Safeguarding Mississippi soybean production from interactive heat and drought stress-induced yield and quality losses (MSPB project Number: 43-2021)

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BACKGROUND AND OBJECTIVES

In the Midwest, soybean yields have been inversely related to average maximum summer air temperatures, with yield suppression of up to 6% under rainfed when the temperatures are above 85°F during critical developmental stages, depending on cultivars. In 2008, a combination of heat and drought stress caused agricultural losses of $8.6 billion in states. In addition to the various impacts observed, detailed analysis highlights that combined stress will amplify a negative effect on seed numbers, seed weight, and seed composition in current and future production systems. Not surprisingly, the highest yield and quality penalty are expected to occur when the heat and drought stresses coincide with flowering and pod filling in soybean (R1 to R6). Heat stress at flowering induces significant damage to male (pollen) reproductive organ viability, causing a linear decline in seed number. Long-duration stress during pod filling impairs physiological and impacts source-sink relations linked to seed size and quality. In general, soybean yield depended on the amount of photo-assimilate produced in the leaf to supply to the seed (source) and the seed (sink) potential to hold that assimilate. In most soybean growing regions, including Mississippi, maximum temperatures during reproductive and seed-filling stages are already >85°F highlighting the crop's vulnerability to heat stress. For every 0.8°C increase above 26.7°C (80ºF), the current mean temperature of the southern United States, soybean yields are expected to decline by 2.4%. Under field conditions, soybean exposed to high temperature (97°F) and drought stress suppresses the plant health, quality, and nutritional value beans by reducing leaf photosynthetic rate, stomatal conductance, and increased canopy temperatures during R1 to R6. To date, soybean breeding programs are successful in increasing yield potential in a favorable environment. However, progress in breeding for interactive stress tolerance has not received similar attention. Here, we aim to quantify soybean plant health, yield, and seed compositional changes in response to heat and drought stress conditions.

The objectives of the project are:

Obj. 1: Determine soybean reproductive and physiological responses to interactive heat and drought stress
Obj. 2: Quantify the impact of heat and drought stress on soybean yield and quality dynamics

REPORT OF PROGRESS/ACTIVITY

Obj. 1: Determine soybean reproductive and physiological responses to interactive heat and drought stress

An experiment was conducted at the RR Foil Plant Science Research Greenhouse Facility, Mississippi State University to quantify the impacts of the drought and hot (heat stress) environments on the reproductive success, and health of soybean. The graduate student-led experiment (Year-1) consists of ten soybean cultivars/lines involving eight from industries (Armor, AgriGold, Local Seed, Dyna-Gro, Progeny Ag, Donmario, and Delta Grow) and two breeding lines (high yielding and high protein). Seeds of ten cultivars were planted in pots (10 cultivars x 4 treatments x 10 replications = 400 pots) filled with the farm soil and were grown under non-stress conditions until flowering. At flowering, plants were subjected to four different treatments; control (32°C daytime temperature + 100% irrigation, characterized as a present growing condition), heat stress (38°C daytime + 100% irrigation), drought (50% irrigation + 32°C daytime temperature) and heat and drought (38ºC daytime temperature + 50% irrigation, future soybean growing conditions) conditions during reproductive and early pod filling stage. Individual and combined stress treatment-induced changes in (i) pollen germination, (ii) stomatal conductance, transpiration, and other photosynthesis-related parameters, including PSII quantum yield, chlorophyll fluorescence, and leaf chlorophyll index, and (iii) canopy/leaf temperature, and other physiological parameters were quantified. All parameters were significantly (p<0.01 to p<0.001) affected by cultivar, treatment, and cultivar x treatment. Compared to the control, pollen germination of all cultivars was significantly decreased by 25% under combined stress followed by drought (16%). Among ten cultivars, six cultivars recorded more than 80% of pollen germination under heat stress, while under drought stress eight cultivars recorded pollen germination of less than 80% (Figure 1A). Compared to plants grown under the control conditions, drought stress alone or in combination with heat stress significantly (p<0.05) decreased stomatal conductance (Figure 1B) and canopy temperature was increased by 9 ºC compared to the control (Figure 1C). Interestingly, cultivars 'R01-416F' and 'DM 45X61' maintained a cooler canopy across treatments compared to the other cultivars.

