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Impact of Seed Coating of Rice Straw Based Biodegradable Water Absorbent (RS-BWAs) Polymer on Morpho-Physiological, Biochemical, Ionic Attributes and Anatomical Modifications in Camelina Sativa Under Drought Stress

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Abstract

Camelina, an important oilseed crop that belongs to the Brassicaceae family, is vital to global food security. Drought is one of the primary factors that cause oxidative damage and reduced plant growth and physiological parameters. It can be reduced by improving soil moisture through the coating of rice-straw-based biodegradable water absorbents (RS-BWAs). The treatments of this study were, (a) Camelina genotypes; (i) G1 = 611 and G2 = 618, (b) Drought stress; (i) Control (D0 = 100% FC), and (ii) D1 = 50% FC) (c) Rice-straw based biodegradable water absorbents; (i) P0 = Control, (ii) P1 = 5 g/kg seed, (iii) P2 = 10 g/kg seed (iv) P3 = 15 g/kg seed. Drought stress caused reduction in morphological parameters of camelina genotypes such as shoot fresh weight, shoot dry weight, shoot length and leaf area up to (31.1%, 26.8%, 20 and 37.5%) in G1-611 and decreased upto (18.5%, 21.4%, 22.2% and 27%), in G2-618. While, these attributes increased upto (48.5, 38.3%, 107.4 and 60.3%) at 15 g/kg seed in G1-611 and upto (52.1%, 51.7%, 125% and 61.3%) at 15 g/kg seed in G2-618. Drought stress increased the content of H_2O_2 up to (33.7, 48.1%) and MDA up to (24, 26%) in both genotypes (G1, G2) accordingly as compared to control. On the other hand, the seed priming of RS-BWAs (15 g/kg seed) caused a maximum improvement in activities of SOD up to (94, 220%), POD (40.3, 35.1%), and CAT (70.5, 87.7%) in G1 and G2 respectively under 50% FC. In Crux, results showed that 15 g/kg seed rice-straw-based BWAs were effective in reducing the adverse effects of drought stress in Camelina by lowering the activity of reactive oxygen species while enhancing the anti-oxidative functions.

Introduction

Camelina (*Camelina sativa* L. Crntz) is an ancient oilseed that is a member of the Brassicaceae family grown worldwide (Haslam et al., 2025). Camelina is a prospective oilseed crop as well as an alternative due to a number of its characteristics. The increasing demand for vegetable oils has necessitated the search for alternative oilseed crops, and camelina is prized for its distinctive fatty acid profile and high-quality oil (Ramzan et al., 2025; Waraich et al., 2020). Native to Europe, camelina may be found on farms in a wide variety of places, from Argentina to Alaska (Weiss et al., 2024). Camelina has its recent reviews due to its exceptional agronomic diversity, environmental flexibility (Boutet et al., 2022; Zanetti et al., 2024).

Camelina seed oil has a completely distinctive fatty acid composition due to higher amounts of alpha-linolenic acid and lower levels of erucic acid (Ahmad et al., 2020). It contains around 90% monounsaturated fatty acids and 60% polyunsaturated fatty acids (Agarwal et al., 2021). In addition to fatty acids and tocopherols, a relatively brief research on the metabolome of plants has led to the discovery of several metabolites found in seeds of camelina, including polyphenols with strong anti-inflammatory and antioxidant properties, such as phenolic acids, flavonols, terpenes, and proanthocyanidins (Alberghini et al., 2022). Furthermore, thiocyanates and isothiocyanates are the breakdown products of glucosinolates, which are found in camelina seeds and have negative and antinutritional effects on animals, a byproduct of cold seed pressing, including thyroid disorders, decreased growth and fertility, and irritation of the gastrointestinal mucosa (Clemente et al., 2025).

Drought stress is mostly caused by low rainfall, high temperatures, intense light and dry winds that enhance water evaporation (Li et al., 2020; Cohen et al., 2021; Ishaq et al., 2023). Plants' biochemical, molecular, and morpho-physiological characteristics are impacted by drought stress, and their use of resources is also decreased (Ahmad et al., 2024). Due to a lack of water, the plant exhibits symptoms like rolling and burning of its leaves, limited growth, and irreversible wilting (Waraich et al., 2020; Seleiman et al., 2021). The availability of H_2O has a significant effect on plant development. By reducing water potential and cell expansion, drought stress results in stomatal closure (Ramzan et al., 2025; Saad-Allah et al., 2021).

Drought stress's alteration causes growth retardation of plant, changes physiological characteristics, including photosynthesis, stomatal regulation, antioxidant system, gaseous exchange and rate of transpiration (Raza et al., 2023). Drought stress negatively affected the plants' transpiration rate and stomatal conductance, ultimately affecting photosynthesis. According to leaves' number and siliques per plant can all be used to screen for high oil content and seed yield (Wang et al., 2023). Mineral-rich plant nutrition significantly reduces the impact of drought stress and enhances the growth of the plants and development with such circumstances (Nisar et al., 2023). As a result, in difficult conditions, camelina can compete with other oilseed crops, especially rapeseed. Additionally, bringing camelina to arid areas has the potential to improve crop rotation and improve soil nutrients, hence sustaining sustainable agriculture (Borzoo et al., 2021).

Hydrogel or super-absorbents might be useful for increasing the amount of water available in the crop root zone since water absorbents can absorb 400–1500 times their dry weight (Malik et al., 2022). Systems of connected hydrophilic networks with the ability to absorb and hold onto water are known as water-absorbents. They can be bio-based (like cotton or starch) or fossil-based (like vinyl polymers). A subclass of water-absorbents known as superabsorbents (SAs) can hold 10-1000 g/g of water (or aqueous solutions) (Liotino et al., 2025). Researchers have been paying close attention to SAPs lately because of their many uses in the healthcare, construction, agricultural, and hygiene sectors (Chen et al., 2022).

Predicting environmental events, absorbing and decomposing organic waste in water, cleaning up oil spills, and eco-engineering restoration of environmental damage brought on by human activities are some of the more inventive uses (Schmidt et al., 2020). Applications of SAPs in agriculture can increase water contents in soil and amend (moisturize) dry soils since they can absorb and release water slowly (Chiaregato et al., 2022). Additionally, by increasing the amount of water that is available, SAPs improve the growing environment for vegetation by facilitating the movement of soil nutrients to plants. Superabsorbents' capacity to boost seed yields is essential, as global food production is expected to increase by 70% by 2050. According to Naderi et al. (2023), superabsorbents may hold 200–500 mL of water for every gram of dry superabsorbents.

A range of synthetic and natural materials can be used to create BWAs, and they can also be cross-linked to create hybrid networks. Synthetic petrochemical-based water absorbents are frequently chosen in industry because of their mechanical characteristics and mass production capacity (Qureshi et al., 2020; Oladosu et al., 2022). However, natural hydrogels are easily available, biodegradable, frequently biocompatible, biologically derived, and typically less expensive to source (Oladosu et al., 2022). Numerous factors also affect SAPs capacity, swelling, porosity, structural integrity, and flexibility (Behera and Mahanwar, 2020; Oladosu et al., 2022). In agricultural applications, SAPs are frequently used as a soil addition to improve soil qualities and promote plant growth (Afzal et al., 2020; Elshafie and Camele, 2021).

Water absorbents are known to be involved in the improvement of soil physical attributes and soil water-holding capacity. These water absorbents hold onto about half a liter of water for every gram of dry superabsorbents (Naderi et al., 2023). Applying SPH improves deep soil percolation, water usage efficiency and decreases evaporative water loss, which boosts plant growth and survival in the drought-stressed environment (Saha et al., 2020). In crops, SAPs can lessen the detrimental effects of dehydration and moisture stress by improving the soil microbiota and reducing water and nutrient loss (Yang et al., 2020; Afzal et al., 2020; Elshafie et al., 2020; Puscaselu et al., 2020).

A decline in rain has contributed to a severe water deficit in crops that need more irrigation over the past ten years. The detrimental effects of drought stress on various oil seed crops have been extensively studied. To preserve food security, farmers and scientists are looking for more sustainable methods as a result of this poor management. Because of their affordability, effectiveness, ease of use and environmental sustainability, BWAs may be used as part of this plan. However, little is known about how biodegradable water absorbents affect camelina performance in drought-stressed environments. It is hypothesized that seed coating with rice straw based water absorbents may lessen the harmful effect of water deficit stress in camelina production and growth. The objectives of the study were to determine the effects of biodegradable water absorbents on the morpho-physiological, and biochemical of *Camelina* grown under drought stress conditions.

Materials and Methods

Synthesis of rice-straw based BSAs

The water absorbents from rice-straw was synthesized using the Bhanu Rekha et al., (2022) technique. After being washed, the rice straw was left to dry in the sun for two days. The dried straw was ground into a powder after being chopped into tiny pieces. For two hours, a 25 g sample of powder was continuously stirred while boiling at 95°C in 750 mL of 0.5 M NaOH. One liter of distilled water was used to rinse, filter, and collect the black sludge. In ethanol, a 20% (v/v) nitric acid solution was combined with the powdered cellulose. After that, the mixture was filtered, cold distilled water was used to wash till it turns pink when exposed to phenolphthalein and a tiny bit of 0.5 M NaOH, the leftover material was subsequently dried in an oven set at 60°C for the entire night. To continue treating the cellulose, the dry cellulose was finally pulverized and placed in a petri dish. To create carboxymethyl cellulose (CMC) through an etherification process, Bhanu Rekha et al., (2022) used cellulose as a precursor.

The following formula was used to determine the cellulose yield as a percentage:

% Yield of cellulose = Weight of cellulose /Weight of rice straw ×100 7

Cooking of rice cellulose

Finally, CMC was used to create biodegradable water-absorbents (BSAs) based on rice straw. Distilled water (53 mL) was used to boil 2.4 g of rice cellulose for 45 minutes at 75°C (Bhanu Rekha et al., 2022).

Preparation of CMC Solution

CMC was mixed with 200 milliliters of distilled water to create the CMC solution, which was then placed on a magnetic stirrer at 60°C for an hour (Bhanu Rekha et al., 2022).

Preparation of Cross-linked Water absorbents Solution

Later, using a Hobart mixer, the aforementioned CMC solution was combined with 697 milliliters of distilled water, and then cooked starch was added. For sixty minutes, the hydrophilic water absorbent mixture was stirred. The water-absorbent solution was then supplemented with 0.2 g of aluminum sulfate octahydrate and distilled water (500 µL). A cross-linked water absorbent gel was produced by mixing the water absorbent slurry for 30 minutes. To create a thin SAP film, the aforementioned cross-linked water absorbent gels were put into a casting tray and dried in a safety oven at 65°C (Bhanu Rekha et al., 2022).

Wirehouse/rain-out shelter experiments

To address the issue, the oilseed crop camelina is facing due to drought, a pot experiment was conducted in the greenhouse of the Crop Physiology building department of the Agronomy department at the University of Agriculture, Faisalabad. The purpose of the experiment was to determine the ideal dosages of biodegradable water-absorbent based on rice straw under drought stress. Throughout the experiment, the mean monthly precipitation was 36 mm, the average humidity was 61%, and the mean maximum temperature was 37°C, and the mean minimum temperature was 8°C. Each genotype was sown in 22 cm x 15 plastic pots containing 3 kg of sand each during the first week of October 2023. Each pot was treated once every two weeks with 500 mL of Hoagland's nutritional solution. For the remaining times, the same volume of solution was subsequently used once again. The following treatments were applied to the 48 pots in the experiment, 24 for each genotype: The sand was treated with i) two genotypes of camelina (G1-611, G2-618); ii) two drought stress levels (100 and 50% FC); and iii) four doses of BSAs based on rice straw (0, 5, 10, and 15 g kg^{-1} seed). The technique described by Bhanu Rekha et al. (2022) was used to create water absorbent based on rice straw. A standard method for assessing field capacity was described by Pennypacker et al., in 1990. Distilled water was added to the pots according to weight to maintain them at control (100% FC) and (50% FC).

Harvesting and sample collection

After 77 days of sowing, the plants were collected to measure the morphological characteristics. Two plants and their roots were taken out of each pot. The fresh leaves were kept in freezer at 20°C for all biochemical analyses. In order to perform ion analysis and determine dry weight, the samples were taken with fresh morphological characteristics and then stored in an oven at 65°C for two weeks.

Growth attributes

An electronic weighing balance was used to observe the fresh weight of the shoot and root instantly as plant samples were picked. After being weighed, plants were dried in an oven that was set at 65°C. After 14 days of oven drying, the total dry weight of the shoot and root was measured using a digital balance. The lengths of the shoots and roots were measured using a measuring scale.

Photosynthetic pigments

The method outlined by Arnon (1949) was used to determine the quantities of carotenoids and chlorophyll *a*, *b*. Five milliliters of an 80% acetone solution were put into tiny plastic bottles that held 100 milligrams of fresh leaf section. The sample vials were kept at 25°C for the entire night. The absorbance of these sample solutions were measured at 663, 645, and 480 nm using a spectrophotometer.

The formulas were used to quantitatively determine the Chl. content:

Chl. *a* (mg/g- F. wt.) = [12.7 (OD663)

Chl. *b* (mg/g F. wt.) = [22.9 (OD645)

Carotenoids (mg/g F. wt.) = Acar/ Em 2.69 (OD645)] × V/1000 × W 4.68 (OD663)] × V/1000 × W 100

Acar = OD 480 + 0.114(OD 663) – 0.638 (OD 645) and Em = 2500

V = Volume of the extract (mL) W = Weight of fresh leaf tissue (g)

Leaf water potential (-MPa)

Ahmad et al., (2021) proposed that to measure the water potential, and reduce the water loss of plants by evapotranspiration, leaves were cut between 8:00 and 10:00 am. The third fully grown leaf from each plant was taken out for this measurement. A pressure chamber was used to assess the leaves' water potential. Upon inserting the leaf into the chamber, its sliced surface emerged out the slot. Until xylem fluid began to appear on the sliced leaf surface, compressed nitrogen was added to the chamber pressure. It was noted how much the chamber was worth. Before undergoing additional transformation, values were initially stated in pounds per square inch (-MPa). The same leaves that were used to determine the water potential were frozen at -20°C for 10 days and then crushed to determine the leaf osmotic potential. Sap was put into the osmometer using a disposable syringe. The solute potential was measured using an osmometer (Wescor 5500).

