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Synergistic Application of γ-Aminobutyric Acid and Salicylic Acid Enhances Drought Resilience, Antioxidant Defense, and Essential Oil Production in Coriander

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ABSTRACT

Water deficit is among the most critical environmental stresses restricting coriander (*Coriandrum sativum* L.) productivity and altering its phytochemical composition through disruption of cellular redox homeostasis and essential oil (EO) metabolism. Although γ-aminobutyric acid (GABA) and salicylic acid (SA) have individually shown potential for improving plant responses to abiotic stress, the consequences of their combined application on drought acclimation and EO accumulation in coriander are still insufficiently characterized. Thus, the present study evaluated the separate and interactive effects of GABA and SA on physiological and biochemical responses, antioxidant activity, biological performance, and EO production under varying water availability conditions. A field trial was performed using a split-plot arrangement within a randomized complete block design with three replications. Irrigation regimes were allocated to main plots, while foliar treatments including distilled water (control), GABA (30 mM), SA (1 mM), and their combined application (GABA + SA) were assigned to subplots. Moderate water limitation stimulated the synthesis of phenolic and flavonoid compounds, whereas severe drought intensified oxidative stress and negatively affected plant growth. Under severe drought conditions, foliar application of GABA + SA enhanced drought tolerance by increasing total phenolic and flavonoid contents by 22% and 41%, respectively, while reducing H_2O_2 accumulation by 33% compared with untreated plants. Furthermore, the combined treatment improved biological yield and EO yield by 27% and 51%, respectively, under severe water stress. Principal component analysis indicated that GABA + SA treatment was closely associated with increased phytochemical accumulation and yield-related characteristics, whereas control plants exhibited stronger relationships with oxidative stress markers. Overall, these results suggest that the combined use of GABA and SA represents an effective approach for alleviating drought-related impairments and improving phytochemical quality and EO productivity in coriander, offering a promising strategy for sustainable production of medicinal and aromatic crops under limited water conditions.

Keywords: Aromatic plants, Osmotic adjustment, Plant biostimulants, Secondary metabolites, Water deficit

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INTRODUCTION

Drought represents a critical abiotic stress factor that severely restricts crop productivity worldwide, and its occurrence and severity are projected to increase as a consequence of ongoing climate change. Limited water availability negatively affects plant development by restricting cell enlargement, photosynthetic activity, nutrient acquisition, and carbon metabolism, while simultaneously triggering excessive generation of reactive oxygen species (ROS) [1, 2]. Elevated ROS levels, particularly hydrogen peroxide (H_2O_2) and superoxide anions, can cause oxidative injury to essential cellular components, including membrane lipids, proteins, and nucleic acids, thereby disrupting membrane stability and normal metabolic functions. In response to ROS-induced damage, plants enhance their antioxidant defense mechanisms through the activation of enzymatic and non-enzymatic systems and the accumulation of secondary metabolites, such as phenolics

and flavonoids, which play important roles in ROS scavenging and maintaining cellular homeostasis [2, 3].

Coriander (*Coriandrum sativum* L.) is recognized as a valuable medicinal and aromatic species with considerable economic significance due to its widespread use in food, pharmaceutical, and industrial sectors, largely attributed to its essential oil (EO) and rich array of bioactive constituents [4]. However, coriander is highly sensitive to water deficit, particularly during reproductive development, leading to substantial reductions in biomass, seed production, and EO yield [5]. Moderate drought may stimulate the accumulation of phenolics and other secondary metabolites as an adaptive response, whereas severe drought generally suppresses plant growth and restricts terpenoid biosynthesis by limiting carbon assimilation and metabolic activity [6, 7]. In coriander, drought-induced biochemical changes and partial alleviation through salicylic acid have been reported [5], yet effective strategies capable of simultaneously improving antioxidant capacity, plant productivity, and EO yield under water-deficit conditions remain limited.

Previous studies have demonstrated that the separate application of GABA or SA can reduce drought-related oxidative injuries in various crops and medicinal plants through the suppression of lipid peroxidation, stimulation of antioxidant defense mechanisms, and improvement of plant growth and yield attributes [12–15]. Furthermore, SA application has been associated with increased phenolic compound accumulation and enhanced EO production in drought-exposed medicinal plants [16–19]. However, most previous studies have focused on the effects of GABA or SA individually, and limited information is available on whether their combined application can provide an additive or synergistic advantage under water-limited conditions. In particular, the interactive effects of GABA and SA on physiological and biochemical responses, oxidative stress regulation, secondary metabolite accumulation, and EO productivity of coriander under contrasting irrigation regimes have not been sufficiently investigated. This knowledge gap is important because GABA and SA may act through complementary regulatory pathways, potentially enabling their combined application to provide greater protection against drought-induced oxidative and metabolic disturbances than either compound applied alone.

Accordingly, this study was designed to determine the individual and interactive effects of foliar-applied GABA and SA on biochemical traits, antioxidant activity, oxidative stress-related parameters, biological performance, and EO yield of coriander exposed to contrasting irrigation regimes. We hypothesized that the combined application of GABA and SA would exert a stronger protective effect against drought-induced oxidative damage than their separate applications by enhancing antioxidant defense mechanisms, stimulating phenolic and flavonoid accumulation, maintaining cellular redox homeostasis, and consequently improving plant growth and EO productivity under water-limited conditions.