Obj. 2: Quantify the impact of heat and drought stress on soybean yield and quality dynamics
At physiological maturity, days to physiological maturity (R8), plant height, number of branches, pod number, and biomass were recorded across treatments. Hand-harvested pods were dried and hand-threshed to evaluate the impacts of heat, drought, and combined stress on (i) yield parameters (pod number, pod weight, seed number, seed weight, 100- seed weight, harvest index), (ii) seed quality parameters (protein, oil, and others) and (iii) mineral constituents (nitrogen, calcium, and others) of soybean. The seed quality traits were analyzed using a Near-Infrared Spectrometer (NIRS) established at the PI laboratory. A significant variation (p<0.001) was observed between cultivar, treatment, and their interactions for yield and quality parameters (Table 1). The pod number and pod weight were reduced by 35% and 43% under combined heat and drought stress treatment. The seed weight was severely impacted by combined stress (46% decline) followed by drought stress (33% decline) and heat stress (23% decline) compared to control (Figure 2A). There was a maximum reduction of seed number under drought stress (46%) followed by combined stress conditions (43%) and heat stress (19%) compared to control (Figure 2B). The seed protein was decreased by 6% under combined heat and drought stress followed by heat stress (Figure 3A). Whereas increased protein (4%) under drought stress decreased by 2% compared to control. The oil content increased by 11% under combined stress conditions (Figure 3B). The protein and oil content were negatively correlated across treatments. The major component of amino acids (i.e., nitrogen) was decreased by 5% under combined stress conditions, decreased by 2% under heat stress, and increased by 3% under drought stress. This result is in line with the observed protein content in the seed. A weaker association of yield parameters between control and stress treatments indicates greater plasticity in response to the individual (drought or heat) and combined stress (Figure 4). This observation suggests that the selection of soybean-based on absolute performance under non-stress or stress conditions may not help minimize heat and drought stress-induced yield and quality losses. Based on our first-year results, the cultivar 'R01-416F' and 'S48XT90' performed consistently well across the stress treatments in terms of seed yield. Therefore, these cultivars can be used to minimize stress damages and can be used by breeders for developing better-performing varieties for unfavorable climatic conditions.

IMPACTS AND BENEFITS TO MISSISSIPPI SOYBEAN PRODUCERS

The primary beneficiaries of the project outcome will be our Mississippi soybean growers (~3000 soybean farms), which represent 2.2 million acres with the production of 120.4 million bushels in 2021. Based on our first-year results, considering up to 23, 33, and 46% yield reduction caused by heat, drought, and combined stress, the estimated economic loss could be $202, $253, and $357 per acre annually under harsh environments, respectively. Second-year funding will help validate the consistency of stress resilience traits and identify superior high-yielding soybeans with better quality under heat and drought stress. The use of such stress-tolerant soybean lines will offer Mississippi growers an edge in the domestic market to enhance their profit.

END PRODUCTS–COMPLETED OR FORTHCOMING

Publications

- Bheemanahalli, R., Poudel, S., Alsajri, F.A. and Reddy, K.R. (2022). Phenotyping of Southern United States Soybean Cultivars for Potential Seed Weight and Seed Quality Compositions. *Agronomy*, *12*(4), 839 https://doi.org/10.3390/agronomy12040839
- Poudel, S., Vennam R.R., Reddy, K.R., and Bheemanahalli, R. (2022). Quantifying the impact of drought stress on pollen germination, physiology, yield and quality in soybean. (In preparation for submission to *Plant Physiology and Biochemistry*).