Leaf turgor potential was measured by:

Leaf turgor potential (MPa) = Leaf water potential (– MPa). –Leaf osmotic potential (– MPa)

Three plants in each replication had leaf samples taken at random in the morning to stop water loss. A computerized electrical balance was used to measure each leaf's fresh weight. After being weighed once more, the identical leaves were soaked in distilled water for a full day. After a day, the leaves were taken out of the beakers, and tissue paper was used to carefully wipe water droplets from their surfaces. The leaves' turgid weight was then calculated using a digital electrical balance. The DW of leaves was subsequently determined after leaf samples were dried for 72 hours at 65°C in an oven.

The RWC of every replication was calculated using the formula below in accordance with the Liu et al., 2009 protocol.

$$RWC=[(FW - DW)]/(TW - DW)]\times 100$$

Here, FW and DW are fresh and dry weight, and TW is its turgid weight.

Gas exchange parameters

The photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (gs) and internal CO_2 concentration (Ci), were all assessed using a portable infrared gas analyzer (IRGA) model (LCA-4 ADC (USA). These measurements were made using the fully formed juvenile leaves of three plants per treatment.

Oxidants activities in camelina leaves

The Velikova et al., (2000) method was used to stop hydrogen peroxide (H_2O_2) from accumulating. In conclusion, 0.25 g of fresh leaf samples were crushed in 3 mL of a 0.5% trichloro-acetic acid solution to assess H_2O_2. After centrifuging for 15 minutes, 0.5 mL of sample extract, 0.5 mL of potassium phosphate buffer, and 1 mL of KI were added to test tubes. A spectrophotometer (Model; Micro Quant ELISA plate reader, Bio-Tek, USA) was used to take a reading at 390 nm after the vortex. Hydrogen peroxide (H_2O_2) accumulation was avoided by using the Velikova et al., (2000) method. To assess H_2O_2, 0.25 g of fresh

leaf samples were crushed in 3 mL of a 0.5% trichloro-acetic acid solution. After a 15-minute centrifugation, test tubes were loaded with 0.5 mL of sample extract, 0.5 mL of potassium phosphate buffer, and 1 mL of KI. After the vortex, the reading at 390 nm was taken using a spectrophotometer (Model; Micro Quant ELISA plate reader, Bio-Tek, USA).

Enzymatic antioxidant activities in camelina leaves

A cooled pestle and mortar was used to smash 250 mg of fresh leaf samples. Each sample received 5 mL of potassium phosphate buffer prior to grinding. Following homogenization, the material was placed in an Eppendorf tube and centrifuged at 12,000 rpm for 15 minutes. Following precipitation, the solution was transferred to a different Eppendorf tube and maintained at 15°C. The CAT, SOD, and POD activities were assessed using the appropriate techniques.

Chance and Maehly developed a technique for calculating catalase (CAT) activity in 1955. A cuvette was filled with 0.1 mL of fresh plant material, 1 mL of H_2O_2, and 1.9 mL of cold potassium phosphate buffer. At intervals of 0, 30, 60, and 90 seconds, the absorbance at 240 nm was measured using the spectrophotometer (Model; Micro Quant ELISA plate reader, Bio-Tek, USA).

The Spitz and Oberly (2001) approach was used to quantify the activity of superoxide dismutase (SOD). Plastic cuvettes were filled with 0.4 mL of filtering water, 250 µL of cold potassium phosphate buffer, 0.1 mL of L-methionine solution, 0.1 mL of Triton X solution, 0.05 mL of nitroblue tetrazolium (NBT) solution, 0.05 mL of plant extract, and 0.05 mL of riboflavin solution. The cuvettes were then left in front of a fluorescent light source for fifteen minutes. The blank sample run did not use the plant sample. The absorbed wavelength of each sample and the blank sample was measured at 560 nm using an ultraviolet–visible spectrophotometer (Model; Micro Quant ELISA plate reader, Bio-Tek, USA).

The peroxidase (POD) activity was determined using the procedure outlined by Chance and Maehly (1955). The cuvette was gradually filled with 50 µL of plant extract, 0.1 mL of guaiacol, 0.1 mL of H_2O_2, and 750 µL of buffer. The absorbance was measured at 470 nm using a spectrophotometer (Model; Micro Quant ELISA plate reader, Bio-Tek, USA) at intervals of 0, 30, 60, and 90 minutes.

Ion analysis

To identify inorganic ions, the Allen et al., (1986) approach was applied. The digestion flask was filled with 100 mg of the dried shoot and root material from mustard plants and three milliliters of H_2SO_4. After covering the digesting flasks with aluminum foil, they were left for sixteen hours. Drops of H_2SO_4 solution were then added to the flasks on a hot plate until the mixture became clear. Whatman's filter paper 4 was then used to filter the solutions after they had been placed in plastic bottles. The solutions were mixed with distilled water to reach a final volume of 50 mL.

A flame photometer (Sherwood Model 410, UK) was used to test the amounts ions, including K^+, Na^+, and Ca^{2+}.

Root morphological parameters

Each treatment's roots were taken out and cleaned with tap water after 45 days of sowing. Root length (cm), root surface area (cm^2), and root average diameter (mm) were measured using WINRHIZO's image analysis system and root scanner.

Functional and anatomical characterization

Only a tiny sample of each leaf, stem, and root was collected in order to study the morphological and functional characteristics. The collected plant specimens were preserved for 24 hours using a formalin-acetic alcohol solution consisting of v/v 5% formalin, 50% ethanol, 10% acetic acid, and 35% distilled water. The plant components were then added to an acetic alcohol solution that contained v/v 75% ethyl alcohol and 25% acetic acid in order to prolong its preservation. The plant components were cut using a freehand cutting technique with a multipurpose razor blade. The plant components were dried using a repeated ethyl alcohol method to create the permanent slides (Ruzin, 1999). Live and actively functioning tissues were stained with fast green, and lignin tissues were stained with safranin. After positioning the transverse portions on DPX, a coverslip was applied to the material. The permanent slide photos were taken using a Meiji Techno MT4300-LV-HD digital compound microscope with a camera. Measurements were taken with a visual micrometer and calibrated with a stage micrometer.

Statistical data processing and analysis

Three replications and a complete randomized design (CRD) were employed in the experiment. Statistix 8.1 was used to do a three-factorial analysis of variance, and Tukey's test was used to compare means at the $p \leq 0.05$ level of significance. R-studio (V 4.3.3) was utilized to generate a heatmap with a correlation matrix using the "corrplot" package and a dendrogram utilizing the "pheatmap" package in order to assess the relationship between the examined attributes. Principal component analysis (PCA) was carried out using OriginPro2024 software, and Microsoft Excel (Version, 2016) (Microsoft Corporation, Redmond, WA, USA) was used to construct the graphs.

Results

Morphological parameters

Statistical analysis showed that the individual effect of genotype, drought and water absorbents (RS-BWAs) and all two-way and three-way interaction among genotype, drought, and water absorbent was statistically significant ($p \leq 0.05$) for morphological parameters. Drought (50% FC), decreased the shoot fresh weight, shoot dry weight, shoot length and leaf area up to (31.1%, 26.8%, 20 and 37.5%) in G1-611. However, these attributes decreased upto (18.5%, 21.4%, 22.2% and 27%), in G2-618, respectively in comparison with control. Seed priming of RS-BWAs improved shoot fresh weight, shoot dry weight, shoot length and leaf area up to (40%, 25.9%, 77% and 34.5%) at 10 g/kg seed and upto (48.5, 38.3%, 107.4 and 60.3%) at 15 g/kg seed in G1-611. While, these attributes

increased upto (41.5%, 41.8%, 116% and 38.2%) at 10 g/kg seed and upto (52.1%, 51.7%, 125% and 61.3%) at 15 g/kg seed in G2-618. However, under drought stress (50% FC) demonstrated a significant improvement in root length, fresh and dry weight of root up to (33.9, 54.4% and 51.1%) in G1-611. Moreover, these attributes also increased upto (53.6%, 31.8% and 61.7%), in G2-618, respectively in comparison with control. Seed priming of RS-BWAs improved root length, fresh and dry weight of root up to (18, 42.7% and 24%) at 10 g/kg seed and upto (31, 56.7% and 32.1%) at 15 g/kg seed in G1-611. While, up to (29.2%, 44.5% and 38.8%) at 10 g/kg seed and upto (34.6%, 60.3% and 34.5%) at 15 g/kg seed in G2-618, correspondingly under 100% FC (Fig. 1).

Photosynthetic pigments

Analysis of variance revealed significant variations ($p \leq 0.05$) in photosynthetic pigments for individual effect of genotype, drought and water absorbents (RS-BWAs) and all two-way and three-way interactions were statistically significant ($p \leq 0.05$) for photosynthetic pigments. Drought stress (50% FC) decreased the contents of Chl. *a*, Chl. *b*, total Chl., Chl. *a*/*b* and carotenoids up to (27.8, 34.2%, 9.57% 31.6% and 24.4%) in G1-611. However, these attributes decreased upto (8.81%, 19.1%, 15.2%, 14.5% and 20.6%) in G2-618, respectively relative to control. Seed priming of RS-BWAs improved Chl. *a*, Chl. *b*, total Chl., Chl. *a*/*b* and carotenoids up to (16.7%, 21.6%, 42% 19.4% and 25.6%) at 10 g/kg seed and upto (28.8, 33.8%, 3.91% 31.6% and 32.9%) at 15 g/kg seed in G1-611. while, up to (27.8, 34.2%, 9.57% 31.6% and 24.4%) at 10 g/kg seed and upto (20%, 24.4%, 4.79% 22.5% and 33.5%) at 15 g/kg seed in G2-618 (Fig. 2).

Root attributes

Statistical data showed that there were notable differences ($p \leq 0.05$) in the root attributes of both camelina genotypes under drought stress through the seed priming of RS-BWAs. Drought stress significantly increased the root surface area (RSA) up to (6, 37.5%), root density (RD) (29.2, 21.4%), and root projected area (RPA) up to (10.5, 10.5%), while root volume (RV) was decreased up to (35.8, 41.3%) in both genotypes (G1, G2) as compared to control. While, seed priming of RS-BWAs (10 g/kg seed) caused improvement in RSA, RPA, RV and RD up to (66.8, 16.2, 61.8, and 36.8%) in G1 and (41.7, 10.7, 64, and 32.5%) in G2 as compared to control. In contrast with control, Seed priming of RS-BWAs (15 g/kg seed) further increased the RSA, RPA, RV and RD up to (97.5, 21, 77.6, and 51.4%) in G1 and (64, 17.7, 74.8, and 45.9%) in G2 under stress conditions (Fig. 3).

Gaseous exchange parameters

Significant variations ($p \leq 0.05$) in gaseous exchange attributes were recorded for camelina genotypes under drought stress conditions and seed priming of RS-BWA water absorbent. In contrast with control, under 50% FC, the net photosynthetic rate was reduced by (39, 13%), the transpirational rate by (26.5, 26.1%), internal CO_2 concentration (28.3, 24.8%), and stomatal conductance by (35.3, 29.6%) in G1 and G2 accordingly, when there was no seed coating of water absorbent. While Seed priming of RS-BWAs (10 g/kg seed) improved the net photosynthetic (46.6, 41.2%) and transpiration rate up to (46, 20.6%), CO_2 concentration and stomatal conductance up to (19.5, 22.9%) and (17.5, 22.9%) in G1 and G2, respectively as compared to control, under stress conditions. Seed priming of RS-BWAs (15 g/kg seed) improved the photosynthetic and transpirational rate (54.3, 72.1%), and (46.2, 42.2%) as well as increased the CO_2 concentration and stomatal conductance up to (25.3, 27.7%) and (34.1, 30.2%) in G1 and G2 respectively, under 50% FC (Fig. 4).

Water relations

Analysis of variance showed that significant variations ($p \leq 0.05$) were noted for water relation attributes of camelina genotypes under seed priming of RS-BWAs and 50% FC. Drought stress (50% FC) increased the contents of water and osmotic potential (-MPa) up to (18.3 and 31.3%) in G1-611. However, these attributes decreased upto (27 and 52%) in G2-618, respectively relative to control. Seed priming of RS-BWAs (5 g/kg seed) improved the parameters of water relations as, water, osmotic, turgor potential and relative water content (%), up to (33, 23, 69.6 and 20%) in G1-611 and (48.2, 29.6, 84.9 and 26.4%) in G2-618 as compared to control (no treatment), under stress conditions. Seed priming of RS-BWAs (15 g/kg seed) caused maximum improvement in water potential up to (26.2, 50.6%), osmotic potential (26.6, 33.3%), turgor potential (166, 177%), and leaf relative water content up to (21.3, 23.9%) in G1-611 and G2-618 respectively relative to control, under 50% FC (Fig. 5).

Oxidative stress determinants

Significant variations ($p \leq 0.05$) were recorded among camelina genotypes under drought and water absorbent (RS-BWAs) application for H_2O_2 and MDA. Drought stress increased the content of H_2O_2 up to (33.7, 48.1%) and MDA up to (24, 26%) in both genotypes (G1, G2) accordingly as compared to control. On the other hand, the seed priming of RS-BWAs (5 g/kg seed) decreased the content of H_2O_2 up to (17.7, 24.1%), and MDA up to (23.4, 47.5%) among both genotypes under 50% FC. The Seed priming of RS-BWAs (15 g/kg seed) caused a further reduction in H_2O_2 and MDA up to (17, 26.8%) in G1 and (24, 49%) in G2 (Fig. 6).

Enzymatic antioxidants

Compared with the control, a significant difference ($p \leq 0.05$) was observed in the anti-oxidant activity of camelina genotypes on the amendment of (RS-BWAs) water absorbents application under 50% FC. Under 50% FC, the activity of SOD, POD and CAT were increased up to (40.5, 13.4, and 61.1%) in G1 and (41, 16.3, and 78%) in G2, as compared to control, when there was no amendment of water absorbents. The seed priming of RS-BWAs (5 g/kg seed) caused an increment in the content of SOD up to (46, 138%), POD (26.3, 28.3%), and CAT up to (36.6, 28%) in G1 and G2 correspondingly. In addition, the Seed priming of RS-BWAs (15 g/kg seed) caused maximum improvement in activities of SOD up to (94, 220%), POD (40.3, 35.1%), and CAT (70.5, 87.7%) in G1 and G2 respectively under 50% FC (Fig. 6).

