

Foliar Application of Salicylic Acid and Jasmonic Acid Enhances Drought Tolerance in Sesame (*Sesamum indicum* L.) by Modulating Antioxidant Defense, Photosynthetic Efficiency and Seed Yield

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Abstract

Drought stress poses a significant threat to sesame (*Sesamum indicum* L.) productivity, yet the potential of plant growth regulators (PGRs) to mitigate its effects remains underexplored. This study investigated the impacts of foliar-applied salicylic acid (SA) and jasmonic acid (JA) on sesame under varying drought intensities over two growing seasons (2022–2023). A split-plot design was employed with three irrigation regimes (25%, 50%, and 75% soil moisture depletion) and seven PGR treatments (SA at 0.5, 1, and 1.5 mM; JA at 50, 100, and 150 μ M; and a control). Severe drought increased catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) activities by up to 10%, alongside elevated ion leakage (49.88%) and malondialdehyde (MDA) (10.59 μ mol g⁻¹ FW), while reducing relative water content (RWC) to 57.32%. SA at 1.5 mM enhanced CAT (1.66 μ mol mg⁻¹ protein min⁻¹), chlorophyll a (1.80 mg g⁻¹ FW), carotenoids (0.450 mg g⁻¹ FW), and seed yield by 8% (752 kg ha⁻¹), while JA at 100 μ M reduced ion leakage to 44.05% and boosted proline to 1.81 μ mol g⁻¹ FW under 75% depletion. Both PGRs mitigated H₂O₂ accumulation, with SA 1.5 mM achieving the lowest level (1.71 mg g⁻¹ FW). These findings highlight SA's role in photosynthetic protection and JA's contribution to osmoprotection, offering concentration-specific strategies to enhance sesame resilience and productivity in drought-prone environments.

Introduction

Sesame (*Sesamum indicum* L.), one of the oldest oilseed crops known to humanity, is a cornerstone of agriculture in arid and semi-arid regions due to its remarkable adaptability and nutritional richness. With an oil content ranging from 42–56% and protein levels between 17% and 32%, sesame seeds are prized for their high-quality lipids, proteins, and essential minerals, including calcium, phosphorus, potassium, and iron (Pal et al. 2020). The predominance of unsaturated fatty acids such as linoleic and oleic acids in its oil, further underscores its value in food, pharmaceutical, and industrial applications (Jain 2020). Despite its inherent resilience to water-limited conditions, sesame faces escalating challenges from drought stress, a pervasive threat to global crop production exacerbated by climate change (Seleiman et al., 2021; Hewedy et al., 2023). Drought disrupts critical physiological processes such as photosynthesis, water homeostasis, and oxidative balance resulting in diminished vegetative growth, impaired reproductive success, and reduced seed yield, particularly in oilseed crops like sesame (Fang et al. 2023; Arif et al. 2020).

The deleterious effects of drought are mediated through the overproduction of reactive oxygen species (ROS), such as hydrogen peroxide (H₂O₂), which trigger lipid peroxidation, elevate malondialdehyde (MDA) levels, and increase ion leakage, compromising membrane integrity (Haghighi and Saharkhiz 2022). Plants counter these stresses by activating antioxidant defenses, including enzymes like catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), which scavenge ROS, and by accumulating osmoprotectants such as proline to maintain cellular turgor (Abeed et al. 2021; Hayat et al. 2012). However, under severe water deficits, these intrinsic mechanisms often fall short, necessitating innovative strategies to bolster plant resilience and sustain productivity.

Plant growth regulators (PGRs), notably salicylic acid (SA) and jasmonic acid (JA), have gained prominence as effective tools for enhancing plant tolerance to abiotic stresses. SA, a phenolic compound, modulates stress-responsive gene expression, stabilizes photosynthetic pigments (chlorophyll a, b, and carotenoids), and strengthens antioxidant systems, reducing oxidative damage markers like MDA and ion leakage under drought conditions (Zhang and Li 2019; Pai and Sharma, 2024). JA, a lipid-derived signaling molecule, enhances drought tolerance by upregulating antioxidant enzyme activities, promoting proline biosynthesis, and improving photosynthetic efficiency through stomatal regulation and carotenoid accumulation (Ruan et al. 2019; Iqbal et al. 2022). These PGRs collectively mitigate the adverse impacts of water scarcity by optimizing physiological and biochemical responses, potentially sustaining seed yield even under stress (Mabudi et al. 2022; Nigam et al. 2022).

While the beneficial effects of SA and JA have been documented in various crops, their application in sesame under drought stress remains underexplored. Preliminary evidence suggests that foliar application of these PGRs can alleviate drought-induced damage in oilseed species by enhancing photosynthetic parameters, reducing H₂O₂-mediated oxidative stress, and improving yield components (Farhangi-Abriz and Ghassemi-Golezani 2021; Mohi-Ud-Din et al. 2021). However, the efficacy of SA and JA likely varies with concentration, application timing, and drought intensity, raising questions about their optimal use in sesame. Given the crop's economic significance and its cultivation in water-scarce regions where drought is projected to intensify due to climatic shifts understanding these dynamics is imperative (Anderson et al. 2020; Kumar et al. 2022)

This study investigates the potential of foliar-applied SA and JA to mitigate drought stress in sesame, focusing on their effects on photosynthesis, antioxidant enzyme activities (CAT, POD, APX), proline accumulation, carotenoids, H_2O_2 levels, ion leakage, MDA, relative water content (RWC), and seed yield. By examining these parameters across a gradient of drought severities (25%, 50%, and 75% soil moisture depletion) and PGR concentrations (SA at 0.5, 1, and 1.5 mM; JA at 50, 100, and 150 μ M), the research seeks to elucidate how these compounds enhance sesame resilience and to identify practical concentrations for field application. Such insights are critical for developing sustainable agronomic strategies to safeguard sesame production in drought-prone environments, addressing both current challenges and future threats to food security posed by water scarcity.

Materials and Methods

Experimental Site and Design

This study was conducted during the 2022 and 2023 growing seasons at the experimental farm of the Fars Agricultural Research Center, Fasa, Iran, located at 54°15' E longitude, 29°24' N latitude, and 1370 m above sea level. The region features a semi-arid climate with an average annual rainfall of 250 mm and a mean temperature of 18°C. The experiment was designed as a split-plot arrangement within a randomized complete block framework with three replications. The main plot factor consisted of three irrigation regimes based on soil moisture depletion levels: irrigation after 25% (mild stress), 50% (moderate stress), and 75% (severe stress) depletion of available soil water. The subplot factor included seven foliar application treatments: salicylic acid (SA) at 0.5, 1, and 1.5 mM; jasmonic acid (JA) at 50, 100, and 150 μ M; and a control (distilled water). Each experimental plot measured 4 m in length and 3 m in width, containing six planting rows.

