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The protective role of methyl jasmonates (MeJA) in capsicum (*Capsicum annuum* var. *conoide*) under drought stress: Growth, photosynthetic, and biochemical responses

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ABSTRACT

Drought stress severely limits crop productivity and negatively affects the growth and physiology of capsicum (*Capsicum annuum* var. *conoide*). The present study was carried out during 2023–2024 at the Department of Biotechnology, Baba Ghulam Shah Badshah University, Rajouri, Jammu and Kashmir to evaluate the role of foliar-applied methyl jasmonate (MeJA, 25 and 50 µM) in improving drought tolerance. Drought significantly reduced growth, biomass, yield traits, photosynthetic pigments, and induced oxidative damage (H_2O_2 and MDA accumulation). MeJA application, particularly at 25 µM, alleviated these effects by enhancing growth, restoring pigment content, boosting antioxidant enzymes (CAT and SOD), improving protein levels, regulating elemental balance (C, Ca, K), and partially recovering stomatal traits. Statistical analysis confirmed the significance of these improvements. Overall, low-dose MeJA foliar spray effectively enhances drought resilience in *C. annuum* var. *conoide* under water-deficit conditions.

Keywords: Antioxidant defense, Drought resilience, Foliar spray, Stomatal regulation, Water-deficit conditions

Capsicum (*Capsicum annuum* L.), commonly known as sweet pepper, is an economically significant crop cultivated extensively in both temperate and tropical regions, particularly in the Mediterranean (Ballesteros *et al.* 2024). Belonging to the Solanaceae family, it is highly valued for its nutritional and culinary importance, as it provides essential vitamins, antioxidants, and other bioactive compounds that contribute to human health (Soto *et al.* 2024). Beyond its role as a staple vegetable, sweet pepper also holds considerable relevance in the agricultural economy and international trade. However, like many crops, it is highly vulnerable to environmental constraints, with drought representing one of the most severe abiotic stress factors affecting both yield and fruit quality. This challenge is particularly critical in Mediterranean regions, where long, hot summers and irregular rainfall are common (Yavasli and Erlat 2023).

In capsicum, drought stress leads to severe physiological impairments, including reduced photosynthesis, limited nutrient uptake, stunted growth, and yield decline (Muneer *et al.* 2024). At the cellular level, drought induces excessive generation of reactive oxygen species (ROS), disrupting redox homeostasis and damaging membranes, proteins, and organelles (Sachdev *et al.* 2021). Prolonged stress also promotes accumulation of methylglyoxal (MG), a cytotoxic glycolytic by-product that further exacerbates cellular injury (Yu *et al.* 2022). Plants counteract such damage through enzymatic defense systems, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), while glyoxalase enzymes detoxify MG and preserve cellular stability (Akbar *et al.* 2023). Additionally, plants regulate stomatal behaviour to minimise water loss, though prolonged drought still restricts root development and nutrient uptake (Nguyen *et al.* 2023).

Phytohormones play an essential role in drought adaptation by modulating stomatal closure, osmotic adjustment, and antioxidant defenses. Among them, methyl jasmonate (MeJA), a derivative of jasmonic acid, has emerged as a promising regulator of stress responses. MeJA enhances antioxidant enzyme activity, regulates stomatal function to conserve water, promotes osmolyte accumulation (e.g. proline and sugars), and activates stress-responsive genes involved in drought tolerance (Shah *et al.* 2025). It also supports root development, improving water and nutrient acquisition (Tayyab *et al.* 2020). Given the escalating challenges of drought on agricultural sustainability, this study aimed to investigate the potential of exogenous MeJA in improving drought tolerance in capsicum. By analysing its effects on growth, physiology, metabolism,

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and antioxidant defense, the work provides insights into eco-friendly approaches for mitigating drought-induced yield losses in this important crop.

MATERIALS AND METHODS

Plant material and source: The study was carried out during 2023–2024 at the Department of Biotechnology, Baba Ghulam Shah Badshah University, Rajouri (33.35° N, 74.41° E), Jammu and Kashmir. The seeds were procured from the seed repository of Division of Vegetable Science, Sher-e-Kashmir University of Agricultural Science and Technology-Jammu, Jammu and Kashmir.

Preparation of different MeJA concentrations (25µM and 50µM): A 95% (w/v) MeJA solution corresponds to 950 g/L (95 g/100 mL). Based on the molecular weight of methyl jasmonate (224.3 g/mol), molarity was calculated as: 950 g/L ÷ 224.3 g/mol = 4.21 M. Thus, the 95% solution corresponded to approximately 4.2 M MeJA. A 1 mM stock solution was prepared in autoclaved ion-free water. Working concentrations (25 µM and 50 µM) were freshly prepared from the stock using the dilution formula $M_1V_1 = M_2V_2$.

Drought treatment: The plants were grown under optimal conditions and then exposed to severe drought by maintaining soil moisture at 30% field capacity (FC) for five days, while control plants were kept at 100% FC. Soil moisture was regularly monitored using a TRIME-EZ/-IT to ensure uniform stress levels.