Mineral ions

Analysis of variance showed significant variations ($p \leq 0.05$) in mineral ions of both camelina genotypes under drought stress conditions on the seed priming of RS-s water absorbent. Under 50% FC, shoot Na^+ and root Na^+ were increased up to (21.1, 29.1%) and (19, 28.1%) in G1 and G2 respectively, as compared

to control and no seed coating of water absorbent. While, in shoot and root uptake of Ca^{2+} and K^{+} was reduced up to (31, 26, 34, and 35%) in G1 and (21, 29, 20, and 23%) in G2 under 50% FC. Seed priming of RS-BWAs (10 g/kg seed) reduced the uptake of Na^{+} through shoot to root by (11.7, 10%) and (10, 13.1%) in G1 and G2, while enhancing the uptake of Shoot Ca^{2+} by (49.2, 53.9%), root Ca^{2+} upto (12.5, 39.4%), shoot K^{+} upto (24.5, 8.6%) and root K^{+} up to (26.2, 12.2%) relative to control, under 50% FC. Furthermore, as compared to control, RS-BWAs (15 g/kg seed) decreased the uptake of shoot Na^{+} up to (19, 21.2%), and root Na^{+} (16.9, 17.4%) among both genotypes. While seed priming of RS-BWAs (15 g/kg seed) significantly improved the uptake of shoot Ca^{2+} (76.7, 73.1%), root Ca^{2+} (32.3, 53.3%), shoot K^{+} (32.2, 39.3%), and root K^{+} up to (43.6, 52.9%) in G1 and G2 correspondingly, under stress conditions (Fig. 4.7).

Stem anatomy

Analysis of variance showed significant variations ($p \leq 0.05$) in stem anatomical parameters of both camelina genotypes under drought stress conditions on the seed priming of RS-s water absorbent. Statistical analysis revealed that the maximum values of 2.56 for stem cortical area were observed under P0 (control) and drought stress in G1, followed by 2.52 under P3 (15 g/kg seed) and drought stress in G2. However, minimum values for stem cortical area were shown under PI (5 g/kg seed) under control conditions in G1, followed by 0.58 under P0 (control) and drought stress in G2. For stem thickness, maximum values of 13.8 were recorded under control conditions and PI (5 g/kg seed) in G1 and 12.2 in G2 under P0 (control) and drought (50% FC). The minimum values of 7.33 for stem thickness were recorded in G1, followed by 7.47 in G2 under drought (50% FC) and P3 (15 g/kg seed) conditions. Statistical analysis for the stem epidermal thickness maximum values of 0.4 in G2 under control conditions, followed by 0.5 under drought and P1 (5 g/kg seed) in G1. While minimum values of 0.27 were noted in G1 under control conditions, and 0.2 in G2 under P1 (5 g/kg seed) and control conditions. Stem sclerenchyma showed maximum thickness of 1.8 under P1 (5 g/kg seed) and control conditions in G1 and 1.57 in G2 under 50% FC and P0 (control), and minimum values of 0.6 were noted in G1 under 50% FC and P0 (control), and 0.87 in G2 under control conditions. Stem vascular bundle area was increased by the values of 0.6 in G1 under 50% FC, and 0.77 in G2 under control (100% FC) and P0, while minimum values of 0.23 were shown in G1 under P1, and 0.1 under P0 and 50% FC, in G2, respectively (Table 1; Fig. 11).

Root anatomy

Analysis of variance showed significant variations ($p \leq 0.05$) in root anatomy of both camelina genotypes under drought stress conditions on the seed priming of RS-s water absorbent. Statistical analysis revealed that the maximum thickness of the root cortical was 7.63 in G2 under P2 (10 g/kg seed), followed by 7.4 in G1 under P3 (15 g/kg seed) under control conditions and the minimum values of 2.3 in G1 under control and P2 (10 g/kg seed) followed by 4.1 in G2 under P2 (10 g/kg seed) and 50% FC. Root endodermis showed maximum thickness of 0.5 in G1 under P2 (10 g/kg seed), followed by 0.33 in G2 under P0 (no seed treatment) and 50% FC. The minimum value of 0.13 for root thickness was noted in G2 under P3 (15 g/kg seed), followed by 0.2 in G1 under control conditions. Root cortical cell area was maximum 0.33 in G1 under P1 (5 g/kg seed) and control conditions, followed by 0.32 in G2 under P0 and 50% FC, and minimum values of 0.05 in G1 under P2 (10 g/kg seed), followed by 0.06 in G2 under P1 (5 g/kg seed) under 50% FC. Stellar region showed maximum values of 20.1 in G2 under P0 followed by 18.2 in P1 (5 g/kg seed) under P1 (5 g/kg seed) and 50% FC, while the minimum values of 6.8 were showed in G1 under control conditions, followed by 7.6 in G2 under P2 (10 g/kg seed) and 50% FC. Aerenchyma cell area was 1.7 thickened in G1 under P3 (15 g/kg seed), followed by 0.4 in G2 under P2 (10 g/kg seed) under control conditions. Minimum aerenchyma cell area thickness 0.27 was noted in G1 under control conditions and 0.17 in G2 under P3 (15 g/kg seed), respectively (Table 2; Fig. 12).

Midrib anatomy

Analysis of variance showed significant variations ($p \leq 0.05$) in midrib anatomical features of both camelina genotypes under drought stress conditions on the seed priming of RS-s water absorbent. Statistical analysis revealed a maximum midrib thickness of 7.27 in G2 under P3 (15 g/kg seed), followed by 6.27 in G1 under P1 (5 g/kg seed) and 50% FC, and the minimum midrib thickness of 3.47 in G2, followed by 3.63, was shown under control conditions. Lamina thickness was maximum 2.37 in G2 under P0 and control, followed by 1.57 in G1 under P2 (10 g/kg seed) and 50% FC, and the minimum value of 0.27 was noted in G1 and 0.63 in G2 under control conditions. Adaxial thickness was about 0.4 in G2 and 0.37 in G1 under control conditions (no drought and seed treatment), while the minimum thickness was 0.1 in G2 under 50% FC and 0.2 in G1 under control conditions. Abaxial thickness was 0.37 in G1 under 50% FC, followed by 0.3 in G2 under control (no drought) and P3 (15 g/kg seed), and the minimum abaxial thickness was 0.13 in G1 and G2, respectively. The parenchyma cell showed maximum area up to 3.98 in G1 under 50% FC and P0 (no treatment), and minimum parenchyma cell area of 0.09 in G2 under 50% FC and P0 (no treatment), respectively (Table 3: Fig. 13).

Heatmap analysis

A two-way clustered heatmap was drawn to observe the effects of rice straw-based biodegradable water absorbents on camelina genotypes (Fig. 8). Colored squares showed the association between the metrics, which were grouped according to their similarity at the different treatment stages. Blue color indicates a positive correlation while Maroon color indicates a negative association. The heatmap has been categorized into four groups. The 1st group containing the root and shoot Na^{+} Chl. *a*/*b* ratio, MDA, root length, osmotic potential and H_2O_2. These parameters showed strong positive association in G1 and G2 under 50% FC (D1) and control condition (no water absorbent), while negative association under the control condition (no drought), and rice straw based water absorbents (15 g/kg soil). The 2nd group showed association among root fresh and dry weight, root projected and surface area and POD. These parameters showed strong positive association in G1 and G2 at rice straw based water absorbents (15 g/kg seed) under 50% FC (D1), while among both genotypes, negative association was shown under control conditions D0P0 (no stress and water absorbents). Root diameter, transpirational rate, Chl. *a*, *b*, total Chl., photosynthetic rate, root and shoot K^{+} and Ca^{2+}, leaf area, gas exchange, CAT, SOD, and leaf water potential were clustered in 3rd group. These parameters are strongly positively correlated under control (no drought) and water absorbents (15 g/kg seed) application in both genotypes and negatively correlated under 50% FC and no water absorbents. The 4th group containing turgor potential, shoot fresh and dry weight, root volume, relative water content, shoot

length, and carotenoids. These attributes were strongly positively correlated to under control (no drought) and water absorbents (15 g/kg seed) application in both genotypes and negatively correlated under 50% FC and no water absorbent application among both genotypes (Fig. 8).

Correlation matrix

The correlation matrix showed positive and negative correlations in the camelina attributes under drought stress (Fig. 9). The correlation revealed that growth parameters such as SL, SFW, SDW, and LA were negatively correlated with H_2O_2, MDA, OP, RL, RDW, RFW, RSA, and RPA, root and shoot Na^+. Growth parameters such as SL, SFW, SDW, LA, and relative water content were positively correlated with photosynthetic pigments, gas exchange parameters, root and shoot Ca^{2+}, and K^+, leaf water and turgor potential, and root volume. Furthermore, SOD, POD, and CAT were all significantly negatively correlated to growth parameters (Fig. 9).

Principal Component Analysis (PCA)

The PCA analysis revealed that PCA 1 and PCA 2 accounted for 86.13% of the accumulated variations, with 71.03% and 15.10% respectively (Fig. 10) However, the morphological, photosynthetic, water relation, and root properties of genotype 611 and 618 differed significantly under different water absorbents (P0 = 0, P1 = 5, P2 = 10, P3 = 15 g/kg seed), and drought treatments (D0 = 100% FC and D1 = 50% FC). A very strong connection was noted among different photosynthetic, morphological, and ionic contents except shoot and root Na^+ with gas exchange attributes and CAT as well as SOD, in the same treatment (G1D0P3, and G2D0P3), while RL, RDW and RDW, RSA, RPA, indicated close relationships POD, in the same (G1D1P3, and G2D1P2) treatments. Root and shoot Na^+ were closely associated with MDA and H_2O_2, OP, Chl. *a*/*b* ratio and root length respectively in the same (G1D1P0) treatment. In our research, rice straw based water absorbents seed coating showed to be beneficial in alleviating drought stress through enhancing morphological characteristics such as shoot length, photosynthetic attributes, gas exchange, water relation, and ionic content parameters, while decreasing the negative impacts of RL, RDW and SDW, RSA, RD, and RPA, SNa^+, and RNa^+, and OP in camelina plants (Fig. 10).

Discussion

Water stress is a significant problem affecting the yield of agricultural products that directly impacts food security (Tajdari et al., 2024). Compared to other environmental stresses, drought stress significantly lowers growth and yield of crops. Drought affects photosynthetic arrest, stomatal closure, water potential of tissue, reduced cell division, and abnormal metabolism, all of which lead to altered water relations, water use efficiency, leaf size, root growth, leaf number and reduced stem expansion. These changes ultimately result in the suppression of growth (Kausar et al., 2023; Haque et al., 2022).

The results of current study revealed that the camelina genotypes showed a significant decrease in morphological parameters (such as shoot length, shoot dry and fresh weight) under conditions of water scarcity (50% FC), while root length, fresh and dry weight significantly increased under conditions of water stress (50% FC). The same findings were revealed in previous research on wheat (Tefera et al., 2021) and pea (Kausar et al., 2023) which is because of lessened cell turgidity and decreased enzyme activity, which in turn led to decreased plant growth and cell division (Ramzan et al., 2023). Increasing the length of their roots helps plants better absorb water from the deeper soil, which is one way they defend the plants against drought (Ranjan et al., 2022). Water absorbents significantly impacted the morphological parameters of camelina plants similar to previous findings (Başak, 2020; Supare and Mahanwar, 2022). This might be due to that in an agricultural environment, SAPs work as hydrogels, which are soil supplements that can absorb and hold onto water hundreds of times their weight. Over time, they release this stored water gradually, promoting drought tolerance and better plant growth and development (Supare and Mahanwar, 2022).

In our findings water stress prominently declined the photosynthetic pigments (Chl. *a*, *b*, total Chl., and carotenoids) in both camelina genotypes. Consistent with our findings, in pea (Dalal, 2021; Kausar et al., 2023) and spinach (Seymen, 2021). The reduced chlorophyll content in plants may also be caused by the activation of enzymes that degrade chlorophyll, a malfunction in the photosynthetic apparatus, and the generation of oxygen free radicals in unfavorable environments, which degrade pigments and ultimately reduce the quantity of chlorophyll in plants (Miri et al., 2021; Dalal, 2021). The results of the current study showing that camelina plants treated with water absorbents increased their levels of carotenoid and chlorophyll findings in line with previous studies on sunflower (Al-Gahtany et al., 2024), which concluded that SAPs were essential in reducing the negative effects of drought stress on plant development, chlorophyll content, and pigments. These characteristics were positively impacted by the hydrogel application by enhancing water retention, nutrient availability, and physiological responses to drought stress (Al-Gahtany et al., 2024).

According to the results of a recent study, reactive oxygen species like MDA and H_2O_2 were markedly increased in water stress environments. Similar results in pea plants were noted in earlier research (Hasanuzzaman et al., 2020; Pandey et al., 2023) and spinach (Seymen, 2021), as plants under drought stress experience oxidative stress, causing accumulation of hydrogen peroxide and malondialdehyde. Reactive oxygen species (ROS) became high in stressed plants at the cellular level as a result of direct or indirect disturbances to metabolic processes (Saleem et al., 2020). According to our research, seed coating of biodegradable water absorbents decreased MDA and H_2O_2 concentrations. Previous data support our conclusion that applying SAPs reduced the content of MDA and H_2O_2, suggesting that it could be possible to mitigate drought through scavenging reactive oxygen species by enzymatic antioxidants, including POD and CAT are the main enzymes of H_2O_2 removal (Han et al., 2024).

According to current statistical data, the stress of drought considerably raised the levels of enzyme antioxidants such as peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT). Similar research revealed that water scarcity enhanced the activity of SOD, CAT and POD in *Brassica rapa* (Bhuiyan et al., 2019) and *Pisum sativum* L. (Kausar et al., 2023) by disturbing the metabolic pathways. Drought stress and other environmental stressors cause an increase in CAT activity, which is vital for preventing oxidative damage and supporting SOD, APX, and other enzymes in reducing the harmful effects of reactive oxygen species (Kausar et al., 2023). Similar findings from the earlier study demonstrated that seed coating of biodegradable water absorbents

enhanced the activities of CAT, APX, POD, and SOD. While SAPs have the capacity to tolerate drought stress by improving the enzymatic antioxidants, which decrease the amount of active oxygen the plants produce. Thus, the application of SAPs in increased production of antioxidants to overcome this problem of cellular damage caused by drought stress (Nezhad-raeini et al., 2021).

Drought stress increased the root attributes including root projected and root surface area of both camelina genotypes, however root volume was decreased that is similar to (Zhai et al., 2024; Guo et al., 2024), this enlargement is attributed to more root length for the uptake of more water and nutrients from the deeper layer soil (Zhai et al., 2024). Application of water absorbents improved all root attributes of camelina plants. Our results further validated the previous study, since higher water absorbent also markedly improved root attributes because it make water and nitrogen available to plants for longer periods, these increases in plant growth characteristics are directly tied to their retention (Kathi et al., 2021).