Soil Characteristics and Crop Management

Composite soil samples from the 0–30 cm depth were collected prior to planting and analyzed for physicochemical properties (Table 1). The soil was classified as loam, with a pH of 7.11–7.12, electrical conductivity (EC) of 1.21–1.22 dS m^{-1} , and organic carbon content of 0.46–0.48%. Sesame seeds (cv. Darab-1, obtained from the Fars Agricultural Research Center) were sown manually on June 5, 2022, and June 7, 2023, at a depth of 2 cm, achieving a planting density of 50 plants m^{-2} (50 cm row spacing, 4 cm intra-row spacing). To ensure uniform establishment, three seeds were planted per hill and thinned to one plant at the two-leaf stage. Soil preparation included plowing and disking, followed by the incorporation of 100 kg ha^{-1} potassium sulfate (50% K_2O) and triple superphosphate (46% P_2O_5) as basal fertilizers. Nitrogen was applied as urea (46% N) at 120 kg ha^{-1} , divided equally across three stages: seedling, stem elongation, and flowering. Manual weeding was conducted as required, and harvesting took place on October 25, 2022, and October 27, 2023.

Irrigation and Foliar Treatments

Irrigation was administered via a strip irrigation system. Soil moisture was monitored gravimetrically by sampling the root zone (0–30 cm) at the center of each plot. Field capacity (FC) and permanent wilting point (PWP) were determined using a pressure plate apparatus (FC = 24.5% and PWP = 11.2% on a volumetric basis). After two initial uniform irrigations to ensure establishment, drought treatments were applied based on the percentage depletion of available water $[(FC - PWP) \times \text{depletion level}]$. Irrigation volumes were calculated to restore soil moisture to FC for each treatment. Foliar applications of SA and JA were prepared by dissolving analytical-grade compounds (Sigma-Aldrich) in distilled water with 0.1% Tween-20 as a surfactant. Spraying occurred at three growth stages—four-leaf (20 days after sowing, DAS), stem elongation (40 DAS), and flowering (60 DAS)—using a handheld sprayer until runoff (approximately 300 L ha^{-1} per application).

Physiological and Biochemical Measurements

All measurements were performed at the flowering stage (60–65 DAS) using five randomly selected plants per plot. Fresh leaf samples were collected, immediately frozen in liquid nitrogen, and stored at -80°C for biochemical analyses unless otherwise specified.

- **Proline Content:** Quantified according to Bates et al. (1973). A 0.5 g fresh leaf sample was homogenized in 10 mL 3% sulfosalicylic acid, filtered, and reacted with ninhydrin. Absorbance was measured at 520 nm using a spectrophotometer (Shimadzu UV-1800), and proline concentration was expressed as $\mu\text{mol g}^{-1}$ fresh weight (FW) based on a standard curve (0–0.4 $\mu\text{mol mL}^{-1}$).
- **Antioxidant Enzyme Activities:** Enzyme extracts were prepared by grinding 1 g fresh leaf tissue in 3 mL of 50 mM phosphate buffer (pH 7.2) containing 1 mM EDTA, 1 mM PMSF, and 1% PVP, followed by centrifugation at 14,000 rpm for 15 min at 4°C. The supernatant was used for assays. Catalase (CAT) activity was measured by monitoring H_2O_2 decomposition at 240 nm ($\epsilon = 39.4 \text{ mM}^{-1} \text{ cm}^{-1}$) as described by Aebi (1984). Ascorbate peroxidase (APX) activity was determined by the oxidation of ascorbate at 290 nm ($\epsilon = 2.8 \text{ mM}^{-1} \text{ cm}^{-1}$), following Nakano and Asada (1981). Peroxidase (POD) activity was assessed using guaiacol at 470 nm ($\epsilon = 25.5 \text{ mM}^{-1} \text{ cm}^{-1}$) per Plewa et al. (1991). Activities were expressed as $\mu\text{mol mg}^{-1} \text{ protein min}^{-1}$, with protein content determined by the Bradford method.
- **Ion Leakage:** Measured as electrolyte leakage using a conductivity meter. Leaf discs (0.5 g) were incubated in 20 mL deionized water for 24 h, and initial conductivity (EC_1) was recorded. Samples were then boiled for 20 min, cooled, and total conductivity (EC_2) measured. Ion leakage (%) was calculated as $(\text{EC}_1/\text{EC}_2) \times 100$.
- **Malondialdehyde (MDA):** Quantified using the thiobarbituric acid (TBA) method (Heath and Packer, 1968). A 0.5 g leaf sample was homogenized in 5 mL 0.1% trichloroacetic acid (TCA), and absorbance was read at 532 and 600 nm. MDA concentration was calculated using an extinction coefficient of $155 \text{ mM}^{-1} \text{ cm}^{-1}$ and expressed as $\mu\text{mol g}^{-1}$ FW.
- **Hydrogen Peroxide (H_2O_2):** Measured according to Velikova et al. (2000). A 0.5 g leaf sample was extracted in 5 mL 0.1% TCA, mixed with 10 mM potassium phosphate buffer (pH 7.0) and 1 M KI, and absorbance was recorded at 390 nm. H_2O_2 content was expressed as mg g^{-1} FW.
- **Photosynthetic Pigments: Chlorophyll a, b, and carotenoids** were extracted from 0.2 g fresh leaves in 80% acetone and quantified spectrophotometrically (Lichtenthaler, 1987). Absorbance was measured at 663, 645, and 470 nm, with concentrations calculated as follows:
 - $\text{Chl a } (\mu\text{g mL}^{-1}) = 12.25 \times A_{663} - 2.79 \times A_{645}$
 - $\text{Chl b } (\mu\text{g mL}^{-1}) = 21.50 \times A_{645} - 5.10 \times A_{663}$
 - $\text{Carotenoids } (\mu\text{g mL}^{-1}) = (1000 \times A_{470} - 1.82 \times \text{Chl a} - 85.02 \times \text{Chl b}) / 198$
 - Results were expressed as mg g^{-1} FW.
- **Chlorophyll Fluorescence (Fv/Fm)** was measured using a Pocket PEA fluorimeter (Hansatech, UK). Leaves were dark-adapted for 15 minutes using leaf clips, and the maximum quantum yield of PSII (Fv/Fm) was recorded.
- **Relative Water Content (RWC):** Calculated as $[(\text{FW} - \text{DW}) / (\text{TW} - \text{DW})] \times 100$, where FW is fresh weight, DW is dry weight (oven-dried at 70°C for 48 h), and TW is turgid weight (after 24 h in distilled water).
- **Seed Yield:** Determined by harvesting the central four rows of each plot, drying seeds at 40°C for 48 h, and weighing them to calculate yield in kg ha^{-1} .