Treatment pattern and experimental design: Surface-sterilised seeds of capsicum were sown in pots and transplanted after 25 days after sowing (DAS) into 25 cm × 25 cm earthen pots (four plants/pot) with recommended NPK. At 30 days after transplanting (DAT), plants were sprayed with MeJA (J1, 25 or J2, 50 µM) and exposed to drought, while controls were well-watered. Samples were collected at 55 DAT for growth, physiological, and biochemical analyses. The treatments included under control condition (C): C + J1, C + J2; and under drought conditions (D): D+ J1 and D + J2, were maintained at 25/18°C day/night temperature.

Sampling schedule: To analyse the effect of MeJA on growth and physiological activities, sampling was done five days after all treatments. However, hydrogen peroxide content was done quickly after all treatments. Yield characteristics were evaluated about post 80 days after sown. The fresh leaf samples were frozen and stored at 20°C. Then, biochemical evaluation of different parameters was carried out.

Growth data: Root and shoot length: The root-shoot length defines the distance the plant must grow from the root tip to its highest growing point on the central axis. To prevent desiccation, plants were gently uprooted, cleaned, and then kept on wet filter papers. The length of the roots and shoots was measured and recorded using a centimeter measuring scale (Rehman *et al.* 2019).

Dry and fresh weight: Plants were carefully uprooted, properly washed to eliminate soil, and weighed. Balance was used to determine fresh weight. The plants were dried in a hot air oven at 80°C until a consistent weight was reached, and their dry mass was determined (Rocha *et al.* 2011).

Chlorophyll content estimation: To estimate the chlorophyll content, 1 g of fresh leaves is finely ground using a pestle and mortar with 4 mL of 80% acetone. The homogenate is then centrifuged at 1500 × g for 20 min at 4°C, and the supernatant is collected for chlorophyll and carotenoid quantification. The absorbance of the supernatant is measured at 645 nm and 663 nm using a spectrophotometer. The chlorophyll content was then calculated using specific equations and expressed as mg/g of fresh weight (mg/g fr. wt.) (Arnon 1949).

Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Analysis (EDAX): SEM and EDAX analyses were performed according to Zaid *et al.* (2022). Five days after treatment, leaves were rinsed with PBS and 1 mm × 3 mm sections adjacent to the midrib were fixed in 3% glutaraldehyde (*p*H 7.2) for 2–4 h at room temperature, then stored at 4°C. Samples were washed in 0.1 M PBS, post-fixed in osmium tetroxide (1 h), rinsed, and dehydrated through a graded ethanol series (25–100%). Dried samples were examined under SEM to assess stomatal size, density, and aperture from micrographs. Elemental composition (Ca, O–K, and C) was analysed using EDAX attached to SEM, and elemental weight percentages (wt%) were calculated from characteristic X-ray peak intensities using EDAX software.

Lipid peroxidation content: Lipid peroxidation was estimated by the thiobarbituric acid reactive substances (TBARS) method (Dhindsa and Matowe 1981). Leaf tissues were homogenised in 0.25% thiobarbituric acid (TBA) in 10% Trichloroacetic acid (TCA), heated at 95°C, cooled on ice, and centrifuged at 10,000 × g for 10 min. To 1 mL of supernatant, 4 mL of 20% TCA containing 0.5% TBA was added. Absorbance was read at 532 nm and corrected at 600 nm. TBARS content was calculated using the extinction coefficient 155/mM/cm.

Hydrogen peroxide (H_2O_2) content determination: H_2O_2 content was determined as per Okuda *et al.* (2002). Fresh leaves were homogenised in chilled 200 mM perchloric acid and centrifuged at 1300 × g for 10 min. The supernatant was neutralised with 4 M KOH, and precipitated potassium perchlorate was removed by centrifugation. The 1.5 mL reaction mixture contained 400 µL of 12.5 mM 3-(dimethylamino) benzoic acid in 0.375 M phosphate buffer (*p*H 6.5), 80 µL of 3-methyl-2-benzothiazoline hydrazone, 1 mL eluate, and 20 µL peroxidase (0.25 units). Absorbance was recorded at 590 nm, and H_2O_2 quantified using a standard curve (Grossmann *et al.* 2001).

Catalase (CAT) assay: CAT activity was determined following Aebi (1984). Leaf tissue was homogenised in phosphate buffer (*p*H 7.3) containing EDTA, Triton X-100, and PVP, and centrifuged at 13,280 × g for 25 min at 4°C. The reaction mixture (phosphate buffer, enzyme extract, H_2O_2, and EDTA) was incubated for 5 min, and the decrease in absorbance at 240 nm was recorded. Enzyme activity was calculated using $\varepsilon = 0.036$/mM/cm and expressed as

μmol H_2O_2 decomposed/min.

Superoxide Dismutase (SOD) assay: SOD activity was assayed following Dhindsa and Matowe (1981). The reaction mixture containing sodium phosphate buffer (*p*H 7.5), L-methionine, NBT, riboflavin, EDTA, enzyme extract, and distilled water was illuminated under a 15 W fluorescent lamp at 28°C. Absorbance was recorded at 560 nm against a non-irradiated control. One unit of SOD activity was defined as the amount of enzyme causing 50% inhibition of NBT photoreduction, as described by Naoghare *et al.* (2009).

Estimation of protein concentration: The protein content of leaf extracts was estimated using the method of Lowry *et al.* (1951). Leaf tissue was homogenised in phosphate buffer and centrifuged, and the supernatant was used for analysis. An aliquot (0.1 mL) was mixed with 1 mL alkaline copper reagent and incubated for 10 min at room temperature. Then, 0.1 mL Folin-Ciocalteu reagent was added, followed by 25 min incubation in the dark. Absorbance was measured at 750 nm, and protein concentration was determined using a bovine serum albumin (BSA) standard curve.