Abstracts published or presentations at conferences

1. Poudel, S., Vennam R.R., Reddy, K.R, and Bheemanahalli, R. (2022). Impact of Elevated Temperature and Low Rainfall in Soybean Yield and Quality. 4th Annual MAS Summer Science and Engineering Symposium, June 8 Mississippi State University, MS. (3-Minute Oral Presentation- ***Awarded Second place***)
2. Poudel, S., Vennam R.R., Reddy, K. R, and Bheemanahalli, R. (2022). Phenotypic characterization of soybean cultivars for heat and drought stress tolerance. 4th Annual MAS Summer Science and Engineering Symposium, June 8, Mississippi State University, MS. (Poster presentation)
3. Poudel, S., Bheemanahalli, R., Vennam R.R., and Reddy, K. R. (2022). Independent and Combined Effects of Heat and Drought Stress During Pod Filling on Soybean. 3rd Biennial International Scientific Conference of Association of Nepalese Agricultural Professionals of America, May 28-29, Atlanta, Georgia. (Oral presentation- ***Awarded Second place***)
4. Poudel, S., Bheemanahalli, R., Vennam R.R., and Reddy, K. R. (2022). Impact of Heat Stress on Pollen Germination, Physiology, Yield, and Quality in Soybean. Mississippi Academy of Sciences, *86th* Annual Meeting, March 31- April 01, Biloxi, MS. (Poster presentation- ***Awarded first place***)
5. Poudel, S., Bheemanahalli, R., Vennam R.R. and Reddy, K. R. (2022). Independent and Combined Effects of Heat and Drought Stress During Pod Filling on Soybean. Mississippi Academy of Sciences, *86th* Annual Meeting, March 31- April 01, Biloxi, MS. (Oral presentation)
6. Poudel, S., Bheemanahalli, R., Vennam R.R., and Reddy, K. R. (2022). Interactive Effects of Heat and Drought Stress on Soybean Yield and Quality. Graduate Research Symposium, February 26, Mississippi State University, MS. (Oral presentation)
7. Poudel, S., Bheemanahalli, R., Vennam R.R., and Reddy, K. R. (2022). Drought Stress Impacts on Soybean Pollen Germination, Physiology, and Yield. Southern Branch of American Society of Agronomy, February 12-14, New Orleans, LA. (Poster presentation- ***Awarded Third place***)
8. Poudel, S., Rangappa, R. B., Vennam R.R., and Reddy, K. R. (2022). Interactive Effects of Heat and Drought Stress on Soybean Physiology, Pollen Germination, Yield, and Quality. Southern Branch of American Society of Agronomy, February 12-14, New Orleans, LA. (Oral presentation)
9. Poudel, S., Bheemanahalli, R., and Reddy, K. R. (2021). Interactive Heat and Drought Stress Impacts on Pollen Germination and Physiological Attributes in Soybeans. ASA, CSSA & SSSA Virtual International Annual Meeting, November 9-11, Salt Lake City, UT, USA.
10. Poudel, S., Bheemanahalli, R., Sehgal, A., Brand, D., Walne, C. H., & Reddy, K. R. (2021). Impact of Salt Stress on the Growth and Development of C 3 and C 4 Crop Species. ASA, CSSA & SSSA Virtual International Annual Meeting, November 9-11, Salt Lake City, UT, USA.

TABLE AND GRAPHICS

Table 1. Summary of analysis of variance across the cultivar (C), treatment (T), and their interaction (T x C) for some of the key yield and quality determining parameters.

Parameters	Treatment (T)	Cultivar (C)	T x C
Pollen germination (%)	***	***	***
Chlorophyll content (µg cm^2)	***	ns	***
Stomatal conductance (mol m^{-2} s^{-1})	***	***	***
Canopy temperature (°C)	***	***	**
Pod weight (g $plant^{-1}$)	***	***	***
Pod number ($plant^{-1}$)	***	***	***
Seed number ($plant^{-1}$)	***	***	***
Seed weight (g $plant^{-1}$)	***	***	***
Protein (%, dry basis)	***	***	***
Oil (%, dry basis)	***	***	***

, and *, indicate significance levels at $p < 0.01$ and $p < 0.001$, respectively. 'ns' indicates nonsignificant.