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) in SAS version 9.2 (SAS Institute, Cary, NC, USA). Bartlett's test confirmed variance homogeneity across years, allowing combined analysis. Treatment means were compared using Duncan's multiple range test at a 5% significance level. Interaction effects were evaluated using the L.S. Means procedure when significant.

Results

The combined analysis of variance (ANOVA) across the two growing seasons (2022 and 2023) revealed significant effects of irrigation regimes, plant growth regulators (PGRs), and their interactions on the measured physiological and biochemical traits of sesame (Tables 2 and 9). Below, the results are presented for each trait, supported by mean comparisons from Tables 3–8.

Antioxidant Enzyme Activities

Irrigation regimes, PGRs, and year significantly influenced catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) activities (Table 2). Severe drought (75% moisture depletion) increased CAT activity to $1.68 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$, a significant rise compared to $1.52 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$ at 25% depletion ($P < 0.01$, Table 3). Among PGRs, SA at 1.5 mM elicited the highest CAT activity ($1.66 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$), followed by JA at 100 μM ($1.62 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$), both surpassing the control ($1.54 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$, $P < 0.01$, Table 4). CAT activity was higher in 2022 ($1.62 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$) than in 2023 ($1.59 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$, $P < 0.01$, Table 5).

The interaction between irrigation and PGRs significantly affected POD and APX (Table 2). Under 25% depletion, POD peaked at $12.7 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$ with SA 1.5 mM, while at 75% depletion, it reached $14.8 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$ with the same treatment ($P < 0.01$, Table 6). APX activity increased by 10% and 7% at 50% and 75% depletion, respectively, with SA 1.5 mM compared to the control ($P < 0.01$, Table 6). Year $\times$ PGR interactions showed the highest POD ($14.1 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$) and APX ($10.86 \mu\text{mol mg}^{-1} \text{ protein min}^{-1}$) with SA 1.5 mM in 2022 ($P < 0.01$, Table 7).

Ion Leakage, Malondialdehyde, and Relative Water Content

Drought stress significantly elevated ion leakage and malondialdehyde (MDA) while reducing relative water content (RWC) (Table 2). At 25% depletion, JA 100 μM reduced ion leakage to 44.05%, a 3% decrease compared to the control (47.65%, $P < 0.05$, Table 6). Under 75% depletion, SA 1.5 mM lowered ion leakage to 48.07% versus 49.88% in the control ($P < 0.05$). Year $\times$ PGR interactions confirmed JA 100 μM as the most effective treatment, reducing ion leakage by 3% in both years ($P < 0.01$, Table 7).

MDA levels increased from $9.90 \mu\text{mol g}^{-1} \text{ FW}$ at 25% depletion to $10.59 \mu\text{mol g}^{-1} \text{ FW}$ at 75% depletion in 2022 ($P < 0.01$, Table 8). SA 1.5 mM and JA 100 μM minimized MDA to 9.68 and $9.65 \mu\text{mol g}^{-1} \text{ FW}$, respectively, at 25% depletion, and SA 1.5 mM reduced it by 5% at 75% depletion ($P < 0.05$, Table 6). RWC was highest at 71.38% and 67.23% under 25% and 50% depletion with SA 1.5 mM, respectively, and increased by 4% at 75% depletion compared to the control ($P < 0.01$, Table 6). Year $\times$ irrigation interactions showed a 9% higher RWC at 25% versus 75% depletion in 2022 ($P < 0.01$, Table 8).

Photosynthetic Pigments and Chlorophyll Fluorescence

Irrigation regimes and PGRs significantly affected carotenoids, chlorophyll a, chlorophyll b, and Fv/Fm (Tables 3, 4, and 9). Carotenoids increased by 9% from $0.416 \text{ mg g}^{-1} \text{ FW}$ at 25% depletion to $0.452 \text{ mg g}^{-1} \text{ FW}$ at 75% depletion ($P < 0.01$, Table 3), with SA 1.5 mM boosting it by 8% to $0.450 \text{ mg g}^{-1} \text{ FW}$ compared to the control ($0.417 \text{ mg g}^{-1} \text{ FW}$, $P < 0.01$, Table 4). Fv/Fm declined from 0.768 at 25% depletion to 0.693 at 75% depletion ($P < 0.01$, Table 3), but SA 1.5 mM maintained the highest value (0.754) across treatments ($P < 0.01$, Table 4). Chlorophyll a and b peaked at 1.80 and $0.823 \text{ mg g}^{-1} \text{ FW}$, respectively, with SA 1.5 mM ($P < 0.01$, Table 4). Year $\times$ irrigation interactions showed higher chlorophyll a ($1.85 \text{ mg g}^{-1} \text{ FW}$) and b ($0.850 \text{ mg g}^{-1} \text{ FW}$) at 25% depletion in 2022 compared to 75% depletion ($P < 0.01$, Table 8).

Proline, Hydrogen Peroxide, and Seed Yield

Proline, H_2O_2 , and seed yield were significantly influenced by irrigation, PGRs, and their interactions (Table 9). Proline accumulation rose with drought severity, reaching 1.38 and $1.81 \mu\text{mol g}^{-1} \text{ FW}$ at 25% and 75% depletion, respectively, with SA 1.5 mM ($P < 0.01$, Table 6). JA 100 μM also enhanced proline at all depletion levels ($P < 0.05$). Proline was 2% higher in 2022 ($1.38 \mu\text{mol g}^{-1} \text{ FW}$) than in 2023 ($1.09 \mu\text{mol g}^{-1} \text{ FW}$, $P < 0.01$, Table 5).

H_2O_2 levels increased from $1.88 \text{ mg g}^{-1} \text{ FW}$ at 25% depletion to $2.25 \text{ mg g}^{-1} \text{ FW}$ at 75% depletion in 2022 ($P < 0.01$, Table 8), but SA 1.5 mM reduced it to $1.71 \text{ mg g}^{-1} \text{ FW}$ across treatments ($P < 0.01$, Table 4). Seed yield declined from 752.5 kg ha^{-1} at 25% depletion to 647.8 kg ha^{-1} at 75% depletion ($P < 0.01$, Table 3). In 2022, SA at 1 and 1.5 mM increased the seed yield by 6% (739 kg ha^{-1}) and 8% (752 kg ha^{-1}), respectively, compared to the control (697 kg ha^{-1} , $P < 0.01$, Table 7). In 2023, SA 1.5 mM and JA 50 μM also enhanced yield (710 and 671 kg ha^{-1} , respectively, $P < 0.05$).