In the current study, drought stress increased the leaf water and osmotic potential while decreasing the leaf turgor potential and relative water content. According to Guo et al. (2024), these results are comparable to those for cotton, and the leaf water potential and relative water content are widely considered as crucial indicators for evaluating a plant's ability to tolerate drought stress. Drought stress significantly reduced the water-related properties in this study. Furthermore, it progressively lowers stomatal conductance, which lowers CO_2 assimilation, photosynthetic respiration rate, and the CO_2 molar percentage in chloroplasts. Stomatal closure is a plant's initial response to drought stress and is typically thought to be the main cause of the drought-induced decline (Waraich et al., 2020). The current study demonstrated that seed coating and soil application of biodegradable water absorbents enhanced the water potential attributes of camelina genotypes, which supported earlier findings that SAPs help plants to improve water potential for extended periods of time by absorbing and releasing water gradually, reducing the need for regular watering (Dingley et al., 2024). This feature is especially helpful in areas with few water supplies or in farming methods that try to use as little water as possible without sacrificing crop yields. SAPs kept absorbing water from the soil as it dried, preventing moisture loss and promoting plant hydration (Rosjidi et al., 2025).

In the current study, the gas exchange characteristics of camelina genotypes were reduced by drought stress. This is because chronic water stress causes a reduction in stomatal aperture, which is implied by drought stress. The primary factor slowing the photosynthetic CO_2 assimilation rate is stomatal closure, which restricts the transport of CO_2 into the chloroplasts (Zahra et al., 2024). Rapid stomatal closure is the cause of this decrease, which suggests that there was less water loss to the environment. However, photosynthetic CO_2 uptake and transpirational rate are also suppressed as a result of stomatal closure (He et al., 2024). Long-term stomata closure brought on by the SAPs led to proper carbon dioxide stabilization and higher plant output (Sepehri et al., 2023). According to this study, using superabsorbent increased the amount of chlorophyll in plants under drought stress. Since chlorophylls and nutrients have a strong correlation, the enhanced accessibility of nutrients made possible by superabsorbents is probably what caused the rise in chlorophyll concentration. Thus, the amendment of superabsorbent leads to an increase in chlorophyll, which ultimately increase photosynthetic rate and gas exchange attributes (Gholinezhad et al., 2020).

Our study indicated that uptake of shoot and root Na^+ ions highly increased under water scarcity condition (50% FC). While the K^+ and Ca^{2+} declined under water stress conditions. The same findings were found in past study in rice (Jan et al., 2021). It is highly recognized that under water stress, increased Na^+ concentrations can obstruct K^+ uptake, which can lead to a reduction in plant dry matter and occasionally even death of plants. Mineral nutrients participate in numerous metabolic processes and signaling pathways that make them essential to impart drought stress tolerance in plants. They investigated the relationship between the production of ROS and Na^+ accumulation. Our findings confirmed that seed coating and soil application of biodegradable water absorbents increased the uptake of K^+ and Ca^{2+} ions in shoot and root. The main function of SAPs in this application is to absorb and hold onto essential nutrients, assuring their continued availability for plants. SAPs frequently go through many cycles of swelling and drying in this application, releasing nutrients when circumstances start to dry up and absorbing them when nutrients are abundant (Krasnopeeva et al., 2022; Dingley et al., 2024). Additionally, applying SAPs to soils increases stability and improves nutrient storage by aggregating bigger macronutrients. Furthermore, the use of SAPs enhanced soil nitrogen and nitrogen availability, phosphorus availability, and potassium availability, supporting nutrient needs during plant growth (Zheng et al., 2023).

The results of this study revealed that the yield attributes of camelina genotypes were decreased under drought stress. Sunflower, another oil seed crop, showed similar results (Jafari et al., 2024). This is related to the fact that drought stress speeds up seed development and decreases the transport of nutrients from leaves to seeds, which lowers photosynthesis and lowers seed output (Jafari et al., 2024). Seed germination, seedling development, and biochemical characteristics are all adversely affected by drought stress in sunflower crops (Nikolaou et al., 2020). One of the times when plants are most vulnerable to drought stress is while they are blossoming. Plant physiology, including plant chlorophyll content and subsequent photosynthesis, as well as plant antioxidant activities, is also impacted by drought stress, which has detrimental impacts on plant development and crop output (Zamani et al., 2020).

Our research showed that the use of plant-based biodegradable water absorbents increased camelina production, and drought stress reduced camelina yield features. According to Ahmed et al. (2020), camelina yield and yield-contributing characteristics were greatly influenced by various irrigation regimes; a reduction in soil water availability limited the development of yield-related features and decreased seed output. Shorter seed filling times, fewer siliques, flowers, and silique abortion resulted from the absence of irrigation during the flowering stage, which decreased production. Similarly, Agarwal et al. (2021) discovered that the best method to increase camelina seed output was to water throughout the flowering stage. Lack of soil moisture during the reproductive stage can cause drought stress, which can reduce seed output by causing negative effects such as leaf senescence and a decrease in photosynthetic rate (Sintim et al., 2021).

Water generally has a direct impact on plant physiological development, including cell turgor, photosynthesis, and tissue and cell growth (Waraich et al., 2020). The water deficiency-stomata shutdown was the primary cause of this. Together with the chemical markers generated by roots, the closing of stomata under water deficiency resulted in a decrease in leaf turgor and ambient humidity pressure (He et al., 2020). Since the leaf interacts with the water deficit state by shutting the stomata and restricting the CO_2 supply to chloroplasts, the circumstances of the water deficit minimise total dry matter by decreasing the growth of the leaf surface and photosynthetic capacity (Ahmad et al., 2017).

The suppression of mesophyll behaviour and stomatal closure during stressful situations was the cause of the decrease in photosynthetic rate under restricted water circumstances. Cell development is impacted by water deficiency stress, which also causes membrane proteins to separate. It showed that stomata closure also lowers rubisco activity, ATP synthesis, and Ci concentration (internal CO_2 concentration), all of which, when under water deficiency stress, limit the photosynthetic rate (Pn) (Shah et al., 2021). Water conservation and a slight water deficit by stomata are reflected in the plant's reaction to the decrease in transpiration rate (Hasanuzzaman et al., 2023).

There are two ways for the leaves to respond to water shortage: either they get thicker or they get thinner. Plants can enhance their water-storing capacity and reduce water loss by growing palisade and spongy tissue, as well as by shrinking their leaves and stomata (Zúñiga-Feest et al., 2017). Some plants thin their leaves or produce special leaves to increase the ability of CO2 and inorganic nutrients to permeate the leaves and to improve the exchange of gases to repair and sustain respiration under stress (Brodersen et al., 2017). The interior structure of the leaves is changed to adjust the stomata and maximize transpiration during water stress. But it's unclear what caused this, so more research is needed. The plant's water content affects its stomatal structure, leaf area, leaf thickness, and leaf density (Binks et al., 2016). When plants experience drought, their upper epidermis thickens, which causes their leaves to get thicker. In dry conditions, the grass plants' thick covering of epidermis keeps the leaves from losing a lot of water. In arid conditions, rice varieties with moderate leaf rolling showed a greater drop in leaf thickness than those with more leaf rolling (Conesa et al., 2020). According to the plants' photosynthetic efficiency and net carbon absorption, drought stress causes the leaves to become thinner (Salsinha et al., 2021). Plants with great drought tolerance will exhibit lower biomass losses (Gunnula et al., 2022). The genotype that were highly resistant of drought showed an increase in lamina thickness under arid circumstances. The genotype's lamina epidermal cells, which are somewhat drought resistant, also have thicker cell walls and cuticles. While the highly drought-tolerant genotype showed a decrease in stomata size, moderately drought-tolerant showed an increase in leaf stomata size (Taratima et al., 2020). The intricate relationships between leaf thickness and dryness show the strategies plants employ to endure under hostile conditions. By making it possible for plants to withstand water stress, these adaptations help the ecosystem become more resilient over the long run in addition to improving immediate survival.

In arid environments, plant growth and photosynthesis rate are correlated with leaf thickness. Mesophyll density rose in drought-resistant plants as a result of increased leaf thickness during drought stress (Taratima et al., 2020). Plants under drought stress showed alterations in the vascular sheath, sclerenchyma layer, and mesophyll thickness (Cal et al., 2019; Salsinha et al., 2021). The leaves of drought-adapted plants often have thinner spongy mesophyll cells but more densely packed, elongated cells than those of drought-susceptible plants. Numerous studies have examined how drought stress affects plant leaf growth (Zhang et al., 2018). Physical leaf form and the development of leaf epidermal cells are strongly connected phenomena (Zhu et al., 2019). The guard cells are surrounded by mesophyll, a type of cell that undergoes notable changes in turgor state. Accordingly, it is the best tissue for quickly transforming water stress variations into the ABA biosynthesis required to control stomatal responses (Yavas et al., 2024).

Modifications in vascular anatomy are important for plant acclimation potential. The vascular bundles found in the middle of the leaves act as a source for the distribution of water and nutrients. The vascular bundle's shrinkage under stress conditions with smaller leaves is a sign of the plant's capacity to adapt its structure. The xylem serves as a source of water transport in the vascular bundle. Harsh environmental circumstances cannot be tolerated by plants with larger xylem channel diameters (Qaderi et al., 2019; Balfagon et al., 2021). Stress transpiration, root water uptake, and stem hydraulic capacitance all start to decrease when drought strikes. As a result, the stem's vascular bundles, pith cell area, and cortical thickness are all seen to decrease (Mansoor et al., 2019; Crous et al., 2018). Both the sensitive and tolerant genotypes' morphology changed with increasing drought intensity, according to the study's findings. Interestingly, the tolerant genotype G2-618 displayed higher values for all leaf and stem anatomy metrics under extreme drought stress than the sensitive genotypes. This may be due to the tolerant genotypes' constant adaptability, which allowed them to continue growing and functioning when the water supply became scarce, as opposed to sensitive genotypes, whose growth may have been suddenly impacted by a response that was triggered at much later stages. By enhancing water-flow resistance, decreasing the risk of embolisms, and maintaining continuous nutrition transport, these tolerant genotype changes allowed them to do so (Qaderi et al., 2019).

Conclusion

Drought stress (50% FC) reduced the morphological aspects, particularly shoot fresh and dry weight, as well as shoot length of both camelina genotypes. Drought stress (50% FC) considerably decreased the chlorophyll pigments, including Chl. *a*, Chl. *b*, total chlorophyll and carotenoids. Among both genotypes, reactive oxygen species and stress determinants, including H_2O_2 and MDA increased. The activities of enzymatic antioxidants or cellular defense enzymes activities such as CAT, SOD, and POD were elevated under drought stress conditions. Application of biodegradable water absorbents scavenges the accumulation of free radicals, including H_2O_2, which was increased in water shortage conditions. Drought stress 50% field capacity increased the root and shoot Na^+ and decreased the shoot and root Ca^{2+} and K^+. The application of biodegradable water absorbents improved all morphological parameters, photosynthetic pigments, and increased the activities of enzymatic antioxidants. In seed coating experiment, the dose of 15 g/kg seed performed better in morpho-physiological, biochemical and yield attributes of camelina. Among both genotypes, G-618 performed best under drought stress conditions and water absorbent application.

Abbreviations

ROS
Reactive oxygen species
UV
Ultraviolet
RWC

Relative water content
FW
Fresh weight
DW
Dry weight
TW
Turgid weight
H_2O_2
Hydrogen peroxide
MDA
malondialdehyde
CAT
catalase
SOD
superoxide dismutase
POD peroxidase
K^+
Potassium
Ca^{2+}
Calcium
CRD
Completely randomized design
PCA
Principal component analysis
A
Net photosynthetic rate
E
Transpirational rate
Ci
Internal CO_2 concentrations
GS
Stomatal conductance
PH
Plant height
TP
Leaf turgor potential
LWP
Leaf water potential
and OP
Leaf osmotic potential
SL
shoot length
SFW
Shoot fresh weight
SDW
Shoot dry weight
LA
Leaf area
RL
Root length
RDW
Root dry weight
RFW
Root fresh weight
RSA
Root surface area and RPA:Root projected area
RV
Root volume
RD
Root diameter

Declarations

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Not applicable.

Consent for Publication

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Author's Contributions

Conceptualization: Arslan Haider and Tahrim Ramzan Methodology: Arslan Haider and Tahrim Ramzan, Software: Arslan Haider and Tahrim Ramzan, Formal analysis: Ejaz Ahmad Waraich and Arslan Haider, Moeen Akhtar Investigation: Ejaz Ahmad Waraich and Arslan Haider, Data curation: Tahrim Ramzan and Arslan Haider, Shagufta Malik Writing-original draft preparation: Arslan Haider, Tahrim Ramzan, Jazab Shafqat and Marwah Saif Writing-review and editing, Arslan Haider and Tahrim Ramzan. All authors have read and agreed to the published version of the manuscript.

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Tables

Table 1. Role of rice straw based biodegradable water absorbents on stem anatomy of *camelina sativa* under drought stress.

Table 1. Effect of seed coating of rice-straw based biodegradable water absorbents application on stem anatomical features of camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1=

5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

Genotypes	Drought Stress	Rice straw based water absorbents	Root cortical thickness (mm)	Root endodermal thickness (mm)	Root cortical cell area (cm^2)	Stellar regio
G1-611	100%FC	P0	3.3±0.12g	0.2±0.06a	0.27±0.02a	6.87±0.09k
		P1	5.8±0.12cd	0.23±0.09a	0.33±0.05a	11.2±0.09g
		P2	2.3±0.12h	0.33±0.09a	0.22±0.12a	10.3±0.09h
		P3	7.4±0.12a	0.3±0.12a	0.21±0.05a	7.47±0.09j
	50%FC	P0	7.1±0.12ab	0.43±0.12a	0.05±0.01a	6.33±0.09l
		P1	6.7±0.12b	0.27±0.09a	0.12±0.04a	18.2±0.09b
		P2	5.3±0.12de	0.5±0.12a	0.05±0.02a	10.8±0.09h
		P3	6.13±0.09c	0.3±0.12a	0.14±0.06a	11.3±0.06g
G2-618	100%FC	P0	7.13±0.12ab	0.33±0.09a	0.1±0.05a	12.3±0.09e
		P1	5.7±0.06cd	0.2±0.06a	0.08±0.06a	11.7±0.06f
		P2	7.63±0.09a	0.33±0.09a	0.26±0.09a	13.3±0.06d
		P3	5.27±0.09de	0.13±0.03a	0.06±0.03a	12.4±0.09e
	50%FC	P0	7.53±0.15a	0.33±0.09a	0.32±0.05a	20.1±0.06a
		P1	7.33±0.12a	0.3±0.12a	0.06±0.03a	16.2±0.06c
		P2	4.17±0.09f	0.23±0.03a	0.11±0.07a	7.67±0.09j
		P3	4.77±0.09e	0.27±0.09a	0.18±0.08a	11.3±0.09fg

Table 2. Role of rice straw based biodegradable water absorbents on root anatomy of *camelina sativa* under drought stress.