Statistical analysis: Data were analysed using GraphPad Prism software. One-way analysis of variance (ANOVA) was performed to determine the statistical significance of differences among the treatment groups. A $p<0.001$ was considered highly significant, indicating that the observed variations were unlikely to have occurred by chance and reflected genuine treatment effects.

RESULTS AND DISCUSSION

Growth parameters: Root, shoot, biomass, and reproductive traits: Drought stress significantly reduced growth and yield traits in capsicum (Table 1). Shoot length declined by 31.7%, while MeJA application improved recovery, with J1 and J2 increasing by 31.9% and 21.4%, respectively (Fig. 1a). Root length decreased by 13.7% under drought, but J1 and J2 enhanced it by 27.3% and 11.5% (Fig. 1d). Fresh weight dropped by 17.7%, whereas J1 and J2 increased it by 33.7% and 9.6%, respectively (Fig. 1b). Dry weight declined by 10.6%, yet J1 improved it by 60.3% and J2 by 33.8% (Fig. 1e). Flower count decreased by 41.0% under drought while J1 and J2 enhanced it by 46.0% and 38.5%, respectively (Fig. 1c). Fruit count was reduced by 25.0%, but J1 and J2 improved it by 33.3% and 8.3%, respectively (Fig. 1f).

Table 1 Mean ± SD of physiological, biochemical, anatomical, and elemental parameters of plants under control and drought conditions with jasmonate treatments

Parameters	Control	C + J1	C + J2	Drought	D + J1	D + J2
Shoot length	6.83 ± 0.76^{b}	9.00 ± 1.00^{a}	5.67 ± 0.58^{bc}	4.67 ± 1.15^{c}	5.33 ± 0.58^{bc}	4.00 ± 0.70^{c}
Root length	34.00 ± 1.00^{b}	37.33 ± 1.53^{a}	32.67 ± 0.58^{b}	29.33 ± 1.53^{c}	31.00 ± 1.00^{bc}	27.67 ± 1.53^{c}
Fresh weight	18.17 ± 1.04^{b}	20.00 ± 1.00^{a}	18.00 ± 1.00^{b}	14.97 ± 0.55^{c}	16.40 ± 0.62b^{c}	15.23 ± 1.00^{c}
Dry weight	3.30 ± 0.30^{b}	3.80 ± 0.10^{a}	2.63 ± 0.50^{c}	2.37 ± 0.15^{c}	3.17 ± 0.21^{b}	2.73 ± 0.21^{c}
Flower count	7.33 ± 1.53^{b}	10.00 ± 1.00^{a}	6.00 ± 1.73^{bc}	4.33 ± 0.58^{c}	6.33 ± 0.58^{b}	5.33 ± 0.58^{bc}
Fruit count	5.33 ± 0.58^{b}	8.00 ± 1.00^{a}	5.00 ± 1.00^{b}	4.00 ± 0.00^{c}	5.33 ± 0.58^{b}	4.33 ± 0.58^{bc}
Lipid peroxidation	0.43 ± 0.02^{b}	0.34 ± 0.05^{c}	0.42 ± 0.02^{b}	0.91 ± 0.08^{a}	0.53 ± 0.02^{b}	0.60 ± 0.03^{b}
H_2O_2 level	0.31 ± 0.02^{c}	0.26 ± 0.01^{c}	0.23 ± 0.11^{c}	0.93 ± 0.05^{a}	0.43 ± 0.02^{b}	0.59 ± 0.02^{b}
Chlorophyll a	1.62 ± 0.04^{b}	1.79 ± 0.02^{a}	1.59 ± 0.06^{b}	0.87 ± 0.08^{c}	1.29 ± 0.04^{bc}	1.23 ± 0.05^{bc}
Chlorophyll b	0.90 ± 0.02^{a}	0.90 ± 0.01^{a}	0.86 ± 0.02^{ab}	0.86 ± 0.02^{ab}	0.77 ± 0.08^{bc}	0.64 ± 0.03^{c}
Total chlorophyll	2.52 ± 0.03^{b}	2.69 ± 0.01^{a}	2.69 ± 0.01^{a}	1.45 ± 0.01^{c}	2.04 ± 0.01^{bc}	1.87 ± 0.01^{bc}
Carotenoid content	2.07 ± 0.17^{b}	2.30 ± 0.06^{a}	2.19 ± 0.01^{ab}	1.37 ± 0.02^{c}	1.84 ± 0.06^{bc}	1.59 ± 0.06^{c}
CAT activity	1.22 ± 0.04^{c}	2.59 ± 0.02^{b}	2.23 ± 0.02^{bc}	2.04 ± 0.06^{bc}	2.72 ± 0.01^{a}	2.37 ± 0.10^{b}
SOD activity	0.80 ± 0.09^{c}	1.59 ± 0.06^{b}	1.58 ± 0.19^{b}	1.74 ± 0.02^{b}	2.66 ± 0.11^{a}	2.44 ± 0.11^{a}
Protein concentration	0.21 ± 0.02^{b}	0.24 ± 0.01^{a}	0.22 ± 0.02^{b}	0.15 ± 0.01^{c}	0.18 ± 0.01^{bc}	0.16 ± 0.00^{c}
Stomatal density	11.67 ± 0.58^{c}	9.33 ± 0.58^{c}	9.00 ± 2.00^{c}	20.00 ± 2.00^{a}	15.00 ± 1.00^{b}	12.00 ± 2.00^{bc}
Stomatal dimension (length)	15.6 ± 0.95^{a}	13.34 ± 0.47^{b}	12.26 ± 0.23^{b}	10.80 ± 0.26^{c}	7.52 ± 0.50^{c}	4.41 ± 0.03^{d}
Stomatal dimension (width)	10.24 ± 1.03^{a}	5.03 ± 0.91^{b}	3.56 ± 0.11^{b}	5.69 ± 0.99^{c}	6.27 ± 1.49^{d}	2.46 ± 0.09^{e}
Calcium weight (%)	0.48 ± 0.02^{c}	0.51 ± 0.03^{c}	0.58 ± 0.02^{b}	0.88 ± 0.00^{a}	0.89 ± 0.00^{a}	0.93 ± 0.13^{a}
Oxygen weight (%)	34.73 ± 0.40^{a}	35.08 ± 0.54^{a}	33.56 ± 0.41^{b}	30.90 ± 0.72^{c}	32.25 ± 0.16^{bc}	30.14 ± 0.06^{c}
Carbon weight (%)	55.90 ± 0.40^{a}	56.18 ± 0.17^{a}	56.17 ± 0.42^{a}	51.15 ± 1.79^{b}	49.40 ± 0.06^{bc}	48.55 ± 0.38^{c}
Potassium weight (%)	3.88 ± 0.11^{a}	3.47 ± 0.06^{b}	3.05 ± 0.04^{c}	2.84 ± 0.16^{c}	2.74 ± 0.23^{c}	2.51 ± 0.16^{c}