Discussion

The results of this study underscore the profound impact of drought stress on sesame physiology and the ameliorative potential of salicylic acid (SA) and jasmonic acid (JA) as foliar-applied plant growth regulators (PGRs) (Saleem et al. 2021; Zi et al. 2022).

The observed responses align with recent findings in high-impact journals, providing insights into the mechanisms underlying drought tolerance and the practical implications of PGR use in oilseed crops.

Drought-Induced Oxidative Stress and Antioxidant Responses

Severe drought (75% moisture depletion) significantly elevated catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) activities (Table 3), reflecting an adaptive response to mitigate oxidative stress caused by reactive oxygen species (ROS) accumulation. This is consistent with Abeed et al. (2021), who reported increased antioxidant enzyme activities in maize under water deficit as a mechanism to detoxify H_2O_2 and protect cellular integrity. The higher CAT activity in 2022 ($1.62 \mu\text{mol mg}^{-1} \text{protein min}^{-1}$) compared to 2023 (Table 5) may reflect inter-annual climatic variations, such as higher temperatures in 2022, which exacerbate ROS production (Hasanuzzaman et al. 2020; Karamian et al. 2020).

Foliar application of SA at 1.5 mM and JA at 100 μM significantly enhanced CAT, POD, and APX activities across all irrigation regimes (Tables 4, 6, and 7), corroborating findings by Farhangi-Abriz and Ghassemi-Golezani (2021) in soybean, where SA upregulated antioxidant gene expression under drought. The 10% and 7% increase in APX activity at 50% and 75% depletion with SA 1.5 mM (Table 6) aligns with Khan et al. (2023), who demonstrated that SA enhances ascorbate-glutathione cycle efficiency, a key ROS-scavenging pathway. Similarly, JA's efficacy at 100 μM suggests its role in activating jasmonate-responsive genes encoding antioxidant enzymes, as noted by Raza et al. (2023), reinforcing cellular defense under stress.

Membrane Stability and Water Relations

Drought stress increased ion leakage and malondialdehyde (MDA) levels, indicating membrane damage due to lipid peroxidation (Tables 6 and 8), a response well-documented in oilseed crops under water deficit (Haghighi and Saharkhiz 2022). The lowest ion leakage (44.05%) with JA 100 μM at 25% depletion and the 5% reduction in MDA with SA 1.5 mM at 75% depletion (Table 6) highlight the protective effects of these PGRs. These findings resonate with Pai and Sharma (2024), who reported that SA stabilizes membrane lipids by reducing ROS-mediated peroxidation in wheat, and Ahmad et al. (2022), who linked JA's membrane-protective role to enhanced antioxidant capacity in rice.

The significant increase in relative water content (RWC) to 71.38% and 67.23% at 25% and 50% depletion with SA 1.5 mM (Table 6) reflects improved water retention, likely due to SA-induced stomatal regulation and osmotic adjustment, as reported by Iqbal et al. (2022). The 4% increase in RWC at 75% depletion further supports SA's role in maintaining cellular hydration under severe stress, consistent with Liu et al. (2023), who noted SA's enhancement of aquaporin activity in *Arabidopsis*. JA's moderate effect on RWC (e.g., 68.37% at 25% depletion) may relate to its influence on proline metabolism rather than direct water uptake, as discussed below.

Photosynthetic Efficiency and Pigment Dynamics

Drought stress reduced chlorophyll a and b contents and Fv/Fm while increasing carotenoids by 9% at 75% depletion (Tables 3 and 8), indicating photosynthetic impairment and photoprotective adaptation. The decline in Fv/Fm from 0.768 to 0.693 (Table 3) reflects PSII damage, a common drought response noted by Khorasaninejad et al. (2018) in basil. SA 1.5 mM mitigated these effects, maintaining chlorophyll a at $1.80 \text{ mg g}^{-1} \text{FW}$, chlorophyll b at $0.823 \text{ mg g}^{-1} \text{FW}$, and Fv/Fm at 0.754 (Table 4), likely by enhancing chlorophyll biosynthesis and PSII efficiency, as evidenced by Sharma et al. (2023). The 8% increase in carotenoids with SA 1.5 mM (Table 4) aligns with Wang et al. (2022), who linked SA to carotenoid accumulation as a ROS-scavenging mechanism in tomato.

JA's moderate enhancement of carotenoids and Fv/Fm (Table 4) suggests a complementary role, possibly via upregulation of carotenoid biosynthesis genes, as reported by Raza et al. (2023) in maize. The higher pigment levels in 2022 (Table 8) may reflect optimal light conditions, amplifying drought effects and PGR responses.

Osmoprotection and Oxidative Markers

Proline accumulation increased significantly with drought, reaching $1.81 \mu\text{mol g}^{-1} \text{FW}$ at 75% depletion with SA 1.5 mM (Table 6), consistent with its role as an osmoprotectant and ROS scavenger (Hayat et al., 2012). JA 100 μM also elevated proline (e.g., 1.38

$\mu\text{mol g}^{-1}$ FW at 25% depletion), supporting Ghorbel et al. (2021), who linked JA to proline synthetase activation in barley. The 2% higher proline in 2022 (Table 5) may indicate greater stress intensity, aligning with Hasanuzzaman et al. (2020).

H_2O_2 levels rose under drought (Table 8), but SA 1.5 mM reduced it to 1.71 mg g^{-1} FW (Table 4), reflecting enhanced ROS detoxification, as noted by Khan et al. (2023). JA's lesser effect on H_2O_2 reduction may indicate a stronger role in signaling rather than direct scavenging, consistent with Ruan et al. (2019).

Seed Yield and Agronomic Implications

Seed yield declined by 14% from 752.5 kg ha^{-1} at 25% depletion to 647.8 kg ha^{-1} at 75% depletion (Table 3), reflecting drought's impact on reproductive development, as reported by Fang et al. (2023). SA at 1.5 mM increased yield by 8% in 2022 (752 kg ha^{-1} , Table 7), likely due to improved photosynthesis and water status, aligning with Mohi-Ud-Din et al. (2021) in canola. JA $50 \mu\text{M}$'s yield enhancement in 2023 (671 kg ha^{-1}) suggests a concentration-specific effect, possibly linked to proline-mediated stress tolerance (Ghorbel et al. 2021).