Genotypes	Drought Stress	Rice straw based water absorbents	Root cortical thickness (mm)	Root endodermal thickness (mm)	Root cortical cell area (cm^2)	Stellar regio
G1-611	100%FC	P0	3.3±0.12g	0.2±0.06a	0.27±0.02a	6.87±0.09k
		P1	5.8±0.12cd	0.23±0.09a	0.33±0.05a	11.2±0.09g
		P2	2.3±0.12h	0.33±0.09a	0.22±0.12a	10.3±0.09h
		P3	7.4±0.12a	0.3±0.12a	0.21±0.05a	7.47±0.09j
	50%FC	P0	7.1±0.12ab	0.43±0.12a	0.05±0.01a	6.33±0.09l
		P1	6.7±0.12b	0.27±0.09a	0.12±0.04a	18.2±0.09b
		P2	5.3±0.12de	0.5±0.12a	0.05±0.02a	10.8±0.09h
		P3	6.13±0.09c	0.3±0.12a	0.14±0.06a	11.3±0.06g
G2-618	100%FC	P0	7.13±0.12ab	0.33±0.09a	0.1±0.05a	12.3±0.09e
		P1	5.7±0.06cd	0.2±0.06a	0.08±0.06a	11.7±0.06f
		P2	7.63±0.09a	0.33±0.09a	0.26±0.09a	13.3±0.06d
		P3	5.27±0.09de	0.13±0.03a	0.06±0.03a	12.4±0.09e
	50%FC	P0	7.53±0.15a	0.33±0.09a	0.32±0.05a	20.1±0.06a
		P1	7.33±0.12a	0.3±0.12a	0.06±0.03a	16.2±0.06c
		P2	4.17±0.09f	0.23±0.03a	0.11±0.07a	7.67±0.09j
		P3	4.77±0.09e	0.27±0.09a	0.18±0.08a	11.3±0.09fg

Table 2. Effect of seed coating of rice-straw based biodegradable water absorbents application on root anatomical features of camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

Table 3. Role of rice straw based biodegradable water absorbents on midrib anatomy of *camelina sativa* under drought stress.

Genotypes	Drought Stress	Rice straw based water absorbents	Midrib Thickness (mm)	Lamina thickness (mm)	Adaxial thickness (mm)	Abaxial thickness (mm)	Paren
G1-611	100%FC	P0	3.63±0.09f	0.27±0.09e	0.2±0.06a	0.23±0.09a	1.37±
		P1	4.23±0.09e	0.43±0.09de	0.37±0.09a	0.27±0.09a	0.14±
		P2	5.23±0.09d	1.3±0.06b-d	0.3±0.06a	0.3±0.06a	0.78±
		P3	6.2±0.06c	1.3±0.12b-d	0.37±0.09a	0.23±0.09a	0.62±
	50%FC	P0	3.63±0.09f	1.53±0.15a-c	0.3±0.12a	0.27±0.09a	3.98±
		P1	6.27±0.09bc	1.4±0.12a-d	0.33±0.09a	0.3±0.06a	1.74±
		P2	3.63±0.09f	1.57±0.09a-c	0.27±0.09a	0.27±0.09a	1.81±
		P3	5.53±0.09d	1.13±0.22b-e	0.23±0.09a	0.37±0.09a	0.41±
G2-618	100%FC	P0	3.47±0.09f	0.63±0.48c-e	0.33±0.09a	0.13±0.03a	0.21±
		P1	7.27±0.09a	1.23±0.43b-e	0.27±0.09a	0.3±0.06a	0.15±
		P2	6.47±0.09bc	1.43±0.09a-d	0.2±0.06a	0.13±0.03a	0.12±
		P3	5.27±0.09d	1.3±0.12b-d	0.27±0.07a	0.3±0.06a	0.15±
	50%FC	P0	6.7±0.12b	2.37±0.09a	0.1±0a	0.23±0.09a	0.09±
		P1	6.23±0.09c	1.63±0.09a-c	0.4±0.06a	0.23±0.07a	0.12±
		P2	5.3±0.12d	1.9±0.12ab	0.23±0.03a	0.23±0.09a	0.11±
		P3	7.2±0.06a	1.83±0.15ab	0.23±0.09a	0.23±0.09a	0.33±

Table 3. Effect of seed coating of rice-straw based biodegradable water absorbents application on midrib anatomical features of camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

Scheme 1

Scheme 1 is available in the Supplementary Files section.

Figures

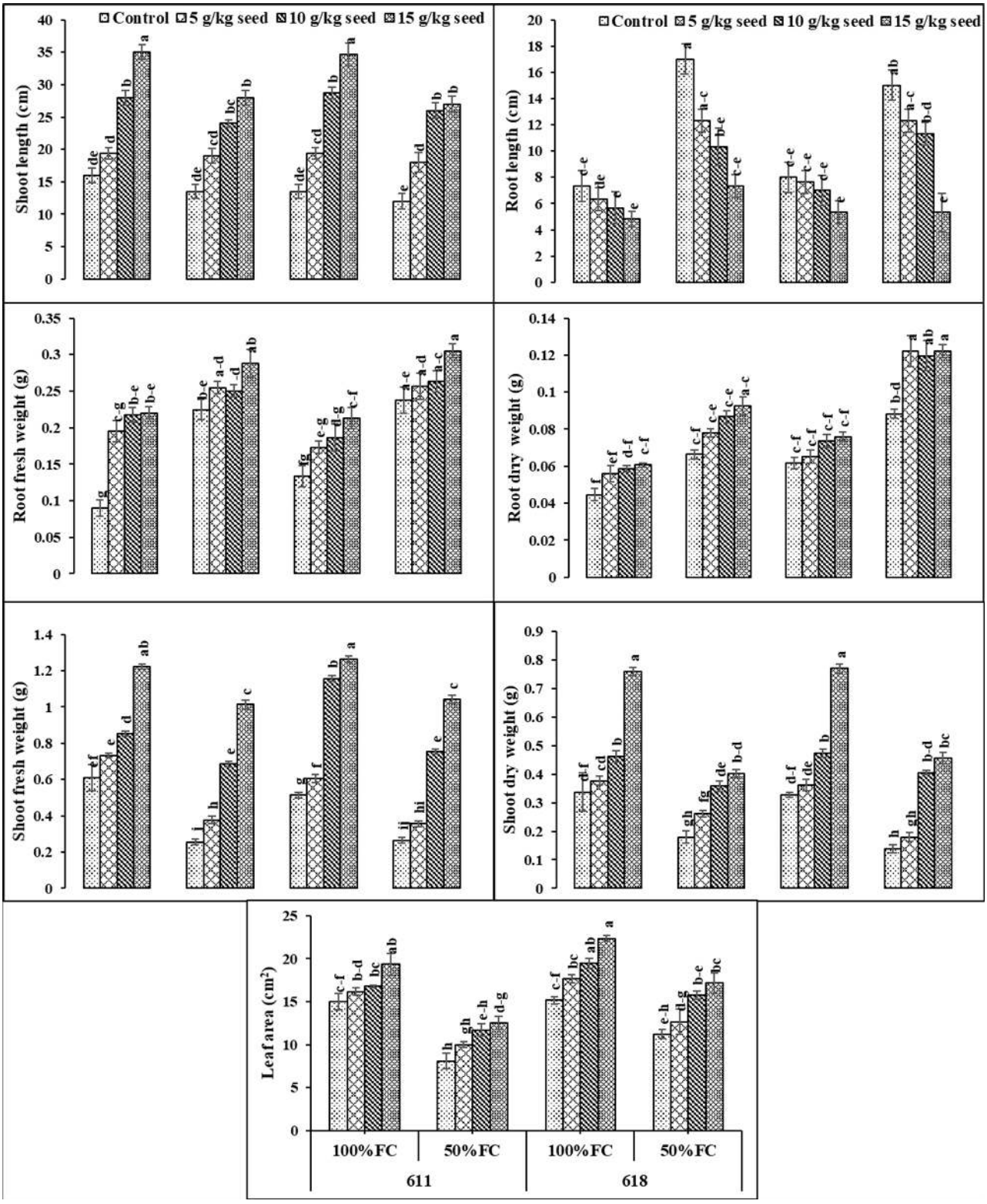


Figure 1

Effect of seed coating of rice-straw based biodegradable water absorbents application on shoot length, root length, shoot fresh weight, shoot dry weight, root fresh weight, root dry weight and leaf area in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

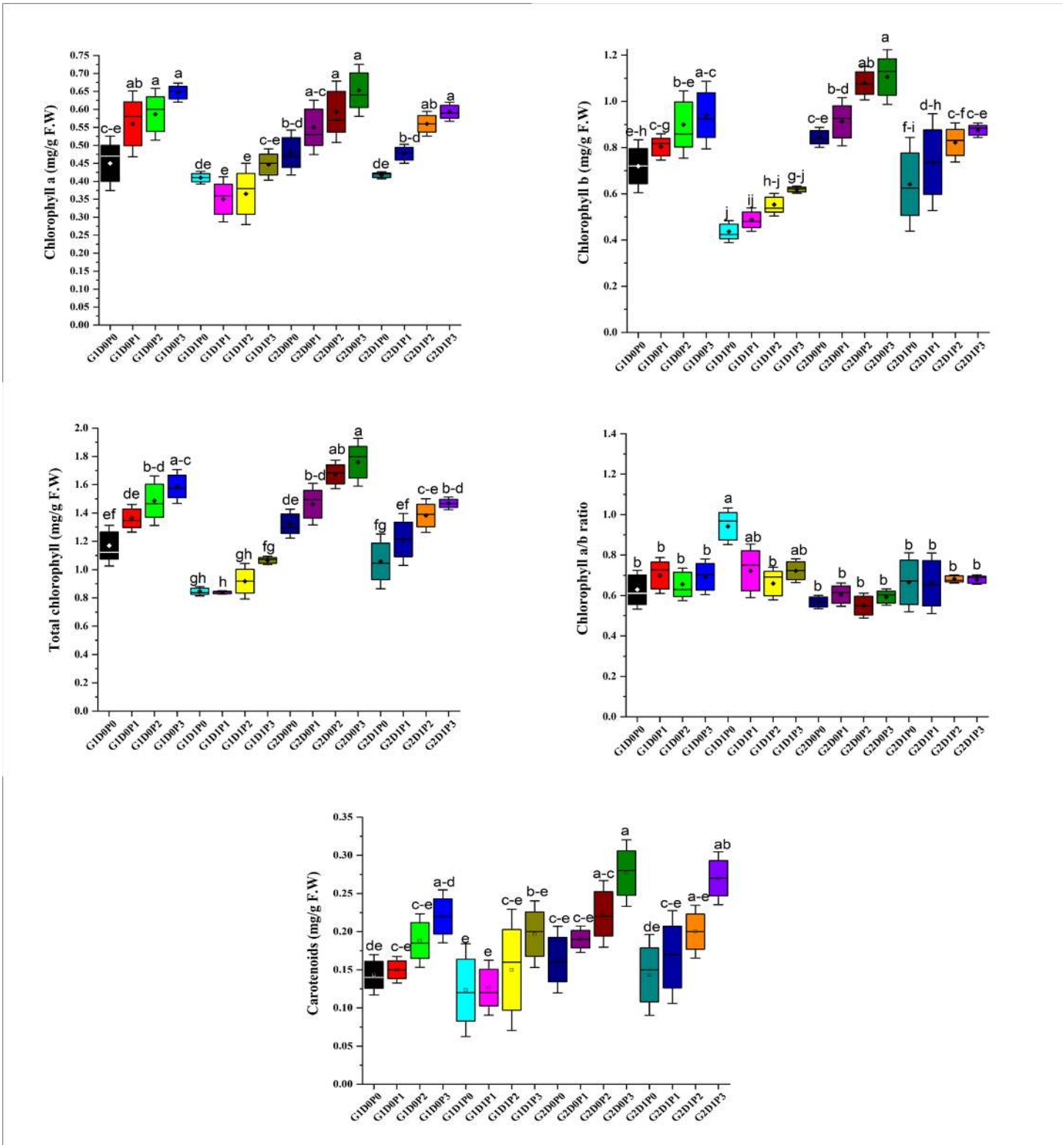


Figure 2

Effect of seed coating of rice-straw based biodegradable water absorbents application on Chl. *a*, Chl. *b*, Chl. *a*/*b*, total Chl. and carotenoids in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