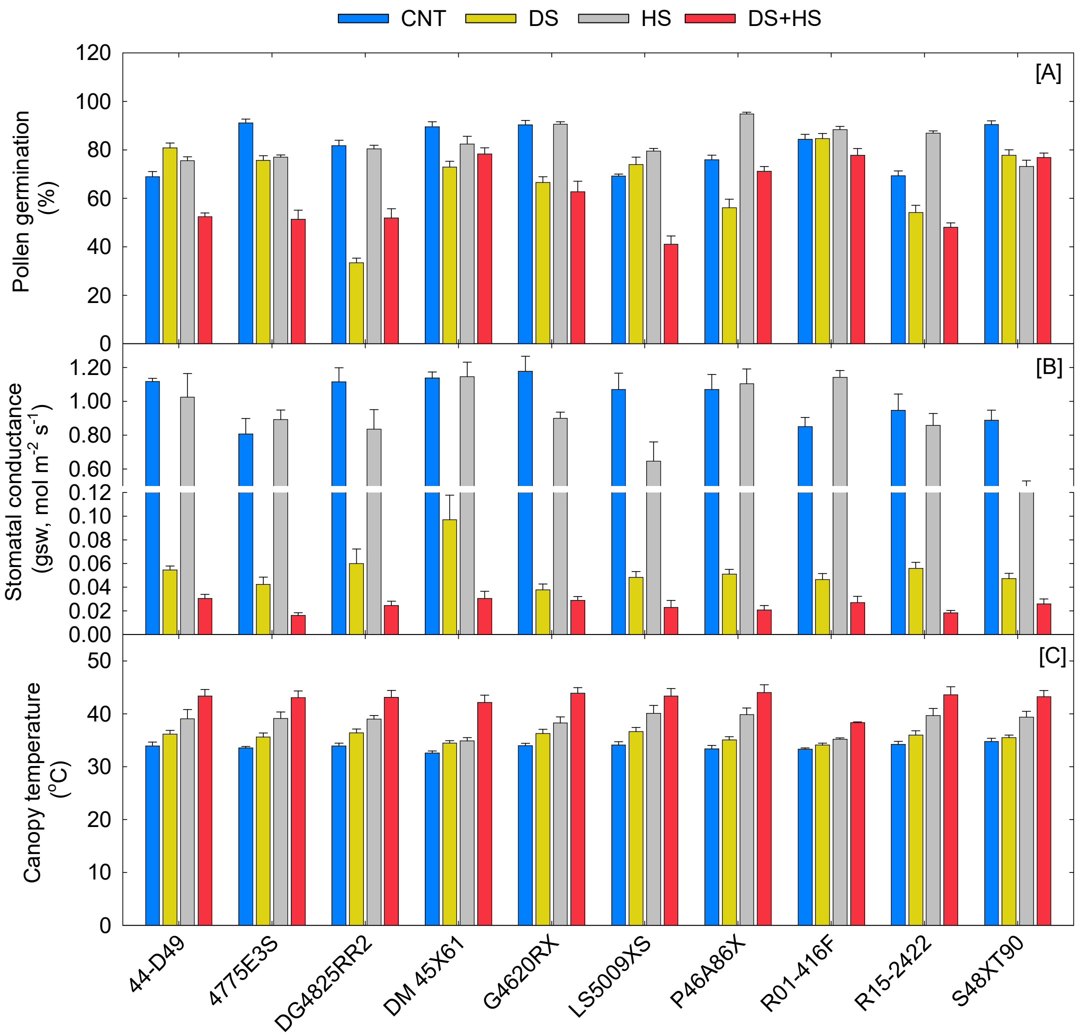

Figure 1. Impact of drought and heat stress on soybean pollen germination (A) and stomatal conductance (B) and canopy temperature (C). CNT- control, DS- drought stress, HS- heat stress, and DS+HS- combined drought and heat stress.