The differential efficacy of SA and JA highlights their complementary roles: SA excels in photosynthetic protection and water retention, while JA enhances osmoprotection and antioxidant capacity. These findings have practical implications for sesame cultivation in drought-prone regions, suggesting SA 1.5 mM and JA $100 \mu\text{M}$ as optimal treatments for sustaining yield under varying stress levels, consistent with recent agronomic advances (Liu et al. 2023; Es-sbihi et al. 2021).

Conclusion

The pronounced increase in catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) activities under severe drought (75% depletion), coupled with elevated ion leakage, malondialdehyde (MDA), and H_2O_2 levels, confirms the oxidative burden imposed by water deficit. However, SA at 1.5 mM and JA at $100 \mu\text{M}$ effectively mitigated these effects by enhancing antioxidant enzyme activities, reducing oxidative damage markers by up to 5% and 3%, respectively, and maintaining relative water content (RWC) at levels up to 71.38% under mild stress. These responses underscore the PGRs' capacity to bolster cellular defense systems, aligning with and extending recent findings in other crops. A key scientific contribution of this work lies in elucidating the differential impacts of SA and JA on photosynthetic efficiency and osmoprotection. The maintenance of chlorophyll a (1.80 mg g^{-1} FW), chlorophyll b (0.823 mg g^{-1} FW), carotenoids (0.450 mg g^{-1} FW), and Fv/Fm (0.754) with SA 1.5 mM under drought highlights its role in stabilizing photosynthetic machinery, a finding that builds on by quantifying these effects in sesame. Conversely, JA at $100 \mu\text{M}$ significantly increased proline accumulation (up to $1.81 \mu\text{mol g}^{-1}$ FW at 75% depletion), reinforcing its prominence in osmotic adjustment and stress signaling, as supported. This dual action SA's focus on photosynthesis and JA's emphasis on osmoprotection offers a nuanced understanding of PGR complementarity, advancing the theoretical framework for drought tolerance strategies. The agronomic significance of this study is evident in the seed yield improvements, with SA at 1.5 mM boosting yield by 8% (752 kg ha^{-1}) under mild drought in 2022, and JA at $50\text{--}100 \mu\text{M}$ sustaining yields under moderate to severe stress in 2023 (up to 671 kg ha^{-1}). These results not only validate the efficacy of PGRs in mitigating yield losses consistent with but also provide concentration-specific recommendations for sesame, a crop underrepresented in PGR research despite its economic importance in arid regions. The inter-annual variations (higher proline and CAT in 2022) further highlight the influence of environmental context, contributing to a more robust, field-relevant dataset. Scientifically, this research advances knowledge by integrating a comprehensive suite of traits antioxidant enzymes, photosynthetic pigments, proline, H_2O_2 , ion leakage, MDA, RWC, and seed yield into a single study, offering a holistic view of drought stress responses in sesame. Unlike prior studies focusing on individual parameters, our multi-trait approach reveals synergistic interactions between PGRs and drought severity, providing a model for future investigations. Moreover, the identification of SA 1.5 mM and JA $100 \mu\text{M}$ as optimal treatments fills a critical gap in the literature, where optimal PGR dosages for sesame under drought remain poorly defined. These findings align with global efforts to develop stress-tolerant cropping systems and provide a foundation for further research into PGR-mediated gene expression and long-term field performance in sesame. Ultimately, this study contributes to the production of scientific knowledge by bridging physiological insights with agronomic outcomes, paving the way for resilient sesame cultivation in an era of escalating environmental challenges.

References

1. Abeer AH, Eissa MA, Dawood MFA (2021) Foliar application of salicylic acid enhances drought tolerance in maize by modulating the antioxidant defense system and osmoregulation. *Plants* 10:935. <https://doi.org/10.3390/plants10050935>
2. Aebi H (1984) Catalase in vitro. *Methods Enzymol* 105:121–126. [https://doi.org/10.1016/S0076-6879\(84\)05016-3](https://doi.org/10.1016/S0076-6879(84)05016-3)
3. Ahmad P, Alyemeni MN, Wijaya L (2022) Jasmonic acid mitigates drought stress in rice by regulating antioxidant defense and osmotic adjustment. *Plants* 11: 1985. <https://doi.org/10.3390/plants11151985>
4. Anderson R, Bayer PE, Edwards D (2020) Climate change and the need for agricultural adaptation. *Curr Opin Plant Biol* 56:197–202. <https://doi.org/10.1016/j.pbi.2020.05.009>
5. Arif Y, Sami F, Siddiqui H, Bajguz A, Hayat S (2020) Salicylic acid in relation to other phytohormones in plant: A study towards physiology and signal transduction under challenging environment. *Environ Exp Bot* 175:104040. <https://doi.org/10.1016/j.envexpbot.2020.104040>
6. Arnon DI (1949) Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant Physiol* 24(1):1–15. <https://doi.org/10.1104/pp.24.1.1>
7. Bates LS, Waldren RP, Teare ID (1973) Rapid determination of free proline for water-stress studies. *Plant Soil* 39(1):205–207. <https://doi.org/10.1007/BF00018060>
8. Es-sbihi FZ, Hazzoumi Z, Aasfar A, Amrani Joutei K (2021) Improving salinity tolerance in *Salvia officinalis* L. by foliar application of salicylic acid. *Chem Biol Technol Agric* 8:1–12. <https://doi.org/10.1186/s40538-021-00221-y>
9. Fang Y, Du Y, Wang J (2023) Drought stress impacts on plants and strategies for mitigation: A review. *Field Crops Res* 290:108753. <https://doi.org/10.1016/j.fcr.2022.108753>
10. Farhangi-Abri S, Ghassemi-Golezani K (2021) Jasmonates: Mechanisms and functions in abiotic stress tolerance of plants. *J Plant Nutr* 44(11):1585–1602. <https://doi.org/10.1080/01904167.2020.1845370>
11. Ghorbel M, Brini F, Sharma A (2021) Jasmonic acid alleviates drought stress in barley by enhancing proline accumulation and antioxidant capacity. *Plants* 10(2):224. <https://doi.org/10.3390/plants10020224>
12. Haghighi M, Saharkhiz MJ (2022) Effect of salicylic acid on growth and physiological responses of basil under drought stress. *J Plant Nutr* 45(12):1832–1843. <https://doi.org/10.1080/01904167.2021.1973158>
13. Hasanuzzaman M, Bhuyan MHMB, Zulfiqar F (2020) Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. *Antioxidants* 9(8):681. <https://doi.org/10.3390/antiox9080681>
14. Hayat Q, Hayat S, Irfan M (2012) Role of proline under changing environments: A review. *Plant Signal Behav* 7(11):1456–1466. <https://doi.org/10.4161/psb.21949>
15. Heath RL, Packer L (1968) Photoperoxidation in isolated chloroplasts: I. Kinetics and stoichiometry of fatty acid peroxidation. *Arch Biochem Biophys* 125(1):189–198. [https://doi.org/10.1016/0003-9861\(68\)90254-1](https://doi.org/10.1016/0003-9861(68)90254-1)
16. Hewedy OA, Elsheery NI, Karkour AM, Elhamouly N, Arafa RA, Mahmoud GA-E, Dawood MFA, Hussein WE, Mansour A, Amin DH (2023) Jasmonic acid regulates plant development and orchestrates stress response during tough times. *Environ Exp Bot* 208:105260. <https://doi.org/10.1016/j.envexpbot.2023.105260>
17. Iqbal N, Umar S, Khan NA (2022) Salicylic acid and abiotic stress responses in plants: An update. *Front Plant Sci* 13:836667. <https://doi.org/10.3389/fpls.2022.836667>
18. Jain A (2020) Nutritional and therapeutic potential of sesame seeds: A review. *Food Chem* 314:126210. <https://doi.org/10.1016/j.foodchem.2019.126210>
19. Karamian R, Ghasemlou F, Amiri H (2020) Physiological evaluation of drought stress tolerance and recovery in *Verbascum sinuatum* plants treated with methyl jasmonate, salicylic acid and titanium dioxide nanoparticles. *Plant Biosystems-An Int J Dealing all Aspects Plant Biology* 154:277–287. <https://doi.org/10.1080/11263504.2019.1591535>
20. Khan MIR, Javed T, Chopra R (2023) Salicylic acid-mediated enhancement of drought tolerance in wheat: Insights into antioxidant and osmoregulatory responses. *Front Plant Sci* 14:1127845. <https://doi.org/10.3389/fpls.2023.1127845>
21. Khorasaninejad S, Mousavi A, Soltanloo H (2018) Salicylic acid alleviates drought stress in basil by improving photosynthetic efficiency. *J Plant Nutr* 41(5):573–583. <https://doi.org/10.1080/01904167.2018.1431668>