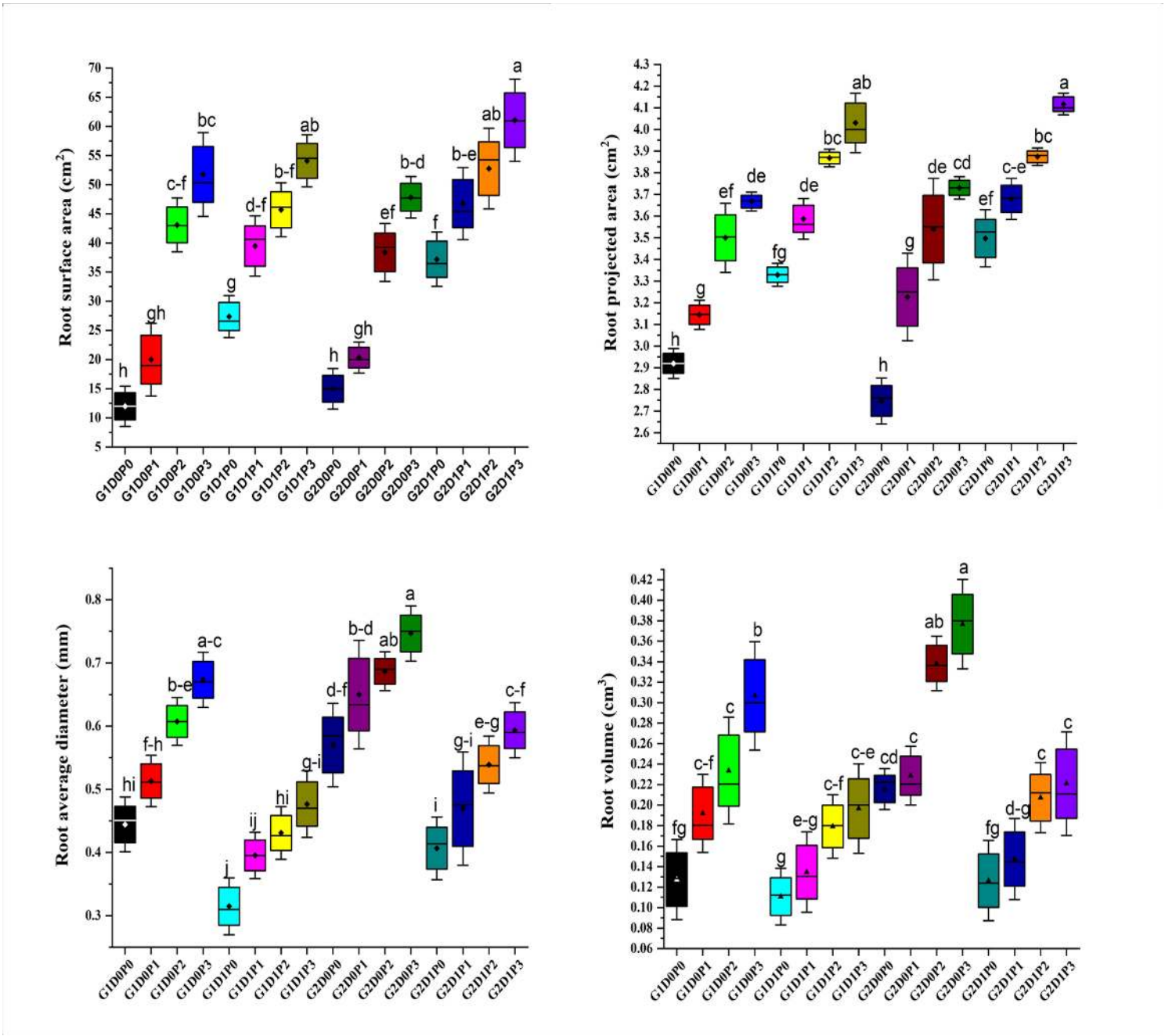


Figure 3

Effect of seed coating of rice-straw based biodegradable water absorbents application on root projected area, root surface area, root volume and root diameter in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

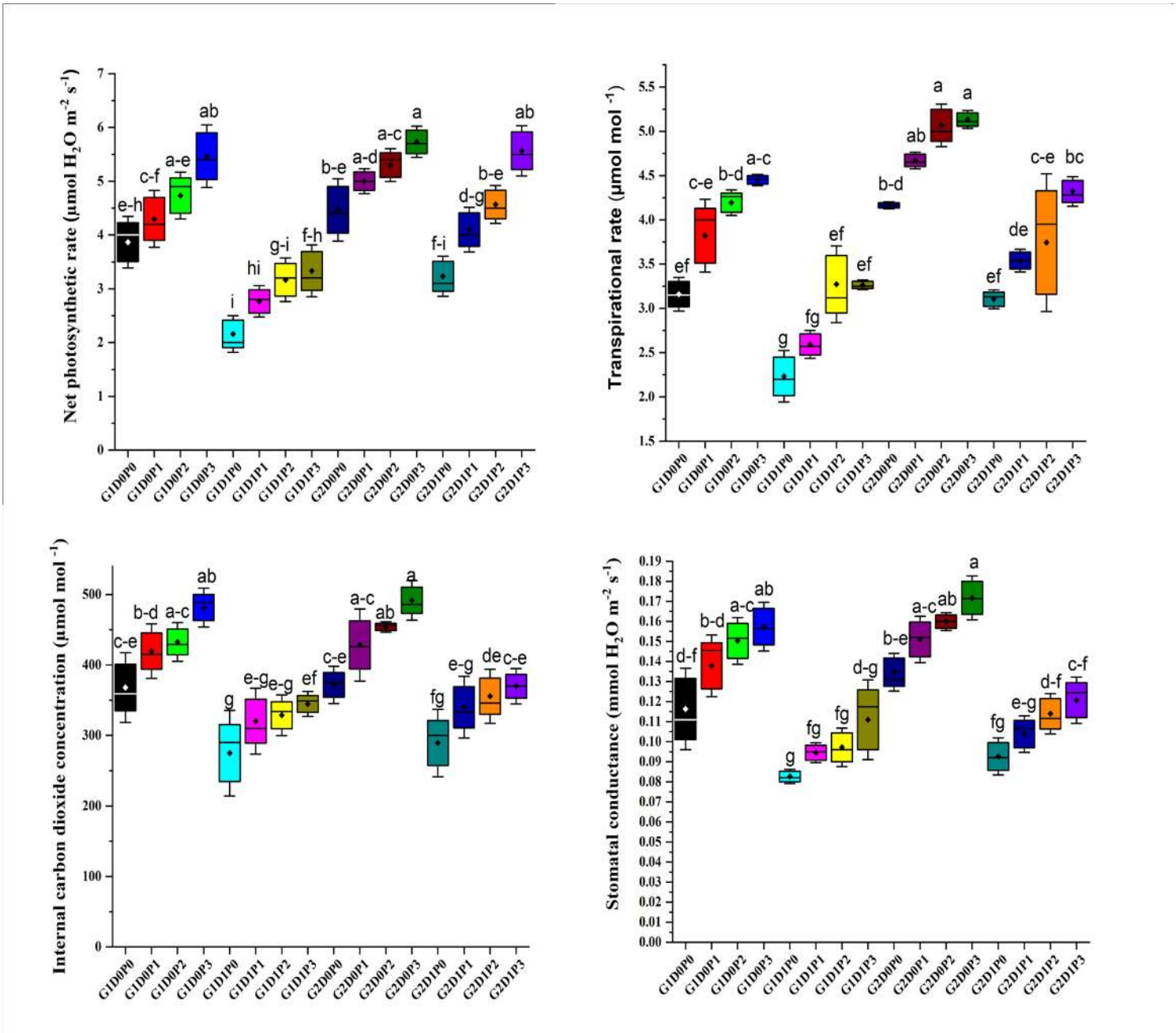


Figure 4

Effect of seed coating of rice-straw based biodegradable water absorbents application on net photosynthetic rate, transpirational rate, internal carbon dioxide concentration and stomatal conductance in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

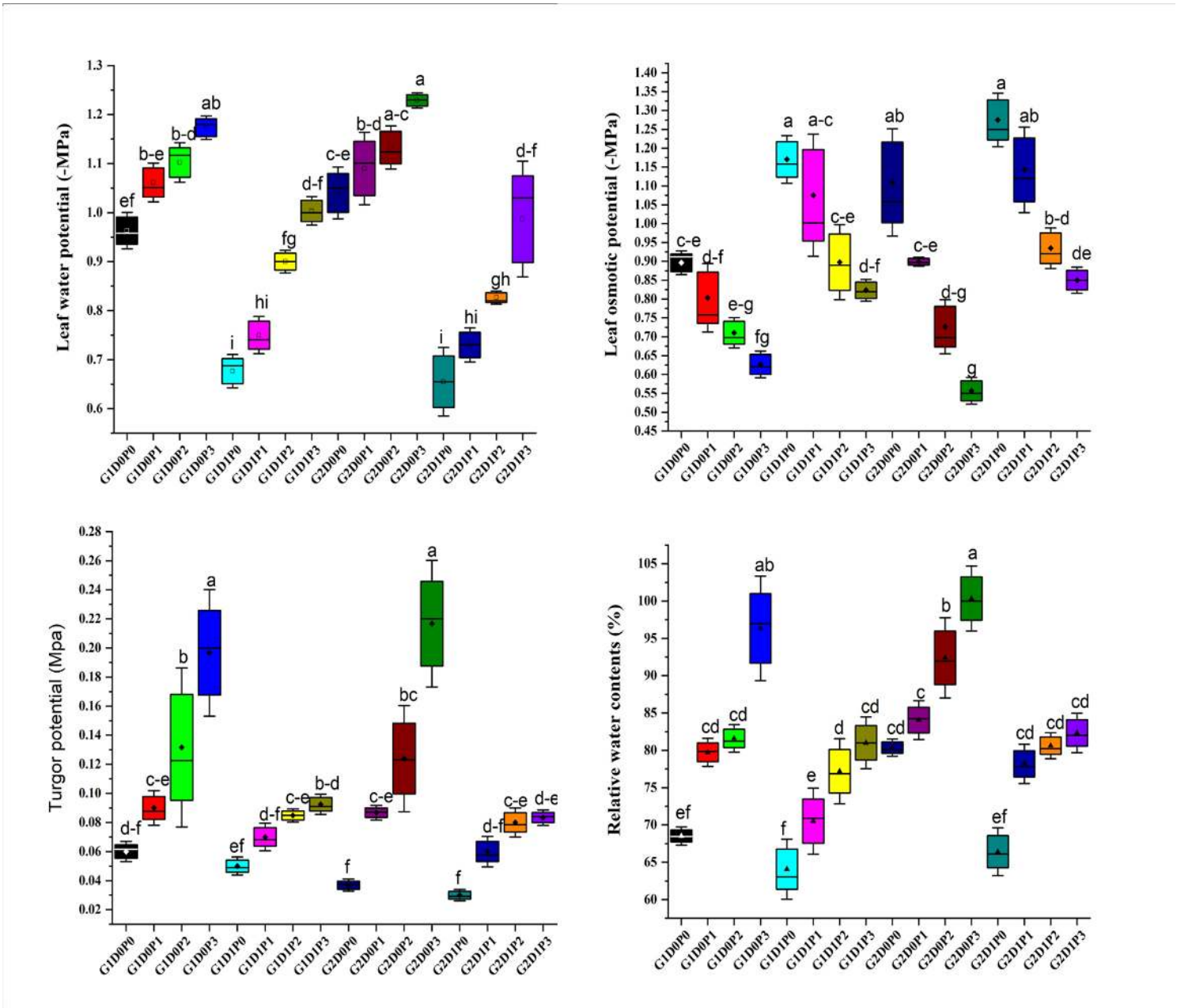


Figure 5

Effect of seed coating of rice-straw based biodegradable water absorbents application on leaf water potential, leaf osmotic potential, leaf turgor potential and relative water contents in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

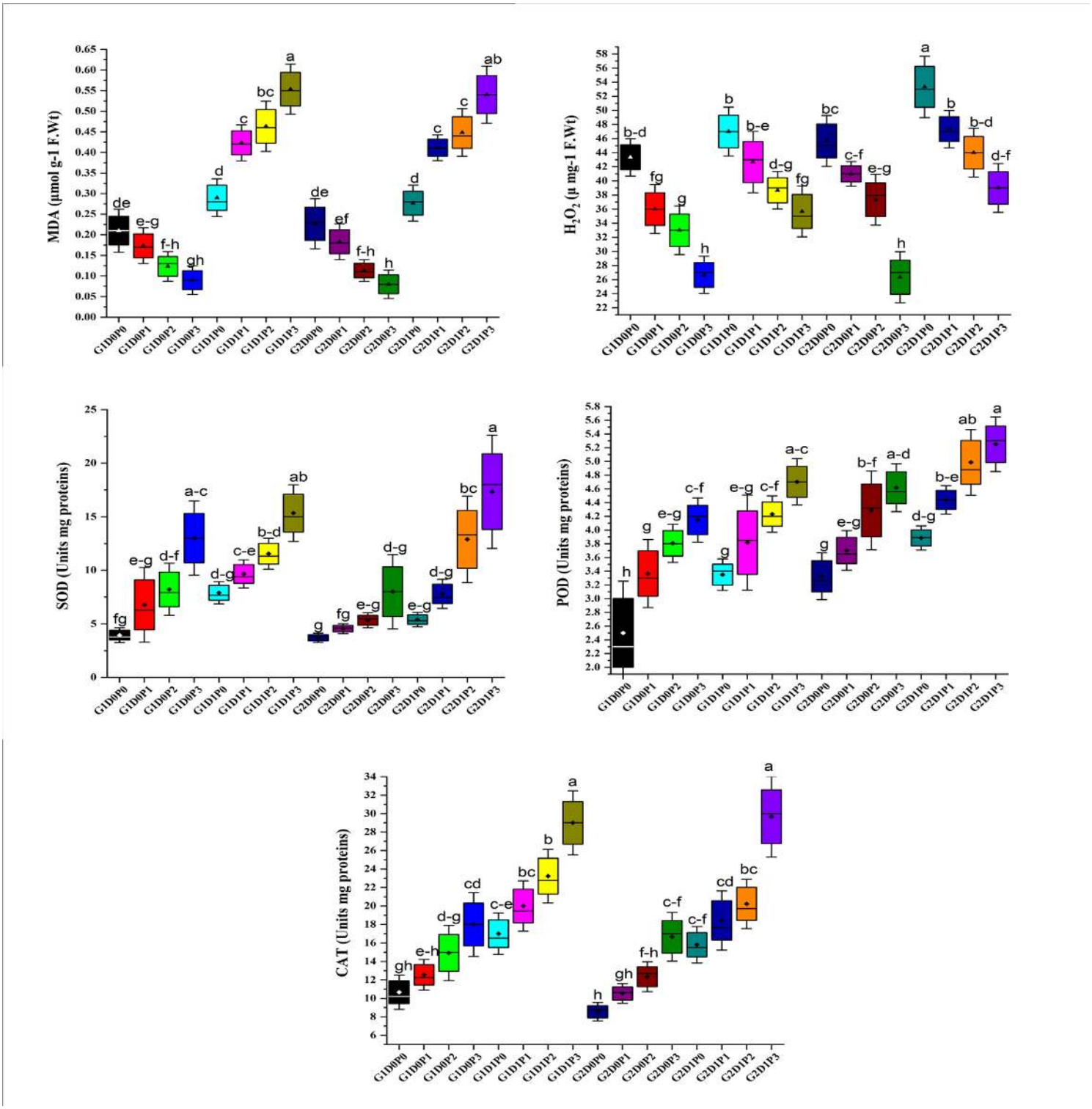


Figure 6

Effect of seed coating of rice-straw based biodegradable water absorbents application on MDA, H_2O_2, SOD, POD, and CAT contents in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