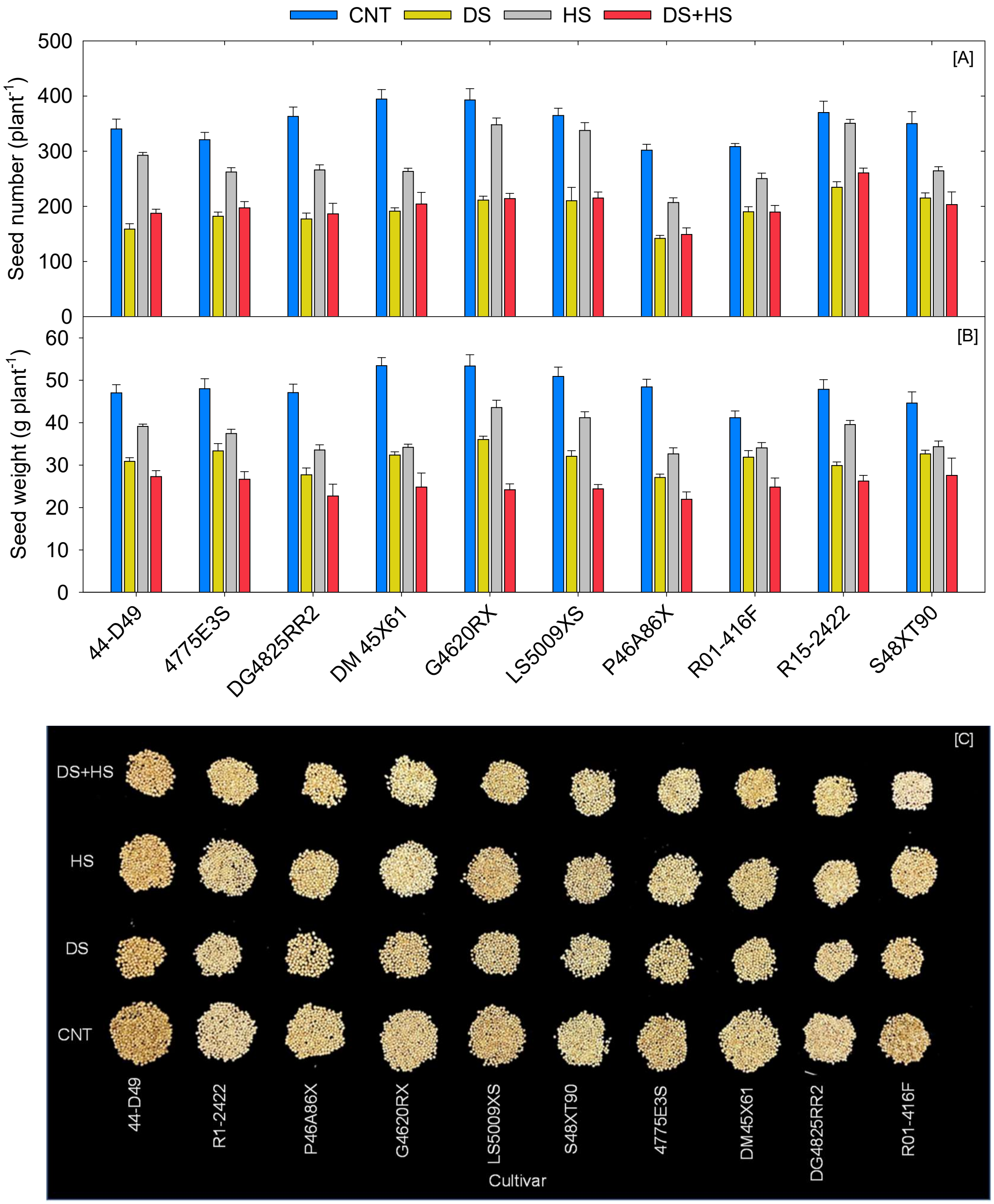

Figure 2. Seed number (A) and seed yield (B) responses of the ten soybean cultivars to control (CNT), drought stress (DS), heat stress (HS), and combined drought and heat stress (DS+HS). Image showing the impact of the individual (heat or drought) and combined stresses (*C*) on yield (per plant).

