate (2010) and Sehgal et al. (2018) confirm that drought stress during seed initiation

substantially decreases seed number and overall soybean yield.

Drought stress significantly reduces the pod filling rate in soybean plants, leading to fewer seeds per pod and, consequently, a decline in overall yield (Nadeem et al. 2019). Similar findings were reported by Zhao et al. (2018), who observed notable reductions in seed weight and size, further contributing to yield losses. Drought conditions also increase tiny, shriveled, and wrinkled seeds (Wijewardana et al. 2019; Abdelhamied et al. 2021). In our study, it was observed that small, shriveled and wrinkled seeds ratio increased under drought conditions. Studies by Pathan et al. (2010) and Fried et al. (2019) corroborate these results, demonstrating significant reductions in seed yield under drought conditions. The decline in seed production per plant under water-limited conditions is closely linked to critical developmental stages, mainly flowering and pod filling, which are highly sensitive to drought stress (Kobraei et al. 2011; Cerezini et al. 2016; Nadeem et al. 2019).

The findings of this study align with those of Nadeem et al. (2019), who reported that grain yield losses under drought conditions are influenced by factors such as drought severity, duration, the crop's growth stage, and genetic variability among varieties. Similarly, consistent with Farooq et al. (2009), our research indicates that water deficits during the reproductive stage significantly reduce soybean yield. This reduction is primarily attributed to declines in key yield traits, including the number of pods per plant and the number of seeds per pod. Our results corroborate Mwale et al. (2017), who observed genotype-specific responses to drought stress in cowpeas. Variations in grain yield among genotypes under different drought stages are consistent with prior studies (Mabulwana 2013; Hossain et al. 2014), demonstrating that genotypic behavior varies under diverse environmental conditions (Fikere et al. 2014).

The response of plants to drought stress varies depending on the timing and intensity of the stress and differences between genotypes, even under identical conditions (Nadeem et al. 2019). Chiipanthenga (2020) reported a reduction in plant height when comparing drought-treated plants to control treatments. Similarly, our findings indicate a decrease in plant height from T1 to the control group T0 (Table 4). This reduction is attributed to inhibited cell division and elongation under drought conditions (Farooq et al. 2009). A decrease in plant height impacts the total number of pods per plant, ultimately reducing the final yield (Mabulwana 2013). These findings are consistent with Mwenye (2018), who demonstrated that plant height does not significantly impact yield among soybean varieties under drought conditions.

Additionally, plant height was identified as an ineffective trait for distinguishing drought-tolerant varieties from drought-sensitive ones. Similarly, our results are similar to the previous study by Giordani et al. (2019), who reported no significant correlation between per-plant yield and plant height across varying drought levels. So, plant height is not a reliable yield indicator under different drought conditions. While drought stress did not significantly affect the number of branches across genotypes, it notably influenced branch length and the number of pods on lateral branches, depending on the severity and timing of the drought (Frederick et al. 2001).

The 1000-seed weight is a key parameter for assessing soybean grain quality. Drought stress significantly reduces seed quality by increasing the proportion of smaller seeds and lowering overall seed vigor (Ahmed et al. 2011). Drought stress also leads to smaller seed sizes, resulting in reduced 1000-seed weight and a decline in overall seed quality (Kananji et al. 2013). Similarly, Ku et al. (2013) documented a decrease in seed size and 1000-seed weight under drought conditions, attributing this to an increased proportion of smaller seeds in water-limited environments. Our study's findings regarding 1000-seed weight are consistent with previous research. Similar to earlier studies, we observed that drought stress reduces seed size and decreases 1000-seed weight, reflecting the increased proportion of smaller seeds under water-limited conditions.

Conclusion

The findings emphasize the critical influence of water availability on plant performance, particularly for characteristics such as plant height, pod number, seed yield, and 1000-seed weight. Drought significantly reduced seed yield among genotypes compared with the control group. While the first pod height was largely unaffected, with minimal differences across treatments, pod number and seed yield exhibited high sensitivity, demonstrating the critical role of water

during pod setting and flowering stages. The findings revealed that soybean plants were most sensitive to drought stress during the pod-setting stage, with more significant reductions in yield observed from the control group to the pod-setting stage than the flowering stage. In conclusion, this study underscores the critical need to develop and identify drought-tolerant soybean genotypes. A combined analysis of data from both years revealed that G7 exhibited the highest tolerance to water-limited conditions, followed by G10, offer valuable insights for future breeding programs. Expanding research to include a broader range of genotypes and environmental scenarios is essential for understanding drought adaptability and ensuring agricultural sustainability in the face of increasing climate variability. These results highlight the interplay between genotypic factors and environmental stress, with genotype-specific responses underscoring the importance of breeding for drought tolerance. While genetic variation among genotypes influenced branching patterns and pod production, treatment effects dominated under severe drought conditions, showing the impact of water stress on productivity. This study will help the scientific community and farmers identify and select genotypes with enhanced tolerance to drought conditions.