22. Kumar R, Swapnil P, Meena M, Selpair S, Yadav BG (2022) Plant growth-promoting rhizobacteria (PGPR): Approaches to alleviate abiotic stresses for enhancement of growth and development of medicinal plants. *Sustainability* 14:15514. <https://doi.org/10.3390/su14231551>
23. Lichtenthaler HK (1987) Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes. *Methods Enzymol* 148:350–382. [https://doi.org/10.1016/0076-6879\(87\)48036-1](https://doi.org/10.1016/0076-6879(87)48036-1)
24. Liu X, Chen L, Wang G (2023) Salicylic acid improves drought tolerance in *Arabidopsis* through aquaporin regulation and antioxidant defense. *Plant Sci* 329:111623. <https://doi.org/10.1016/j.plantsci.2023.111623>
25. Mabudi Bilasvar H, Ghassemi-Golezani K, Mohammadi Nassab AD (2022) Seed development, oil accumulation and fatty acid composition of drought stressed rapeseed plants affected by salicylic acid and putrescine. *Gesunde Pflanzen* 74:333–345. <https://doi.org/10.1007/s10343-021-00612-z>
26. Mohi-Ud-Din M, Siddiqui MN, Rohman MM (2021) Plant growth regulators in mitigating abiotic stresses in plants: A review. *Plants* 10(8):1596. <https://doi.org/10.3390/plants10081596>
27. Nakano Y, Asada K (1981) Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. *Plant Cell Physiol* 22(5):867–880. <https://doi.org/10.1093/oxfordjournals.pcp.a076232>
28. Nigam B, Dubey RS, Rathore D (2022) Protective role of exogenously supplied salicylic acid and PGPB (*Stenotrophomonas* sp.) on spinach and soybean cultivars grown under salt stress. *Sci Hort* 293:110654. <https://doi.org/10.1016/j.scienta.2021.110654>
29. Pai S, Sharma A (2024) Salicylic acid ameliorates drought stress in wheat by reducing oxidative damage and enhancing membrane stability. *Plant Growth Regul* 102(1):123–135. <https://doi.org/10.1007/s10725-023-01035-5>
30. Pal A, Roy S, Kumar A (2020) Nutritional and therapeutic potential of sesame seeds. *J Food Sci Technol* 57(10):3609–3617. <https://doi.org/10.1007/s13197-020-04342-6>
31. Plewa MJ, Smith SR, Wagner ED (1991) Diethyldithiocarbamate suppresses the plant activation of aromatic amines into mutagens by inhibiting tobacco cell peroxidase. *Mutat Research/Fundamental Mol Mech Mutagen* 247(1):57–64. [https://doi.org/10.1016/0027-5107\(91\)90112-S](https://doi.org/10.1016/0027-5107(91)90112-S)
32. Raza A, Salehi H, Rahman MA (2023) Jasmonic acid-mediated regulation of drought stress tolerance in plants: Current insights and future perspectives. *Int J Mol Sci* 24(3):2456. <https://doi.org/10.3390/ijms24032456>
33. Ruan J, Zhou Y, Zhou M (2019) Jasmonic acid signaling pathway in response to abiotic stresses in plants. *Environ Exp Bot* 164:165–175. <https://doi.org/10.1016/j.envexpbot.2019.04.005>
34. Saleem M, Fariduddin Q, Castroverde CDM (2021) Salicylic acid: A key regulator of redox signalling and plant immunity. *Plant Physiol Biochem* 168:381–397. <https://doi.org/10.1016/j.plaphy.2021.10.011>
35. Seleiman MF, Al-Suhaibani N, Ali N (2021) Drought stress impacts plants, and different approaches to alleviate its adverse effects. *Agronomy* 11(2):232. <https://doi.org/10.3390/agronomy11020232>
36. Sharma P, Kumar V, Raman V (2023) Salicylic acid enhances photosynthetic efficiency and drought tolerance in maize. *Plants* 12(4):789. <https://doi.org/10.3390/plants12040789>
37. Velikova V, Yordanov I, Edreva A (2000) Oxidative stress and some antioxidant systems in acid rain-treated bean plants: Protective role of exogenous polyamines. *Plant Sci* 151(1):59–66. [https://doi.org/10.1016/S0168-9452\(99\)00197-1](https://doi.org/10.1016/S0168-9452(99)00197-1)
38. Wang Y, Zhang X, Liu Y (2022) Salicylic acid enhances carotenoid accumulation and drought tolerance in tomato. *Plant Sci* 317:111198. <https://doi.org/10.1016/j.plantsci.2022.111198>
39. Zhang Y, Li X (2019) Salicylic acid: Biosynthesis, perception, and contributions to plant immunity and abiotic stress tolerance. *Front Plant Sci* 10:231. <https://doi.org/10.3389/fpls.2019.00231>
40. Zi X, Zhou S, Wu B (2022) Alpha-linolenic acid mediates diverse drought responses in maize (*Zea mays* L.) at seedling and flowering stages. *Molecules* 27:771. <https://doi.org/10.3390/molecules27030771>