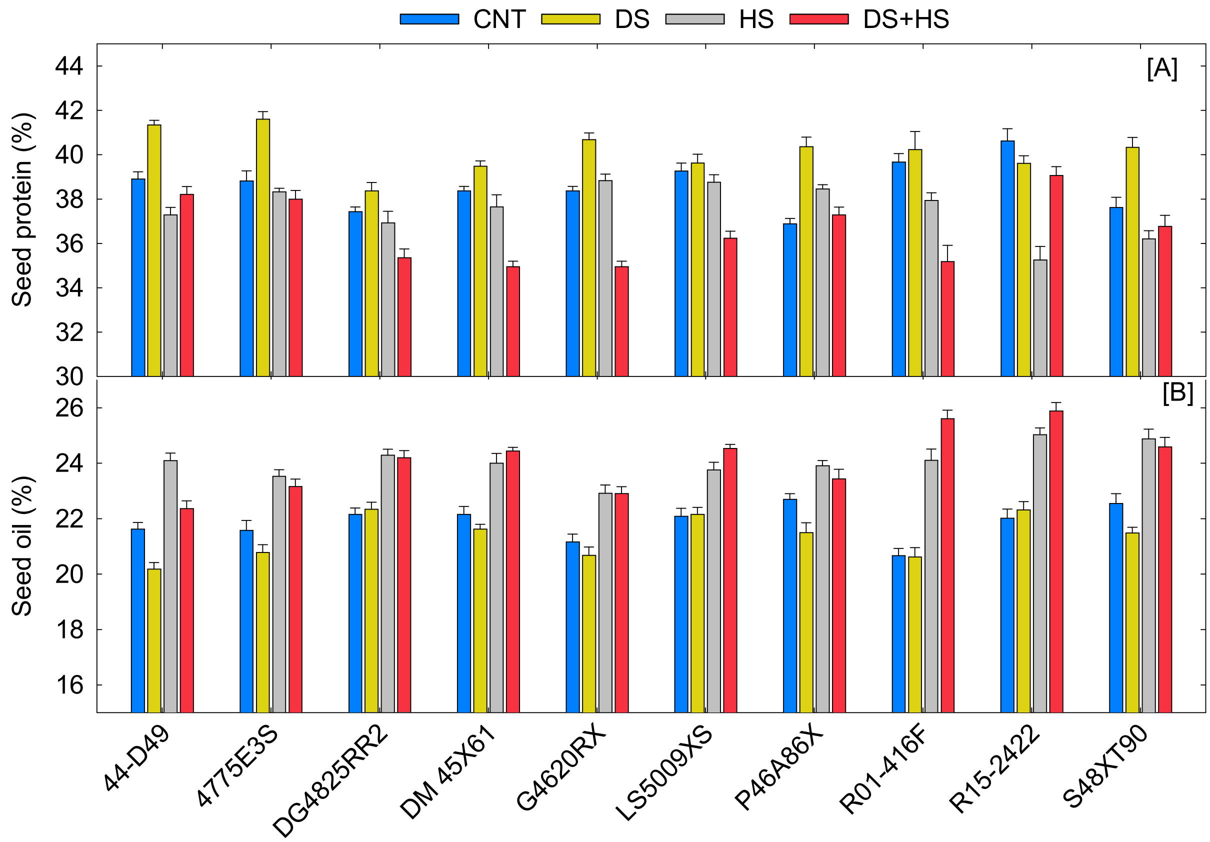

Figure 3. Seed protein (A) and oil (B) composition of ten soybean cultivars under control (CNT), drought stress (DS), heat stress (HS) and combined drought and heat stress (DS+HS).

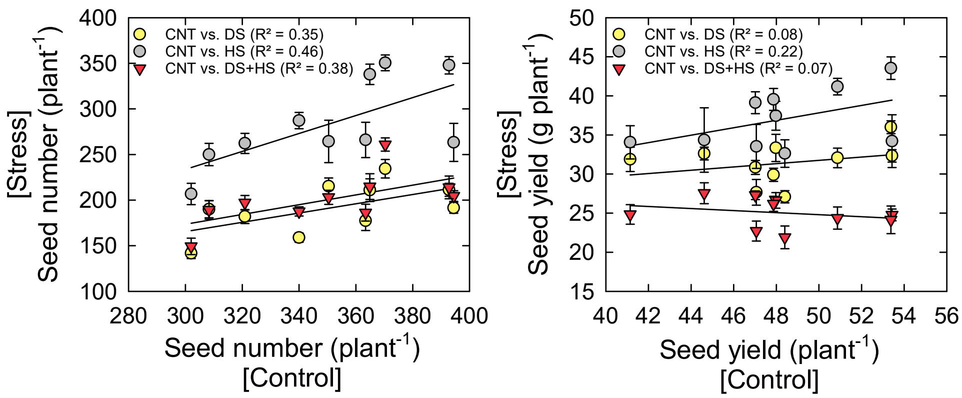

Figure 4. Relationship of seed number (A) and seed yield (B) between control and stress treatments. CNT - control, DS - drought stress, HS - heat stress, and DS+HS - combined drought and heat stress.