Author contribution Conceptualization, M.A and R.U.; Methodology, M.A.; Writing—original draft, M.A.; Writing—review & editing. R.U.; Supervision, R.U.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). The authors have not disclosed any funding.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abdelhamied YS, Kandil AA, El-Badry OZ, Taha MH (2021) Effect of water stress during seed formation on seed quality of irrigated soybean. Nat Vol Essent Oils 8950:13216–13238

Ahmed SA, Diffenbaugh NS, Hertel TW, Lobell DB, Ramankutty N, Rios AR, Rowhani P (2011) Climate volatility and poverty vulnerability in Tanzania. Glob Environ Chang 21(1):46–55

Aziez AF, Prasetyo A (2022) The effect of drought stress on the growth and yield of soybean (*Glycine max* L.). Appl Ecol Environ Res 20(4):3569

Basal O, Szabo A (2019) Does drought stress always negatively affect the yield and quality of soybean in Hungary? Acta AgrariaDebr 2:37–40

Brevedan RE, EglI DB (2003) Short periods of water stress during seed filling, leaf senescence, and yield of soybean. Crop Phys Metab 96(6):170

Cattivelli L et al (2008) Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. Field Crops Res 105(1–2):1–14. https://doi.org/10.1016/j.fcr.2007.07.004

Cerezini P, Kuwano BH, dos Santos MB, Terassi F, Hungria M, Nogueira MA (2016) Strategies to promote early nodulation in soybean under drought. Field Crop Res 196:160–167

Cerezini P, Kuwano BH, Neiverth W, Grunvald AK, Pípolo AE, Hungria M, Nogueira MA (2019) Physiological and N2-fixation-related traits for tolerance to drought in soybean progenies. Pesq Agropecu Bras 54(2019):e00839. https://doi.org/10.1590/S1678-3921.pab2019.v54.00839

Chiipanthenga MK (2020). Drought tolerance in malawian soybean (*Glycine Max* L.) germplasm (Doctoral dissertation, University of the Free State)

Desclaux D, Huynh TT, Roumet P (2000) Identification of soybean plant characteristics that indicate the timing of drought stress. Crop Sci 40(3):716–722

Engels C, Rodrigues FA, Ferreira ADO, Inagaki TM, Nepomuceno AL (2017) Drought effects on soybean cultivation–a review. Annu Res Rev Biol 16(1):1–13

Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA (2009) Plant drought stress: effects, mechanisms and management. Agron Sustain Dev 29:185–212

Fenta BA, Driscoll SP, Kunert KJ, Foyer CH (2012) Characterization of drought-tolerance traits in nodulated soya beans: the importance of maintaining photosynthesis and shoot biomass under drought-induced limitations on nitrogen metabolism. J Agron Crop Sci 198:92–103

Fenta BA, Beebe SE, Kunert KJ, Burridge JD, Barlow KM, Lynch JP, Foyer CH (2014) Field phenotyping of soybean roots for drought stress tolerance. Agronomy 4(3):418–435. https://doi.org/10.3390/agronomy4030418

Fikere M, Bing DJ, Tadesse T, Ayana A (2014) Comparison of biometrical methods to describe yield stability in field pea (*Pisum sativum*) under south eastern Ethiopia conditions. Afr J Agric Res 9:2574–2583

Flexas J et al (2006) Keeping a positive carbon balance under adverse conditions: responses of photosynthesis and respiration to water stress. Physiol Plant 127(3):343–352

Frederick JR, Camp CR, Bauer PJ (2001) Drought-stress effects on branch and mainstem seed yield and yield components of determinate soybean. Crop Sci 41(3):759–763

Fried HG, Narayanan S, Fallen B (2019) Evaluation of soybean [*Glycine max* (L.) Merr.] genotypes for yield, water use efficiency, and root traits. PLoS ONE 14:1–18

Fuganti-Pagliarini R, Ferreira LC, Rodrigues FA, Molinari HBC, Marin SRR, Molinari MDC, Marcolino-Gomes J, Mertz-Henning LM, Farias JRB, de Oliveira MCN, Neumaier N, Kanamori N, Fujita Y, Mizoi J, Nakashima K, Yamaguchi-Shinozaki K, Nepomuceno AL (2017) Characterization of soybean genetically modified for drought tolerance in field conditions. Front Plant Sci 8:1–15

Giordani W, Gonçalves LSA, Moraes LAC, Ferreira LC, Neumaier N, Farias JRB, Nepomuceno AL, Neves de Oliveira MC, Mertz-Henning LM (2019) Identification of agronomical and morphological traits contributing to drought stress tolerance in soybean. Aust J Crop Sci 13(1):35–44