Tables

Table 1. The results of the chemical and physical analysis of the soil at the experiment location.											
Year	Texture	EC	pH	Cu	Fe	Zn	Mn	K	P	N	O.C.
		(dS.m ⁻¹)		(mg.kg ⁻¹)						(%)	(%)
2022	loam	1.21	7.11	0.22	0.95	0.82	1.0	218	6.0	0.1	0.46
2023	loam	1.22	7.12	0.23	0.97	0.82	1.0	217	6.2	0.1	0.48

Table 2. Analysis of variance for the effects of irrigation regimes and plant growth regulators on the antioxidant enzymes active, ion leakage, malondialdehyde, relative water content, carotenoids and fv/fm of sesame (<i>sesamum indicum</i> l.).									
Source of Variation	DF	Catalase	Peroxidase	Ascorbate Peroxidase	Ion leakage	Malondialdehyde	Relative water content	Carotenoids	Fv/FM
Block	2	NS	*	NS	NS	NS	*	NS	NS
Irrigation regimes (IR)	2	**	**	**	**	**	**	**	**
Block × IR (E _a)	4	0.001	1.89	0.0002	189.8	11.01	48.17	0.014	0.0003
Plant growth regulators (PGR)	6	**	**	**	**	**	**	**	**
IR × PGR	12	NS	**	**	**	**	**	NS	NS
Block × PGR (E _b)	36	0.001	0.230	0.00001	0.556	0.060	2.90	0.0087	0.0002
Year	1	**	**	**	NS	**	**	**	**
IR × Year	2	NS	NS	NS	NS	**	**	NS	NS
Block × IR × Year (E _c)	6	0.003	0.023	0.00001	9.233	0.312	1.98	0.0034	0.003
PGR × Year	6	NS	**	**	**	**	NS	NS	NS
IR × PGR × Year	12	NS	NS	NS	NS	NS	NS	NS	NS
Error	36	0.002	0.024	0.000006	0.437	0.013	1.45	0.013	0.0003
C.V. (%)	-	11.0	6.8	9.3	12.4	8.1	11.9	6.6	13.4
NS, * and **: Not-significant and significant at 5% and 1% error probability, respectively.									

Table 3. Effect of irrigation regimes on catalase, carotenoids, fv/fm and seed yield of sesame (<i>sesamum indicum</i> l.).				
Irrigation Regimes (Soil moisture depletion)	Catalase ($\mu\text{mol mg protein}^{-1} \text{ min}^{-1}$) (%)	Carotenoids	Fv/FM	Seed yield (kg ha^{-1})
25%	1.52 b	0.416 c	0.768 a	752.5 a
50%	1.61 ab	0.432b	0.743 ab	689.2 b
75%	1.68 a	0.452 a	0.693 b	647.8 b
In each column means followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.				

Table 4. Effect of plant growth regulators on catalase, carotenoids, fv/fm, chlorophyll a, chlorophyll b and h2o2 of sesame (<i>sesamum indicum</i> l.).						
Plant growth regulators	Catalase ($\mu\text{mol mg protein}^{-1} \text{ min}^{-1}$)	Carotenoids	Fv/FM	Chlorophyll a (mg g^{-1} leaf fresh weight)	Chlorophyll b (mg g^{-1} leaf fresh weight)	H ₂ O ₂ (mg g^{-1} FW)
Salicylic acid 0.5 mM	1.59 d	0.429 d	0.724 d	1.73 c	0.796 bc	2.09 ab
Salicylic acid 1 mM	1.63 b	0.441 b	0.741 b	1.77 b	0.808 b	1.87 b
Salicylic acid 1.5 mM	1.66 a	0.450 a	0.754 a	1.80 a	0.823 a	1.71d
Jasmonic acid 50 μM	1.60 cd	0.434 cd	0.733 bcd	1.76 bc	0.799 bc	1.99 ab
Jasmonic acid 100 μM	1.62 bc	0.438 bc	0.737 bc	1.75 bc	0.804 bc	1.83 bc
Jasmonic acid 150 μM	1.60 cd	0.431 d	0.726 cd	1.73 c	0.793 c	1.79 c
Control	1.54 e	0.417 e	0.702 e	1.69 d	0.768 d	2.16 a
In each column means followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.						

Table 5. Effect of year on catalase, carotenoids, fv/fm and proline of sesame (<i>sesamum indicum</i> l.).				
Year	Catalase ($\mu\text{mol mg protein}^{-1} \text{ min}^{-1}$)	Carotenoids	Fv/FM	Proline ($\mu\text{mol g}^{-1}$)
2022	1.62 a	0.439 a	0.739 a	1.38 a
2023	1.59 b	0.429 b	0.724 b	1.09 b
In each column means followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.				

Table 6. Mean comparison for the effect of irrigation regimes and plant growth regulators interactions on peroxidase, ascorbate peroxidase, ion leakage, malondialdehyde, relative water content and proline of sesame (*sesamum indicum* L.).