C, Control condition; D, Drought condition; J1, Methyl jasmonate @25 μM; J2, Methyl jasmonate @50 μM; SD, Standard deviation; CAT, Catalase; SOD, Superoxide dismutase. Mean separation was performed using the LSD test at $p\leq0.05$. Values are mean ± SD.

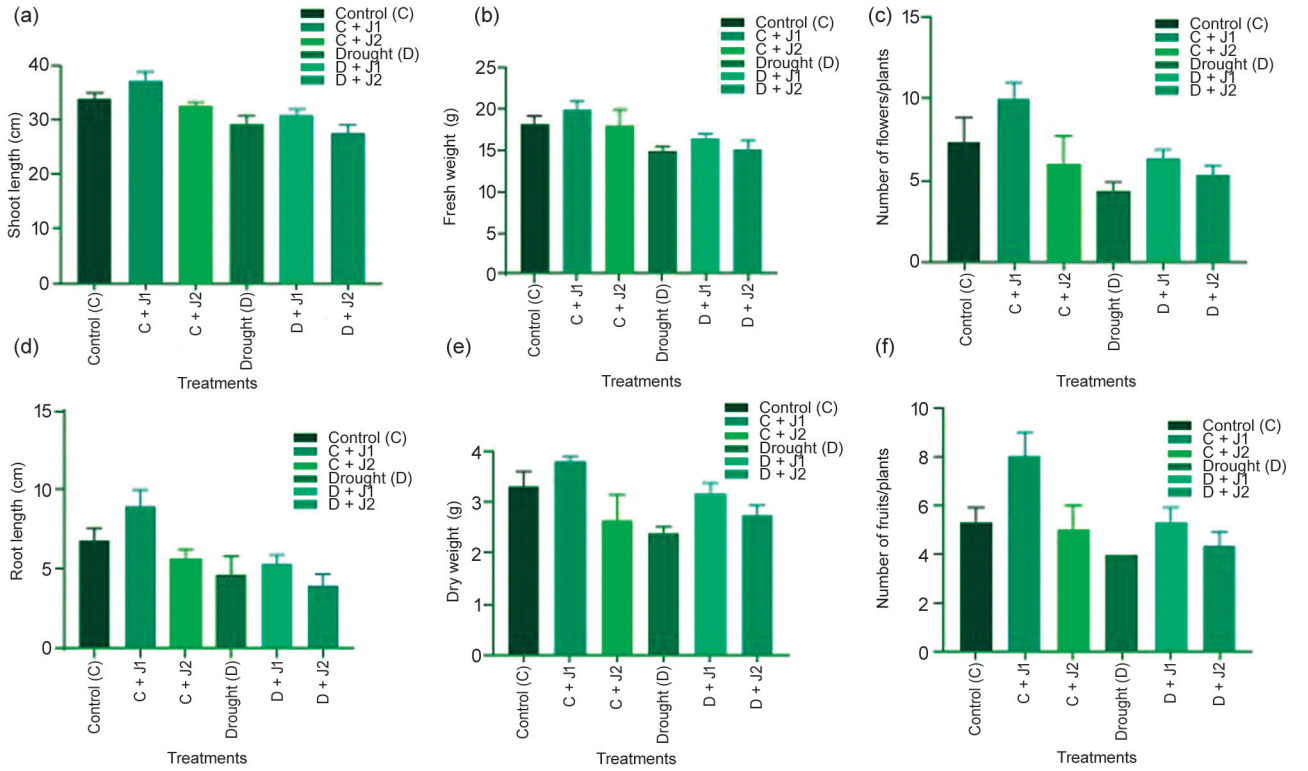

Fig. 1 Effect of drought stress and MeJA treatments on shoot length, root length, fresh weight, dry weight, flower count, and fruit count.
C, Control condition; D, Drought condition; J1, Methyl jasmonate @25 µM; J2, Methyl jasmonate @50 µM.