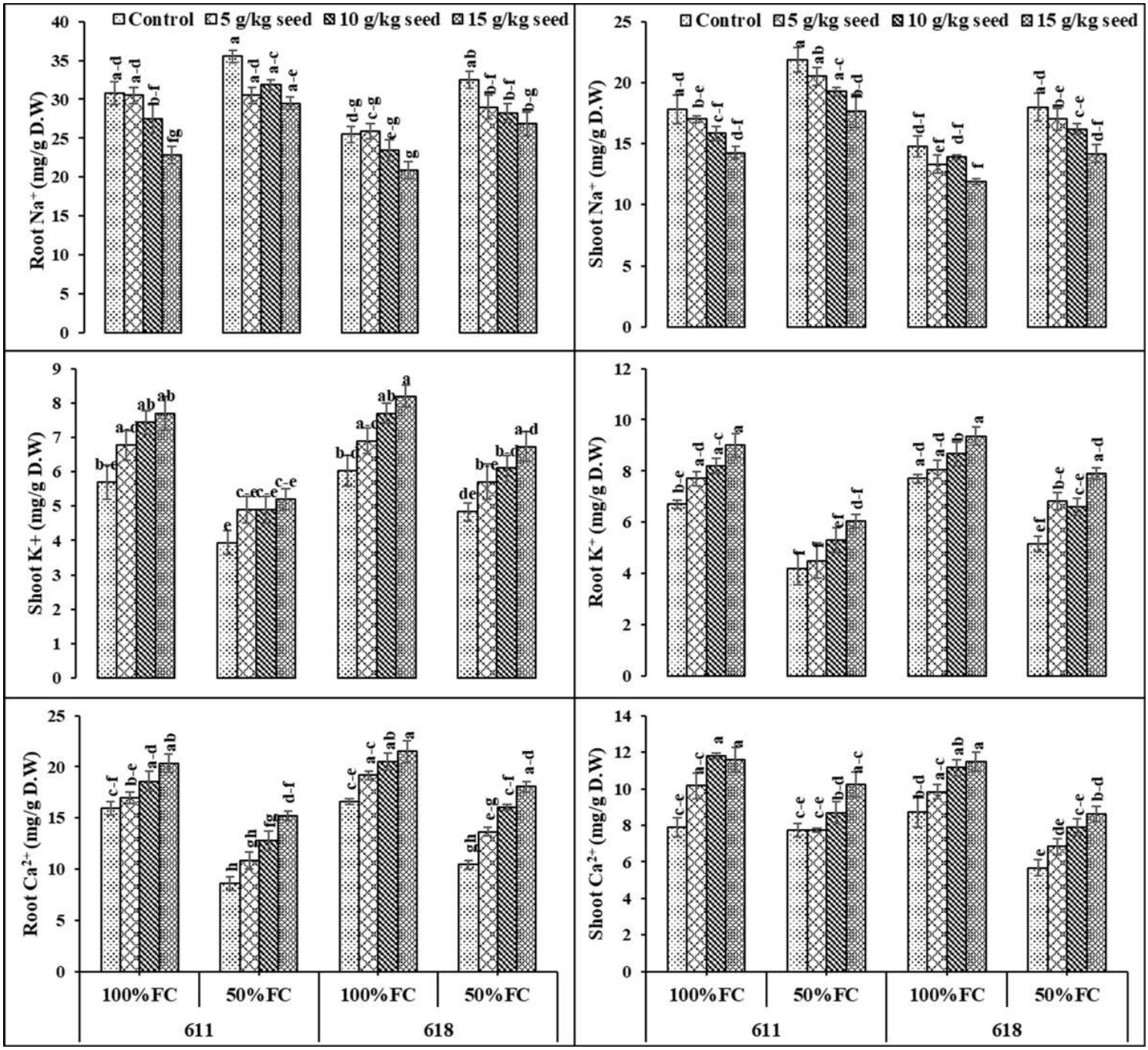


Figure 7

Effect of seed coating of rice-straw based biodegradable water absorbents application on root Na^+ and shoot Na^+, shoot K^+, root K^+, root Ca^{2+} and shoot Ca^{2+}, contents in camelina under drought (D0=100% FC) and (D1=50% FC) stress. Camelina genotypes (G1=611, and G2=618), rice-straw seed coating water absorbents P0= no water absorbent, P1= 5 g/kg seed, P2= 10 g/kg seed and P3= 15 g/kg seed.

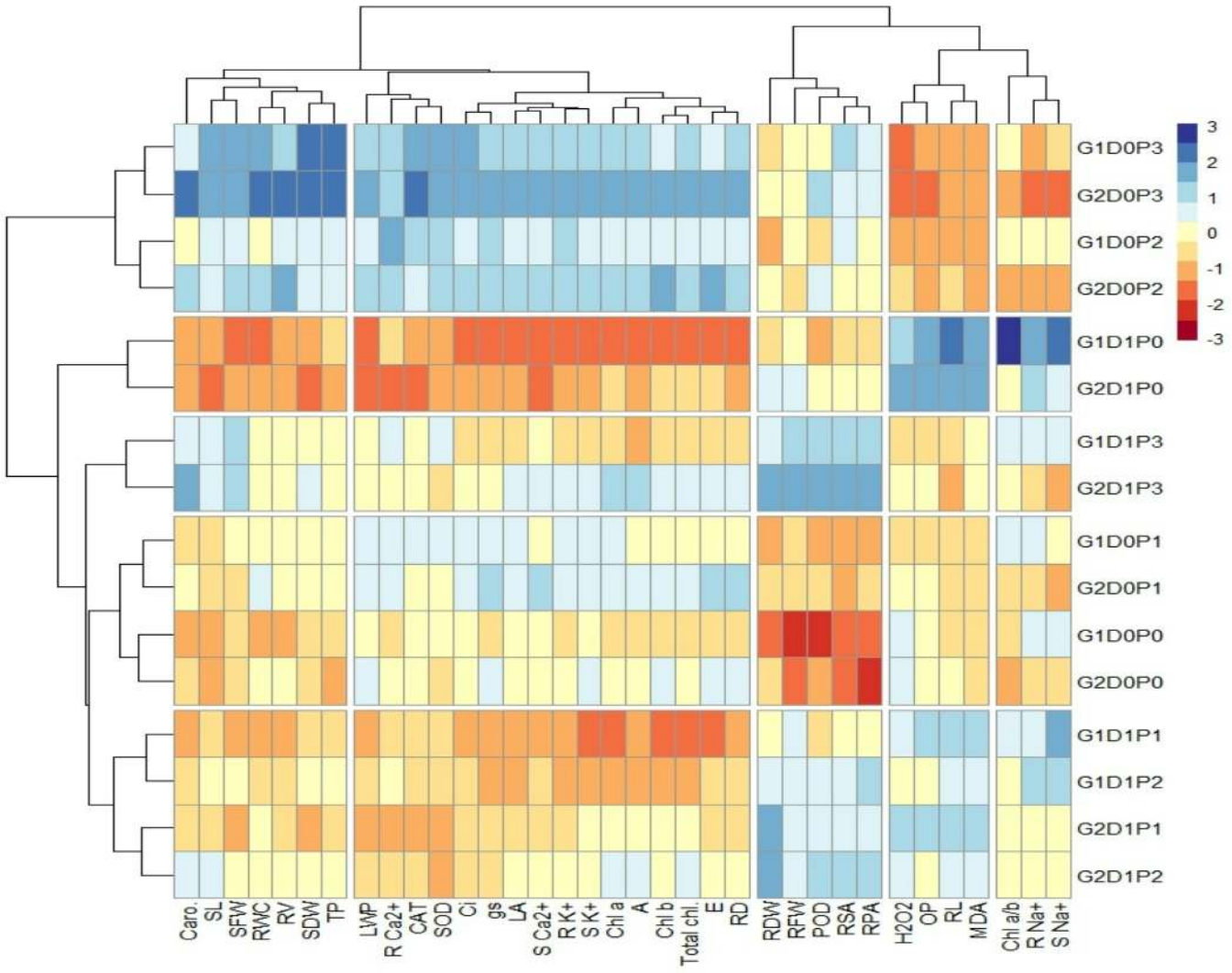


Figure 8

Heatmap analysis between morpho-physiological, biochemical and ionic attributes of camelina genotypes. RNa^+,(root sodium), SNa^+ (shoot sodium), Chl. *a/b*, MDA (malondialdehyde), RL (root length), OP (osmotic potential), H_2O_2 (hydrogen peroxide), RSA (root surface area), RFW (root fresh weight), RDW (root dry weight), POD (peroxidase), RPA (root projected area), RD (root diameter), E (transpiration rate), total Chl., A (net photosynthetic rate), Chl. *a*, *b*, CAT (catalase), SOD (superoxide dismutase), WP (water potential), SCa^{2+} (shoot calcium), RCa^{2+} (root calcium), TP (turgor potential), Caro (carotenoids), RK^+, SK^+ (root and shoot potassium), gs (stomatal conductance), LA (leaf area), RWC (relative water contents), Ci (internal carbon dioxide concentration), RV (root volume), SL (shoot length), SDW (shoot dry weight), SFW (shoot fresh weight).

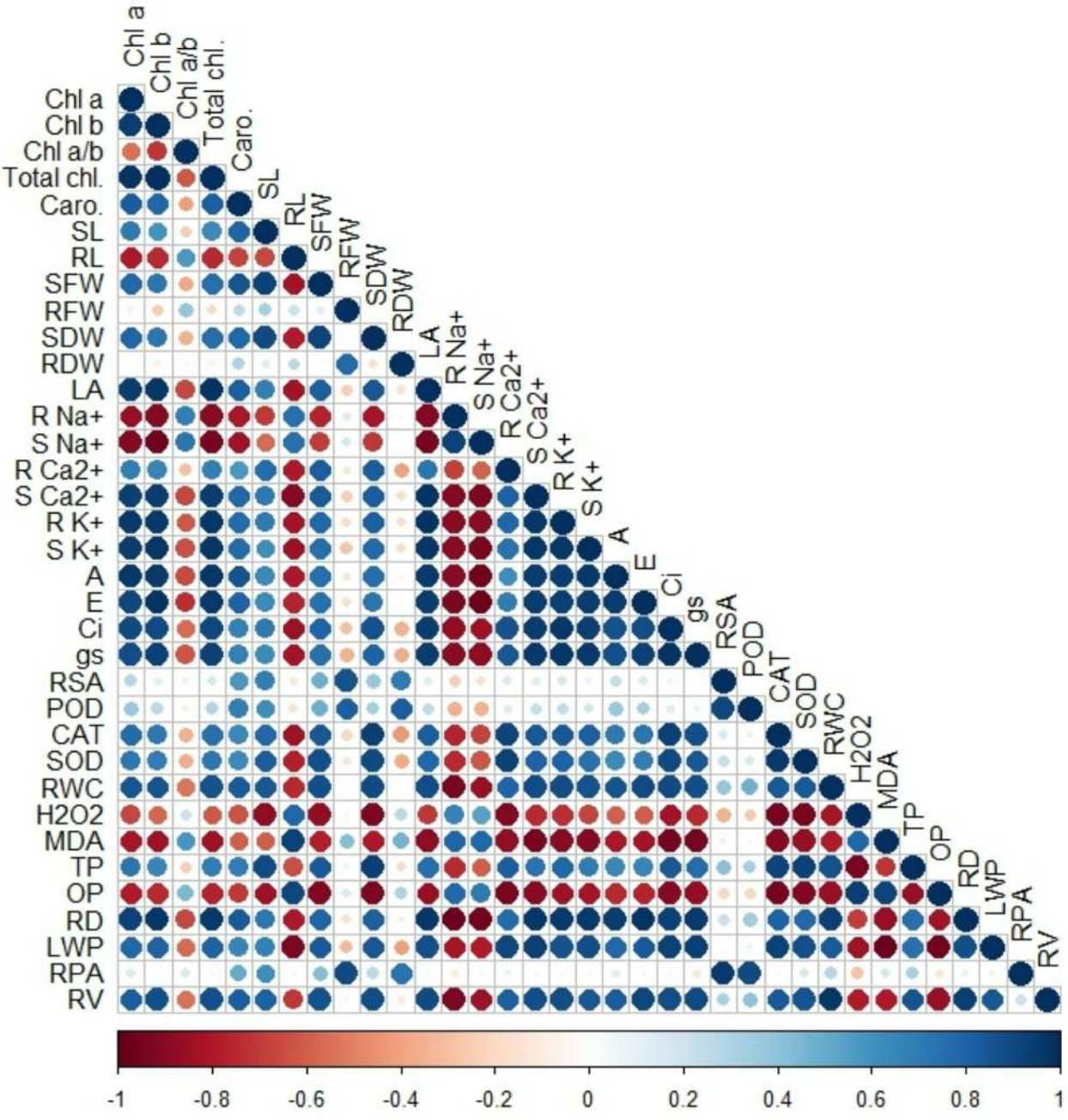


Figure 9

Correlation analysis between morpho-physiological, biochemical and ionic attributes of camelina genotypes.