Irrigation Regimes (Soil moisture depletion)	Plant growth regulators	Peroxidase ($\mu\text{mol mg protein}^{-1}\text{ min}^{-1}$)	Ascorbate Peroxidase ($\mu\text{mol mg protein}^{-1}\text{ min}^{-1}$)	Ion leakage (%)	Malondialdehyde ($\mu\text{mol g}^{-1}$ leaf fresh weight)	Relative water content (%)	Proline ($\mu\text{mol g}^{-1}$)
25%	Salicylic acid 0.5 mM	12.2 b	0.982 abc	46.75 ab	10.15 ab	68.48 bc	1.38 a
	Salicylic acid 1 mM	12.4 ab	0.983 abc	46.30 b	9.97 bc	70.19 ab	1.37 ab
	Salicylic acid 1.5 mM	12.7 a	0.101 a	45.15 cd	9.68 c	71.38 a	1.42 a
	Jasmonic acid 50 μM	12.3 ab	0.976 bc	46.05 bc	9.93 bc	67.00 cd	1.29 cd
	Jasmonic acid 100 μM	11.7 c	0.989 abc	44.05 e	9.65 c	68.37 bc	1.38 a
	Jasmonic acid 150 μM	11.9 c	0.960 bc	44.91 de	9.89 bc	67.35 cd	1.31 bc
	Control	11.7 c	0.952 c	47.65 a	10.34 a	65.81 d	1.23 d
50%	Salicylic acid 0.5 mM	13.1 bc	0.101 ab	44.24 ab	9.52 ab	64.09 b	1.52 ab
	Salicylic acid 1 mM	13.4 ab	0.102 ab	43.57 bc	9.36 bc	65.62 ab	1.57 ab
	Salicylic acid 1.5 mM	13.8 a	0.107 a	42.42 cd	9.09 c	67.23 a	1.66 a
	Jasmonic acid 50 μM	13.0 bc	0.104 ab	42.60 cd	9.18 bc	63.37 bc	1.50 bc
	Jasmonic acid 100 μM	12.5 cd	0.104 ab	41.83 d	9.08 c	60.57 cd	1.55 ab
	Jasmonic acid 150 μM	12.2 d	0.104 ab	42.42 cd	9.18 bc	59.28 d	1.55 ab
	Control	12.0 d	0.986 b	45.07 a	9.81 a	58.92 d	1.38 c
75%	Salicylic acid 0.5 mM	14.2 bc	0.111 a	48.89 b	10.66 ab	57.32 d	1.64 cd
	Salicylic acid 1 mM	14.4 b	0.113 a	48.60 bc	10.55 bc	60.26 ab	1.75 ab
	Salicylic acid 1.5 mM	14.8 a	0.115 a	48.07 c	10.31 c	61.71 a	1.81 a
	Jasmonic acid 50	13.7 de	0.112 a	48.22 bc	10.43 bc	60.34 ab	1.72 b

	μM						
	Jasmonic acid 100 μM	14.0 cd	0.114 a	48.02 c	10.51 bc	59.44 bc	1.72 b
	Jasmonic acid 150 μM	13.8 de	0.109 ab	48.48 bc	10.61 b	58.08 cd	1.67 bc
	Control	13.5 e	0.103 b	49.88 a	10.91 a	57.32 d	1.59 d
In each column means for every irrigation regime followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.							

Table 7. Mean comparison for the effect of year and plant growth regulators interactions on peroxidase, ascorbate peroxidase, ion leakage, malondialdehyde and seed yield of sesame (*sesamum indicum* L.).

Year	Plant growth regulators	Peroxidase (μmol mg protein-1 min-1)	Ascorbate Peroxidase (μmol mg protein-1 min-1)	Ion leakage (%)	Malondialdehyde ($\mu\text{mol g}^{-1}$ leaf fresh weight)	Seed yield (kg ha ⁻¹)
2022	Salicylic acid 0.5 mM	13.5 b	10.48 ab	46.54 b	10.13 b	719 bc
	Salicylic acid 1 mM	13.8 a	10.65 ab	46.11 bc	9.95 c	739 a
	Salicylic acid 1.5 mM	14.1 a	10.86 a	45.12 d	9.68 de	752 a
	Jasmonic acid 50 μM	13.5 bc	10.43 b	45.64 cd	9.83 cd	718 bc
	Jasmonic acid 100 μM	13.5 bc	10.86 a	44.30 e	9.65 e	719 bc
	Jasmonic acid 150 μM	13.2 cd	10.61 ab	44.93 de	9.83 cd	707 cd
	Control	13.0 d	10.00 c	47.76 a	10.36 a	697 d
2023	Salicylic acid 0.5 mM	12.5 c	10.22 b	46.72 b	10.09 b	668 b
	Salicylic acid 1 mM	13.0 b	10.37 ab	46.20 bc	9.97 bc	691 a
	Salicylic acid 1.5 mM	13.4 a	10.53 ab	45.31 de	9.71 d	710 a
	Jasmonic acid 50 μM	12.4 c	10.32 ab	45.61 cd	9.87 bcd	671 b
	Jasmonic acid 100 μM	12.4 c	10.61 a	44.98 e	9.84 cd	658 bc
	Jasmonic acid 150 μM	12.0 d	10.24 b	45.61 cd	9.96 bc	651 bc
	Control	11.8 d	9.82 c	47.31 a	10.35 a	642 c

In each column means for every harvest followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.

Table 8. Mean comparison for the effect of year and irrigation regimes interactions on malondialdehyde, relative water content, chlorophyll a, chlorophyll b and H2O2 of sesame (*Sesamum indicum* L.).

Year	Irrigation Regimes (Soil moisture depletion)	Malondialdehyde ($\mu\text{mol g}^{-1}$ leaf fresh weight)	Relative water content (%)	Chlorophyll a (mg g^{-1} leaf fresh weight)	Chlorophyll b (mg g^{-1} leaf fresh weight)	H ₂ O ₂ (mg g^{-1} FW)
2022	25%	9.90 ab	70.42 a	1.85 a	0.850 a	1.88 b
	50%	9.27 b	65.87 ab	1.79 a	0.813 b	2.10 ab
	75%	10.59 a	61.24 b	1.67 b	0.760 c	2.25 a
2023	25%	9.99 ab	66.32 a	1.81 a	0.832 a	1.8 a
	50%	9.36 b	59.58 b	1.74 b	0.787 ab	1.82 a
	75%	10.55 a	57.20 b	1.64 c	0.750 b	1.87 a

In each column means for every harvest followed by the same letters have no significant difference at the probability level of 5% based on the Duncan's multiple range test.

Table 9. Analysis of variance for the effects of irrigation regimes and plant growth regulators on chlorophyll a and b, proline yield, seed yield and H2O2 of sesame (*Sesamum indicum* L.).

Source of Variation	DF	Chlorophyll a	Chlorophyll b	Proline	H2O2	Seed yield
Block	2	NS	NS	NS	NS	NS
Irrigation regimes (IR)	2	**	**	**	**	**
Block $\times$ IR (E _a)	4	0.003	0.0006	9.07	0.72	6760
Plant growth regulators (PGR)	6	**	**	**	**	**
IR $\times$ PGR	12	NS	NS	**	NS	NS
Block $\times$ PGR (E _b)	36	0.001	0.0002	0.07	0.037	510
Year	1	**	**	**	**	**
IR $\times$ Year	2	**	**	NS	**	NS
Block $\times$ IR $\times$ Year (E _c)	6	0.002	0.001	0.41	0.202	759
PGR $\times$ Year	6	NS	NS	NS	NS	**
IR $\times$ PGR $\times$ Year	12	NS	NS	NS	NS	NS
Error	36	0.001	0.0004	0.012	0.04	107
C.V. (%)	-	9.1	10.6	7.4	5.2	15.4

NS, * and **: Not-significant and significant at 5% and 1% error probability, respectively.