MeJA markedly alleviated drought-induced reductions in shoot and root length, biomass, flowering, and fruiting of capsicum. Similar growth declines under drought have been reported in capsicum cultivars, with 20.99–53.71% reductions in shoot and root length (Wubetie *et al.* 2023). Biomass losses are also well documented; Krishna (2018) observed significant decreases in fresh and dry weights. In our study, drought reduced fresh and dry weights by 17.7% and 10.6%, respectively, whereas MeJA (J1) increased them by 33.7% and 60.3%, respectively. Comparable biomass recovery with MeJA has been noted in *Impatiens walleriana* and maize (Nimrah *et al.* 2020), highlighting its growth-promoting role under stress.

Drought also reduced flower and fruit numbers, consistent with reports in tomato (Grozeva and Ganeva *et al.* 2024). MeJA (J1) restored these reproductive traits, similar to findings in *Citrus*. Together with evidence from other crops (Molla *et al.* 2023), these results confirmed MeJA as an effective regulator for improving drought tolerance and productivity.

Chlorophyll and carotenoid content: Drought stress markedly reduced chlorophyll and carotenoid contents in capsicum. In controls, chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids were 1.62, 0.90, 2.52, and 2.07 mg/g FW, respectively. Under drought, chlorophyll a fell by 46% (0.87 mg/g FW), chlorophyll b by 34% (0.59 mg/g FW), total chlorophyll by 42% (1.45 mg/g FW) and carotenoids by 34% (1.37 mg/g FW) (Fig. 2). MeJA mitigated these effects. D + J1 increased chlorophyll a by 47% (1.29 mg/g FW), chlorophyll b by 30% (0.77 mg/g FW), total chlorophyll by 41% (2.04 mg/g FW), and carotenoids by 34% (1.84 mg/g FW). D + J2 showed moderate recovery: chlorophyll a rose by 41% (1.23 mg/g FW), chlorophyll b by 9% (0.64 mg/g FW), total chlorophyll by 29% (1.87 mg/g FW), and carotenoids by 16% (1.59 mg/g FW) (Table 1). Overall, drought significantly suppressed pigment content, while MeJA, particularly J1, promoted partial recovery.

Drought markedly reduced photosynthetic pigments, consistent with reports in moong bean and bermuda grass (Noor *et al.* 2024). Declining chlorophyll under water deficit reflects impaired photosynthesis, a common stress response. MeJA improved chlorophyll a, b, and total chlorophyll under drought. Similar enhancements have been observed in *Portulaca oleracea* (Wang *et al.* 2024) and *Allium tuberosum* (Ma *et al.* 2025). Carotenoids declined by 33.9% under drought but partially recovered with J1 (11.1% increase), whereas J2 showed a slight reduction (9.9%).

Oxidative stress and protein content: Drought stress markedly increased oxidative damage in capsicum. H_2O_2 levels rose nearly 3-fold compared to control, while MeJA treatments reduced them by 2.1-fold (J1) and 1.6-fold (J2) (Fig. 3a). Lipid peroxidation, measured as MDA, also doubled under drought, but declined by 1.7-fold with J1 and 1.5-fold with J2 (Fig. 3b). In contrast, drought reduced total protein concentration by ~32%, whereas J1 and J2 enhanced recovery, showing 1.2-fold and 1.1-fold increases, respectively (Fig. 3c).