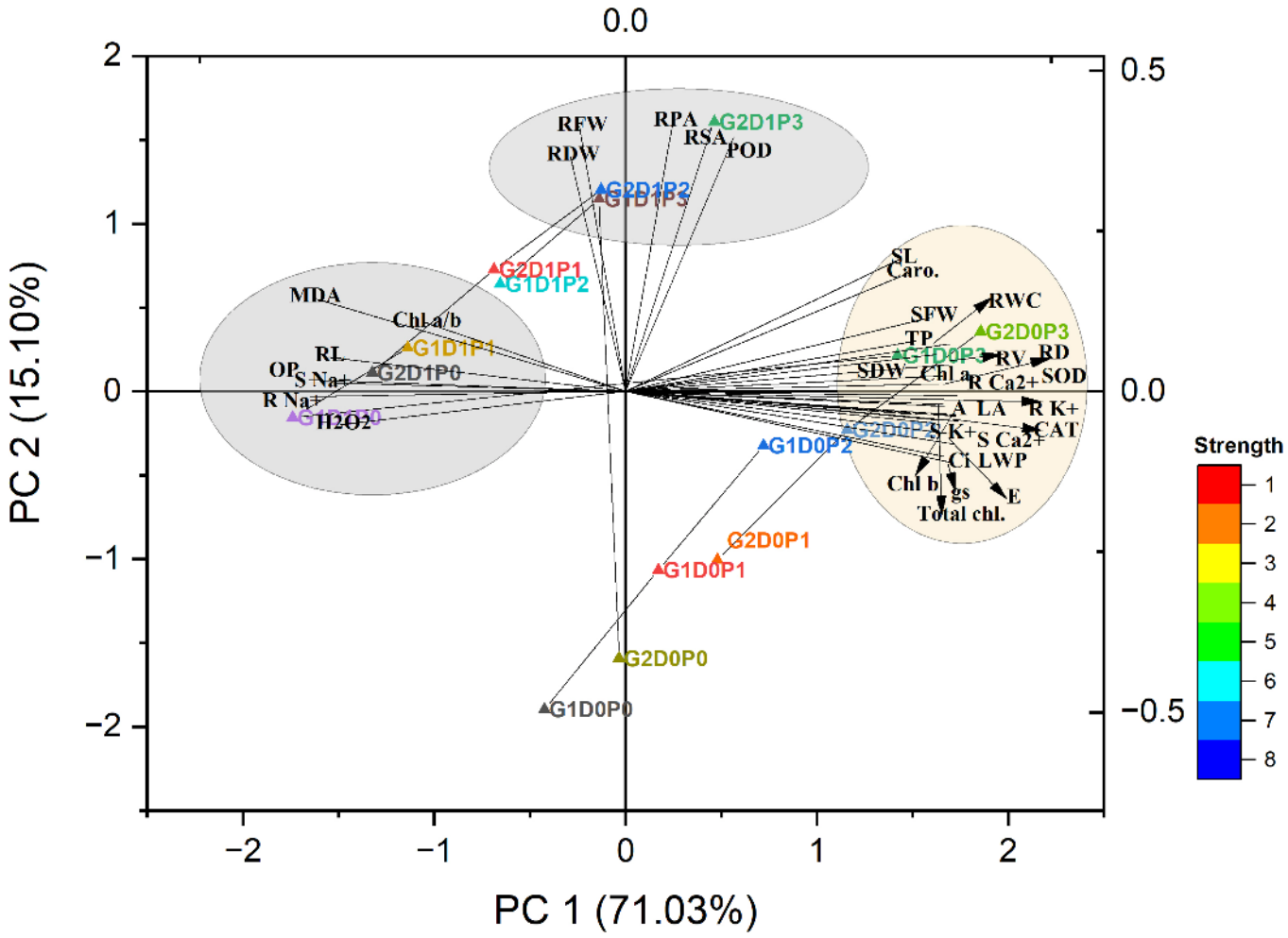


Figure 10

Principal component analysis between morpho-physiological, biochemical and ionic attributes of camelina genotypes.

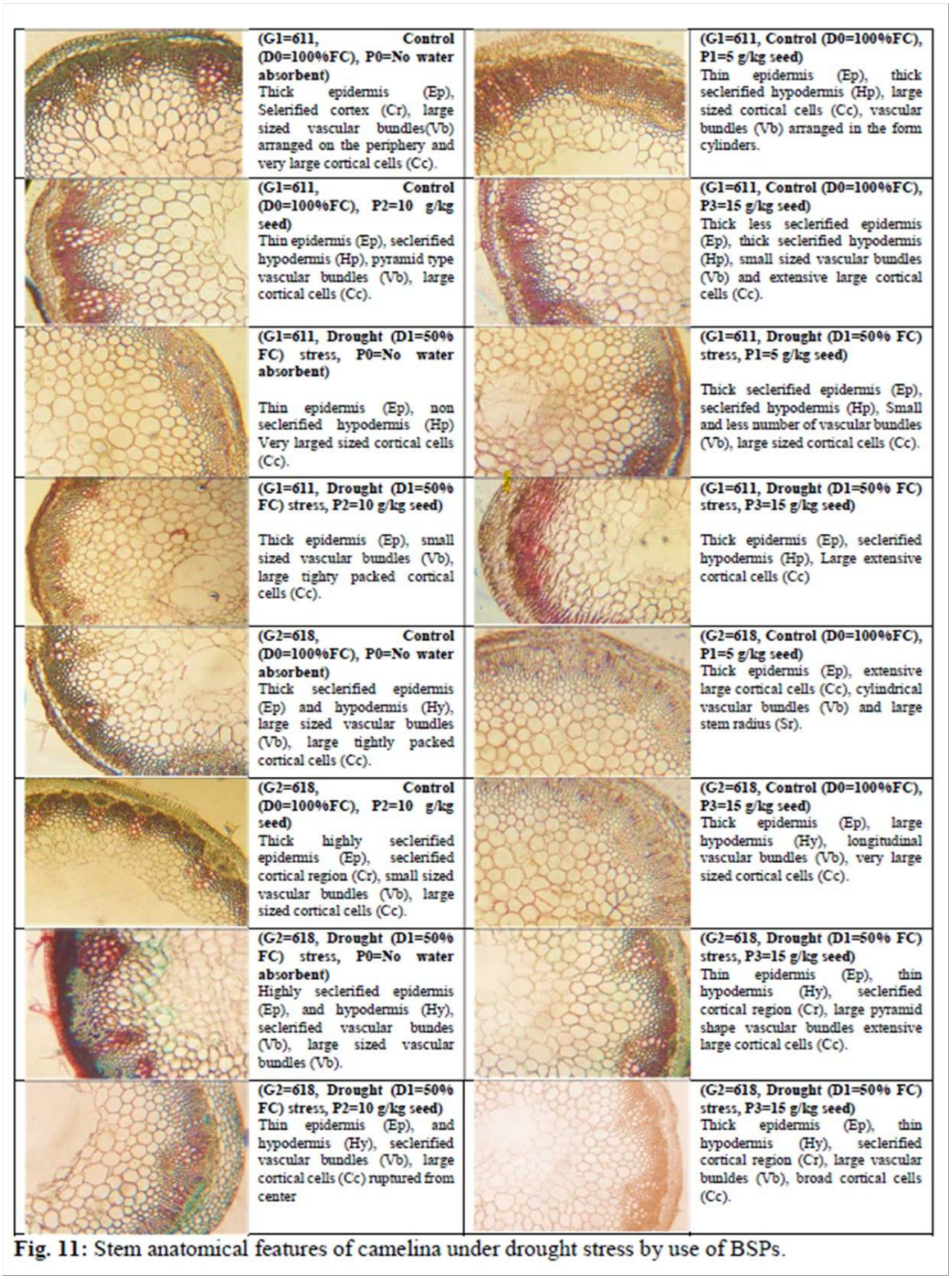


Fig. 11: Stem anatomical features of camelina under drought stress by use of BSPs.

Figure 11

Stem anatomical features of camelina under drought stress by use of BSPs.

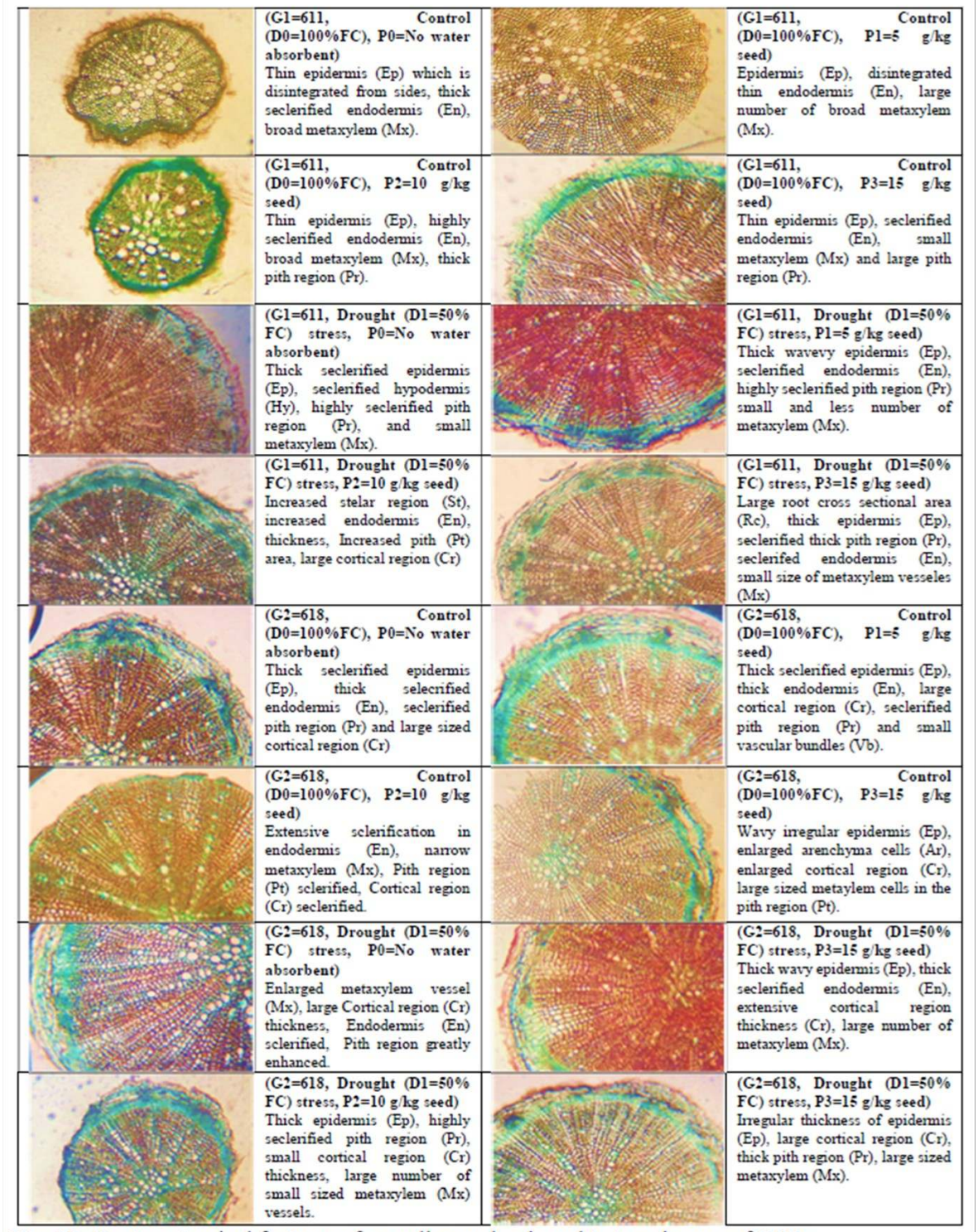


Fig. 12: Root anatomical features of camelina under drought stress by use of BSPs.

Figure 12

Root anatomical features of camelina under drought stress by use of BSPs.

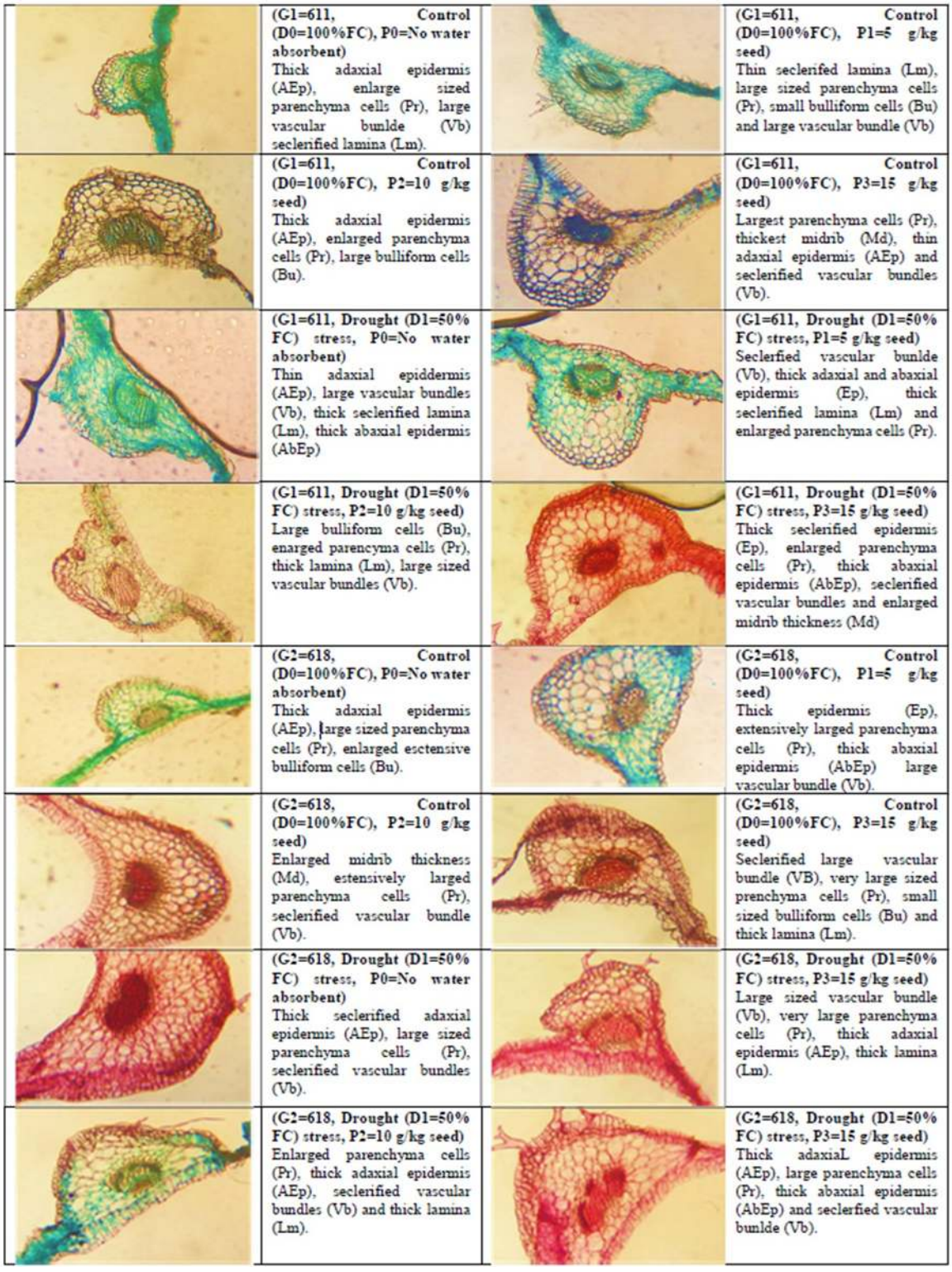


Figure 13

Mid rib anatomical features of camelina under drought stress by use of BSPs.

Supplementary Files

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- floatimage2.jpeg