Goldschein E (2011) The 10 most important crops in the world. http://www.businessinsider.com/10-crops-that-feed-the-world-2011-9?op=1#ixzz3hpepX Bf5. Accessed on 4 Aug 2015

Guimarães-Dias F, Neves-Borges AC, Viana AAB, Mesquita RO, Romano E, de Fátima M, Grossi-de-Sá AL, Nepomuceno ME, Loureiro MAF (2012) Expression analysis in response to drought stress in soybean: Shedding light on the regulation of metabolic pathway genes. Genet Mol Biol 35(1 suppl 1):222–232. https://doi.org/10.1590/S1415-47572012000200004

Han M-L, Lv Q-Y, Zhang J, Wang T, Zhang C-X, Tan R-J, Wang Y-L, Zhong L-Y, Gao Y-Q, Chao Z-F, Li Q-Q, Chen G-Y, Shi Z, Lin H-X, Chao D-Y (2022) Decreasing nitrogen assimilation under drought stress by suppressing DST-mediated activation of nitrate reductase 1.2 in rice. Mol Plant 15(1):167–178. https://doi.org/10.1016/j.molp.2021.09.005

Hossaina MM, Liub X, Qic X, Lama HM, Zhang J (2014) Differences between soybean genotypes in physiological response to sequential soil drying and rewetting. Crop J 2:366–380

ICM (2017) Integrated Crop Management News at Iowa State University. https://crops.extension.iastate.edu/cropnews/2017/07/influence-drought-corn-and-soybean.

Igiehon NO, Babalola OO, Cheseto X, Torto B (2021) Effects of rhizobia and arbuscular mycorrhizal fungi on yield, size distribution and fatty acid of soybean seeds grown under drought stress. Microbiol Res 242:126640. https://doi.org/10.1016/j.micres.2020.126640

Islam MR, Hoque MN, Hoshain S (2022) Growth, yield and seed quality of soybean under drought stress: a review. South Asian J Agric Sci 2:41–47

Jogawat A, Yadav B, Chhaya NL, Singh AK, Narayan OP (2021) Crosstalk between phytohormones and secondary metabolites in the drought stress tolerance of crop plants: a review. Physiol Plant 172(2):1106–1132. https://doi.org/10.1111/ppl.13328

Kananji GAD, Yohane E, Siyeni D, Mtambo L, Kachulu L, Chisama BF, Malaidza H, Tchuwa F, Mulekano O (2013) A Guide to soybean production in Malawi. Lilongwe, Malawi. p 21

Kisman A, Sudarmawan AK (2002) Effect of genotype, environment and their interactions on yield and yield components of soybean in south Lombok

Kivuva BM (2013) Breeding sweet potato (*Ipomoea batatas* [L.] Lam.) for drought tolerance in Kenya. PhD thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa. p 181

Kness A (2020) Yield impact on heat and drought-stressed soybeans. University of Maryland Extension, Maryland Extension News

Kobraei S, Etminan A, Mohammadi R, Kobraee S (2011) Effects of drought stress on yield and yield components of soybean. Ann Biol Res 2:504–509

Liu F, Jensen CR, Andersen MN (2004) Pod set related to photosynthetic rate and endogenous ABA in soybeans subjected to different water regimes and exogenous ABA and BA at early reproductive stages. Ann Bot 94:40–411

Lobato AKS, Neto MAM, Meirelles ACS, Silva LI, Marochio CA, Monteiro ER, ZeniNeto H et al (2009) Relationship between leaf relative water content and total soluble proteins in soybean exposed to short water deficit. Res J Biol Sci 4(9):1061–1067

Mabulwana PT (2013) Determination of drought stress tolerance among soybean genotypes using morphological and physiological markers. MSc Thesis. University of Limpopo, Limpopo, South Africa. p 83

Marinho JP, Pagliarini RF, Molinari MDC, Marcolino-Gomes J, Caranhoto ALH, Marin SRR, Oliveira MCN, Foloni JSS, Melo CLP, Kidokoro S, Mizoi J, Kanamori N, Yamaguchi-Shinozaki K, Nakashima K, Nepomuceno AL, Mertz-Henning LM (2022) Overexpression of full-length and partial DREB2A enhances soybean drought tolerance. Agro Sci Biotech 8:1–21

McConnell I, Li G, Brudvig GW (2010) Energy conversion in natural and artificial photosynthesis. Chem Biol 17(5):434–447

Munné-Bosch S, Alegre L (2004) Die and let live: leaf senescence contributes to plant survival under drought stress. Funct Plant Biol 31(3):203–216

Mwale SE, Ochwo-Ssemakula M, Sadik K, Achola E, Okul V, Gibson P, Edema R, Singini W, Rubaihayo P (2017) Response of cowpea genotypes to drought stress in Uganda. Am J Plant Sci 8:720–733