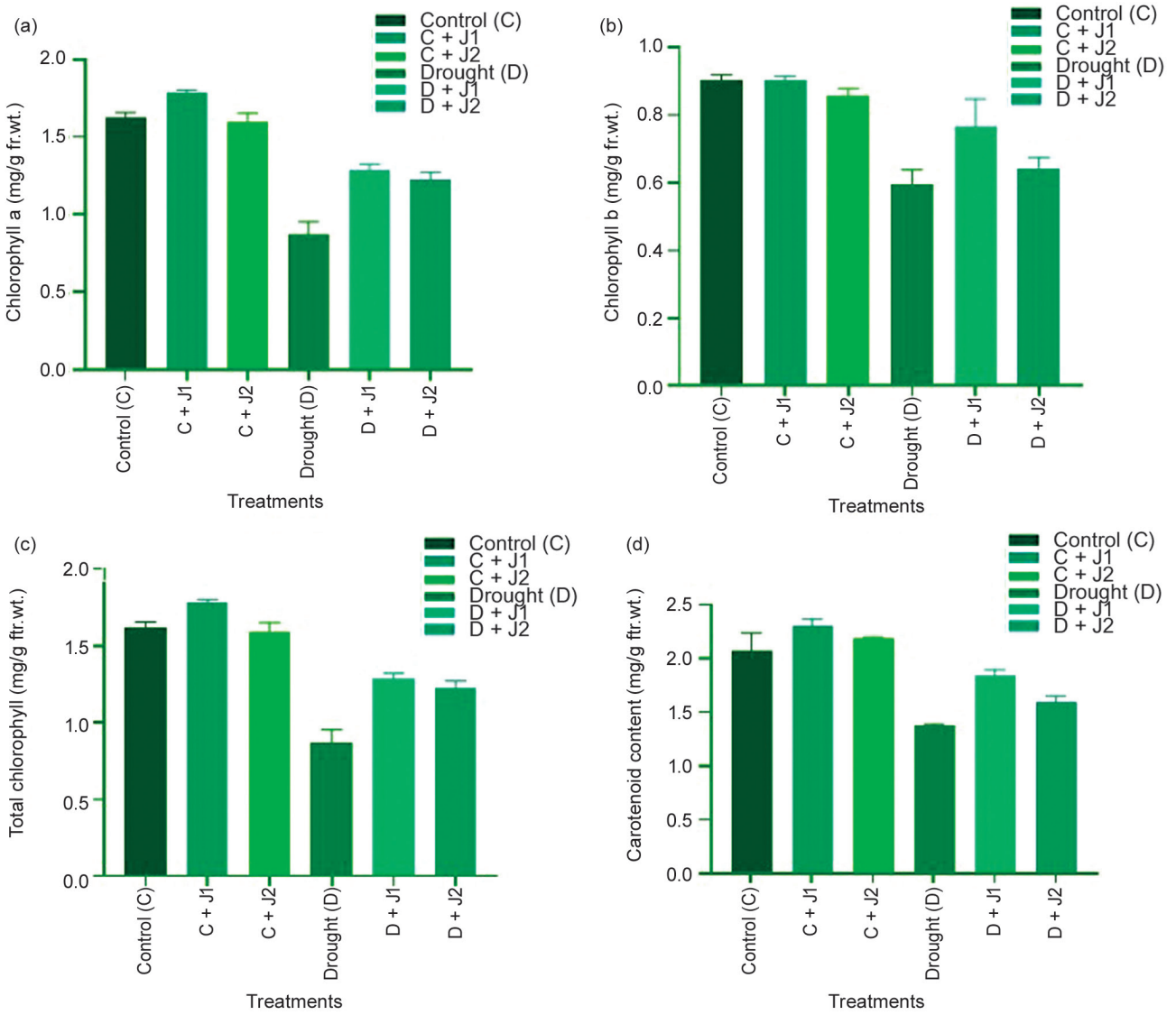

Fig. 2 (a) Chlorophyll a, (b) Chlorophyll b, (c) Total chlorophyll, and (d) Carotenoid content under different treatments. C, Control condition; D, Drought condition; J1, Methyl jasmonate @25 µM; J2, Methyl jasmonate @50 µM.

Drought significantly increased oxidative stress markers, with H_2O_2 rising nearly threefold and MDA more than doubling compared to control plants. Similar increases have been reported in rice and *Cenchrus americanus* (Samanta and Roychoudhary 2025). Protein content declined by ~32%, consistent with findings in maize (Huang *et al.* 2022) and wheat (Khan *et al.* 2024) indicating impaired protein synthesis under drought.

MeJA application mitigated oxidative damage, reducing H_2O_2 by 2.1-fold and MDA by 1.7-fold compared to drought-stressed plants. Similar protective effects were observed in *Impatiens walleriana* and *Phaseolus vulgaris* (Ghoname *et al.* 2023), highlighting its role in membrane protection and redox regulation.

Antioxidant enzyme activity: To evaluate the antioxidant defense response, CAT and SOD activities were measured. CAT activity increased 1.8-fold under drought stress relative to control, and further rose with MeJA, showing 2.1-fold (J1) and 1.9-fold (J2) increases (Fig. 4a). Similarly, SOD activity was 1.9-fold higher under drought, with J1 enhancing it to 2.0-fold and J2 to 1.5-fold compared to drought-stressed plants (Fig. 4b) (Table 1).

CAT and SOD activities increased significantly under drought and were further enhanced by MeJA application. Similar antioxidant upregulation has been reported in *Vicia faba* and *Pistacia khinjuk* (Kesawat *et al.* 2023). Exogenous MeJA further strengthened antioxidant defenses, increasing SOD and CAT activities in *Vitis vinifera* (Guihua *et al.* 2024).

Stomatal density and dimensions: Stomatal density and dimensions were analysed using SEM to evaluate transpiration regulation under drought and MeJA treatments. Drought stress reduced stomatal density from 18.67 (control) to 11.67 stomata/20 µm² (Fig. 5a, d). MeJA further lowered density to 9.33 (J1) and 8.33 (J2) stomata/20 µm² (Fig. 5b, c, e, f), suggesting improved water-use efficiency. Drought also caused a 30% reduction in stomatal length.

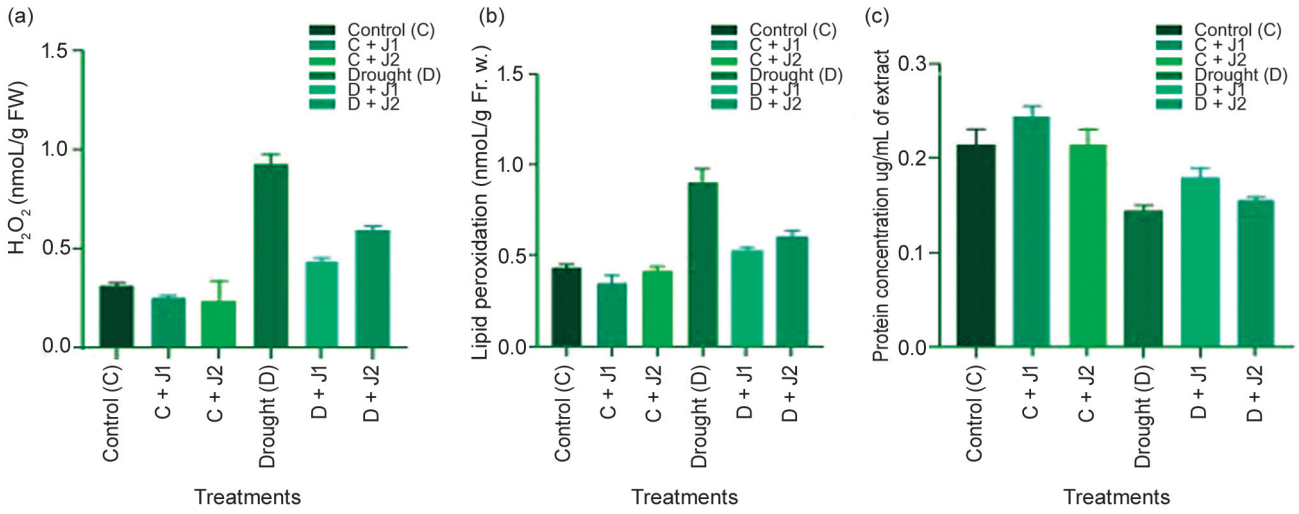

Fig. 3 Effect of treatments on (a) H_2O_2 levels; (b) Lipid peroxidation; and (c) Protein concentration.
C, Control condition; D, Drought condition; J1, Methyl jasmonate @25 µM; J2, Methyl jasmonate @50 µM.

J1 recovered 12.5% of this loss, while J2 exacerbated it by 51.8%. Stomatal width declined by 50% under drought, but J1 and J2 treatments partially restored it, increasing by 23.7% and 6.7%, respectively (Fig. 5a–f, Supplementary Fig. 1, Table 1).

MeJA significantly modified stomatal traits under drought, contributing to water conservation. Drought reduced stomatal density (11.67 stomata/20 µm²), as also reported in *Ulmus szechuanica* (Yaqin *et al.* 2022). MeJA further lowered density to 9.33 (J1) and 8.33 (J2), similar to findings in *Arabidopsis thaliana* (Xiao *et al.* 2018) and *Cenchrus americanus* (Ndiaye *et al.* 2022).

Elemental analysis: SEM-EDAX analysis revealed significant shifts in elemental composition under drought and MeJA treatments (Supplementary Fig. 2). Carbon content decreased by 7.9% under drought, with J1 increasing it by 1.5%, while J2 caused a further 1.3% decrease. Oxygen declined by 10.9% under drought; J1 improved it by 4.4%, whereas J2 reduced it by 7.3%. Calcium increased by 28.3% under drought, with J1 and J2 further raising it by 2.2% and 5.7%, respectively. Potassium dropped by 26.4% under drought, with J1 slightly improving it by 2.5%, while J2 led to an additional 8.9% reduction. Stomatal length declined by 30% under drought (Hatice *et al.* 2023). J1 partially restored length (12.5%), whereas J2 caused a further reduction, indicating dose-dependent effects. Similar MeJA-induced reductions in stomatal aperture were noted in *Arabidopsis* (Yan *et al.* 2014).

This study demonstrated that foliar application of MeJA enhanced drought tolerance in capsicum by improving growth, photosynthetic pigments, and antioxidant defense. Among the tested doses, 25 µM (J1) was most effective in reducing oxidative damage (H_2O_2 and MDA) and promoting recovery of biomass and physiological traits. These findings