Mwenye OJ (2018) Root properties and proline as possible indicators for drought tolerance in soybean. PhD Thesis, University of the Free State, Bloemfontein, South Africa. p 125

Nadeem M, Li J, Yahya M, Sher A, Ma C, Wang X, Qiu L (2019) Research progress and perspective on drought stress in legumes: a review. Int J Mol Sci 20:1–32

Passioura JB, Angus JF (2010) Improving productivity of crops in water-limited environments. Adv Agron 106:37–75

Pathan S, Nguyen HT, Sharp RE, Shannon JG (2010) Soybean Improvement for drought, salt and flooding tolerance. Korean J Breed Sci 42:329–338

Rotundo JL, Westgate ME (2010) Rate and duration of seed component accumulation in water-stressed soybean. Crop Sci 50:676–684

Rudy CT, Coto Z (2003) Effects of drought stress on growth and yield of soybean. Science Philosophy. p702

Sehgal A, Sita K, Siddique KHM, Kumar R, Bhogireddy S, Varshney RK, HanumanthaRao B, Nair RM, Prasad PVV, Nayyar H (2018) Drought or/and heat-stress effects on seed filling in food crops: impacts on functional biochemistry, seed yields, and nutritional quality. Front Plant Sci 9:1705

Siebers MH, Yendrek CR, Drag D, Locke AM, Rios Acosta L et al (2015) Heat waves imposed during early pod development in soybean (*Glycine max*) cause significant yield loss despite a rapid recovery from oxidative stress. Glob Change Biol 21:3114–3125

Soba D, Cesar A, Iker A (2022) Additive effects of heatwave and water stresses on soybean seed yield is caused by impaired carbon assimilation at pod formation but not at flowering. Plant Sci 321:1–13

Staton M (2020) Moisture stress and high temperature effects on soybean yields. Michigan State University Extension

Vaghar MS, Sayfzadeh S, Zakerin HR, Kobraee S, Valadabadi SA (2020) Foliar application of iron, zinc, and manganese nano-chelates improves physiological indicators and soybean yield under water deficit stress. J Plant Nutrit 43(18):2740–2756

Wei Y, Jin J, Jiang S, Ning S, Liu L (2018) Quantitative response of soybean development and yield to drought stress during different growth stages in the huaibei plain, china. Agronomy 8(7):1–16

Wijewardana C, Reddy KR, Krutz LJ, Gao W, Bellaloui N (2019) Drought stress has transgenerational effects on soybean seed germination and seedling vigor. PLoS ONE 14:1–20

Wilson RF, Ganesan B, Anderson C (2011) Soybean composition and nutritional value. In Soybeans: Chemistry, Technology and Utilization pp 13–48

Yan C, Song S, Wang W, Wang C, Li H, Wang F, Sun X (2020) Screening diverse soybean genotypes for drought tolerance by membership function value based on multiple traits and drought-tolerant coefficient of yield. BMC Plant Biol 20:1–15

Yee-Shan K, Au-Yeung W-K, Yung Y-L, Li M-W, Wen C-Q, Liu X, Lam H-M (2013) Drought stress and tolerance in soybean. In: Board J (ed) A comprehensive survey of international soybean research - Genetics, physiology, agronomy and nitrogen relationships. InTech, Rijeka. https://doi.org/10.5772/52945

Yee-Shan K, Au-Yeung WK, Yuk-Lin Y, Man-Wah L, Chao-Qing W, Liu X, Hon-Ming L (2013) Drought stress and tolerance in soybean. In: Board JE (ed) A comprehensive survey of international soybean research: genetics, physiology, agronomy and Nitrogen Relationship. In Tech, Rijeka, pp 208–237

Zhang Y, Zhang H-Z, Fu J-Y, Du Y-Y, Qu J, Song Y, Wang P-W (2022) The GmXTH1 gene improves drought stress resistance of soybean seedlings. Mol Breed 42:1–18

Zhang Zhengbin X, Ping SH, Liu Mengjun F, Zhenyan CL (2011) Advances and prospects: biotechnologically improving crop water use efficiency. Crit Rev Biotechnol 31(3):281–293. https://doi.org/10.3109/07388551.2010.531004

Zhao T, Aleem M, Sharmin RA (2018) Adaptation to water stress in soybean: morphology to genetics. In: Andjelkovic V (ed) plant, abiotic stress and responses to climate change. InTech, Rijeka. https://doi.org/10.5772/intechopen.72229

Zhou Q, Song S, Wang X, Yan C, Ma C, Dong S (2022) Effects of drought stress on flowering soybean physiology under different soil conditions. Plant Soil Environ 68(10):487–498. https://doi.org/10.17221/237/2022-PSE

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.