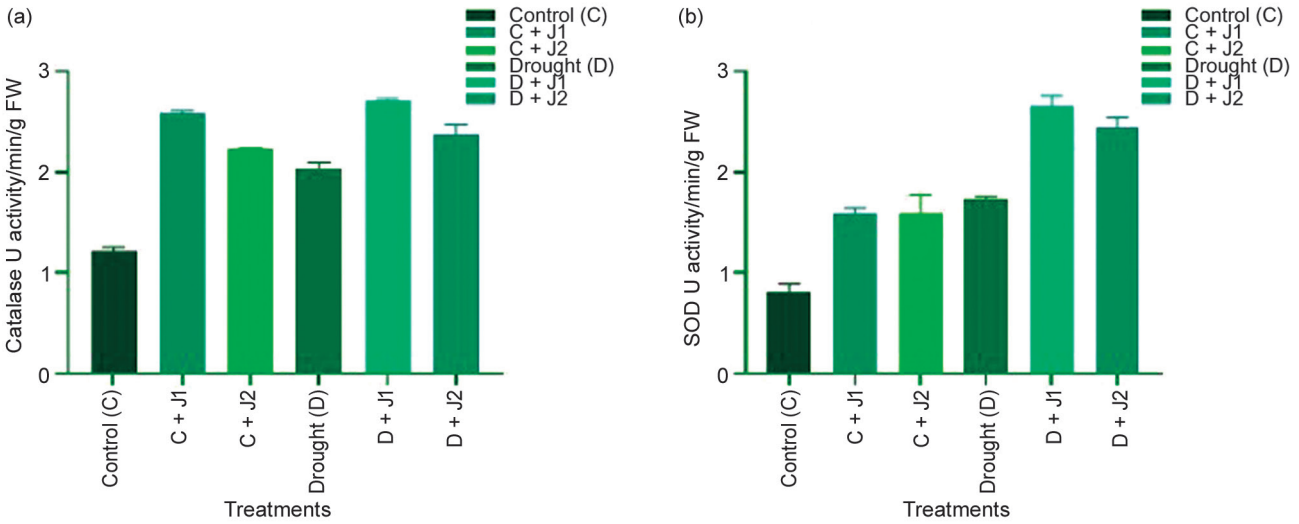

Fig. 4 Effect of treatment on CAT and SOD activities.
C, Control condition; D, Drought condition; J1, Methyl jasmonate @25 µM; J2, Methyl jasmonate @50 µM; SOD, Superoxide dismutase.

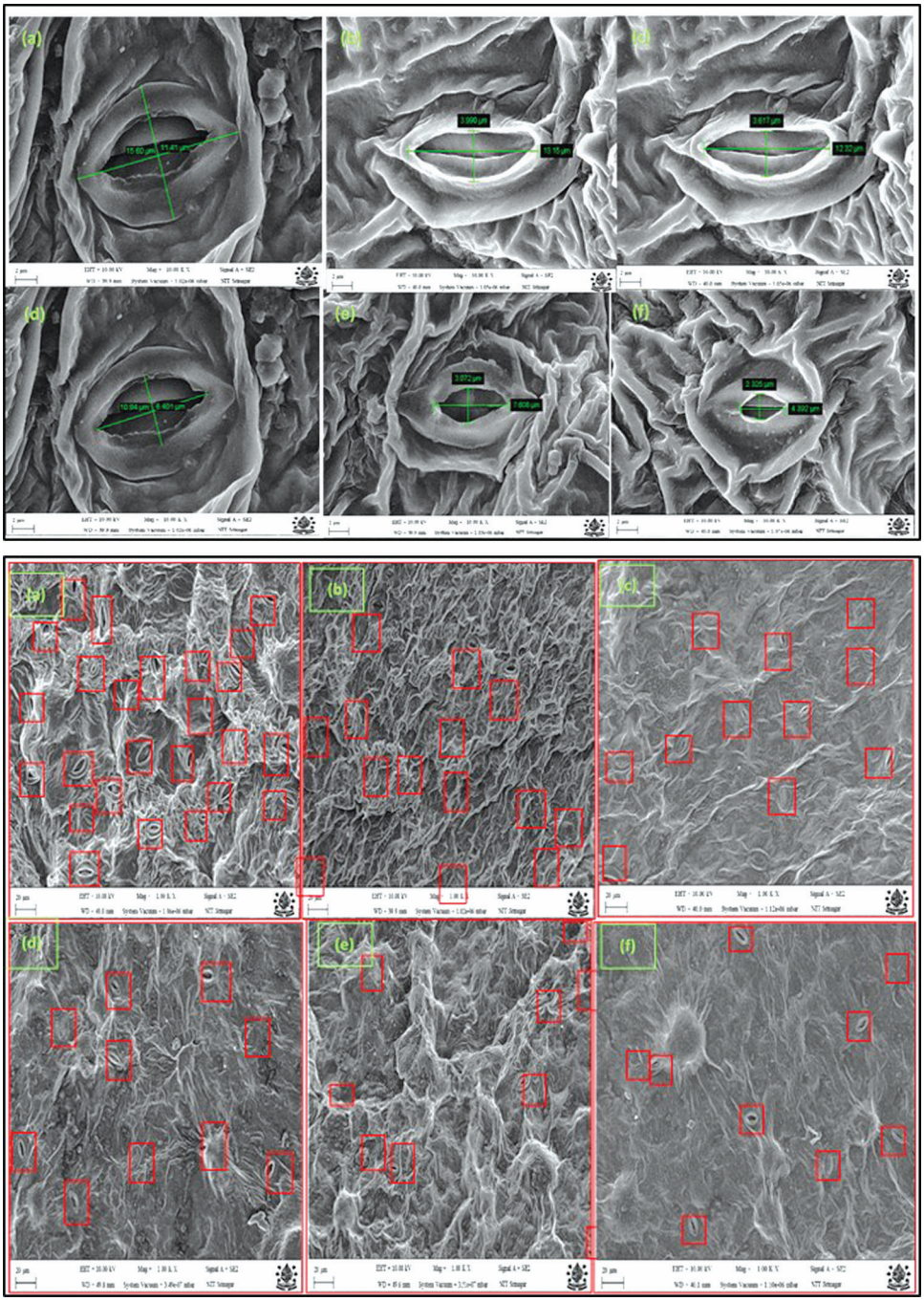

Fig. 5 Stomatal density under different conditions.
(a) Control, (b) Control + J1, (c) Control + J2, (d) Drought, (e) Drought + J1, and (f) Drought + J2. Furthermore Stomatal Dimensions under different conditions. (a) Control, (b) Control + J1, (c) Control + J2, (d) Drought, (e) Drought + J1, and (f) Drought + J2.

highlighted the role of MeJA in strengthening antioxidant activity and stress adaptation, suggesting its potential as an eco-friendly strategy to improve drought resilience in capsicum and other crops under changing climatic conditions.

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