MATERIALS AND METHODS

Experimental Site and Agronomic Operations

A field trial was conducted at the research farm of Kashan, Iran (33°58′57″ N and 51°25′57″ E) during the growing season. The coriander seeds were obtained from Pakan Bazr Company, Isfahan, Iran. Prior to crop establishment, soil samples were collected from the upper 0–20 cm soil layer and analyzed for their physicochemical characteristics. The soil had a slightly alkaline reaction (pH 7.12) and an electrical conductivity of 1.23 dS/m. The concentrations of available phosphorus, available potassium, nitrate nitrogen, and organic carbon were 11.09 mg/kg, 528 mg/kg, 15.12 mg/kg, and 1.04%, respectively. Soil texture analysis indicated 30% clay, 49% silt, and 21% sand, corresponding to a clay loam texture. A field trial was carried out at the research farm of Kashan, Iran (33°58′57″ N and 51°25′57″ E) during the growing season. Prior to crop establishment, soil samples were taken from the upper 0–20 cm layer and analyzed for their physicochemical characteristics. The soil exhibited a slightly alkaline reaction (pH 7.12) and an electrical conductivity of 1.23 dS/m. The concentrations of available phosphorus, available potassium, nitrate nitrogen, and organic carbon were 11.09 mg/kg, 528 mg/kg, 15.12 mg/kg, and 1.04%, respectively. Soil texture analysis showed proportions of 30% clay, 49% silt, and 21% sand, classifying the soil as clay loam.

During the experimental periods, environmental conditions at the experimental site were monitored and recorded. The total precipitation recorded during the 2021 and 2022 experimental periods was 81.3 and 97.3 mm, respectively. Before sowing, standard field preparation practices were performed, including primary tillage by moldboard plowing to a depth of 30 cm, followed by disk harrowing to achieve a uniform and suitable seedbed. Experimental plots were arranged according to the designated experimental layout, with each plot containing four rows spaced 60 cm apart. Coriander seeds were manually placed at approximately 1.5 cm soil depth. Following seedling emergence and establishment, thinning was conducted to obtain a consistent plant population. Weed management was carried out manually throughout the cultivation period to reduce weed interference and competition with coriander plants.

Experimental Design and Treatments

The experiment followed a split-plot arrangement within a randomized complete block design with three replications. Irrigation treatments were assigned to the main plots, whereas foliar treatments were allocated to the subplots. The experiment consisted of three main plots per replication, corresponding to the three irrigation regimes, and each main plot was divided into four subplots corresponding to the four foliar treatments. Thus, the experiment comprised 12 subplots per replication and a total of 36 experimental units across the three replications.

Three irrigation regimes were established according to cumulative evaporation from a Class A evaporation pan: well-watered conditions (irrigation after 55 mm evaporation), moderate drought stress (85 mm evaporation), and severe drought stress (115 mm evaporation). Water stress treatments were imposed after plant establishment and the development of the first four leaves and maintained until harvesting.

Foliar treatments consisted of distilled water (control), GABA, SA, and combined GABA + SA application. GABA and SA were applied at concentrations of 30 mM and 1 mM, respectively, based on preliminary experiments conducted before the main experiment to identify effective concentrations for improving plant performance under water-limited conditions. Foliar spraying was carried out three times at 15-day intervals using a manual sprayer until uniform leaf wetting was achieved. Equal spray volumes were applied across treatments, while control plants received only distilled water. Plants were harvested at physiological maturity after 105 days to evaluate growth characteristics, biochemical responses, and EO production. Biochemical analyses requiring fresh tissue were performed using freshly harvested samples,

whereas total phenolic content (TPC), total flavonoid content (TFC), and EO analyses were conducted using dried plant material.

Total Phenolic Content

Phenolic compounds were extracted from fresh coriander tissue (0.5 g) using 80% methanol (10 mL). After centrifugation (10,000 × g, 10 min), the extract was reacted with Folin–Ciocalteu reagent and sodium carbonate solution. Following incubation in darkness for 30 min, absorbance was measured at 765 nm. Gallic acid was used for calibration, and phenolic concentration was calculated as mg gallic acid equivalents (GAE) g^{-1} FW [20].

Total Flavonoid Content

Total flavonoids were quantified using the $AlCl_3$ colorimetric assay. Methanolic extract (0.5 mL) was mixed with methanol, aluminum chloride, potassium acetate, and distilled water, followed by incubation for 30 min at room temperature. Absorbance was recorded at 415 nm, and flavonoid content was expressed as mg quercetin equivalents (QE) g^{-1} FW using quercetin as the standard [21].

Malondialdehyde Measurement

MDA accumulation was determined using the TBA-based method of Heath and Packer [22]. Fresh tissue (0.5 g) was extracted with 0.1% TCA, and the extract was reacted with TBA-containing TCA solution. After heating at 95 °C for 30 min and cooling, absorbance was recorded at 532 and 600 nm using a UV–Vis spectrophotometer. MDA content was calculated from the corrected absorbance (A532–A600) using an extinction coefficient of 155 mM^{-1} cm^{-1} and expressed as µmol g^{-1} FW.

Hydrogen Peroxide

H_2O_2 accumulation was quantified following the method of Velikova et al. [23]. Fresh tissue (0.5 g) was extracted with 0.1% TCA and centrifuged at 12,000 × g (4 °C, 15 min). The extract was reacted with potassium phosphate buffer and potassium iodide (KI), and absorbance was recorded at 390 nm using a UV–Vis spectrophotometer. H_2O_2 levels were calculated from a standard calibration curve and expressed as µmol g^{-1} FW.

Superoxide Dismutase Measurement

SOD (EC 1.15.1.1) activity was assayed using the NBT photoreduction inhibition method of Beauchamp and Fridovich [24]. Fresh tissue (0.5 g) was extracted with potassium phosphate buffer (50 mM, pH 7.8) containing EDTA and PVPP, and the extract was obtained after centrifugation at 12,000 × g for 20 min at 4 °C. Enzyme activity was evaluated in a reaction mixture containing phosphate buffer, methionine, NBT, riboflavin, EDTA, and enzyme extract under fluorescent illumination. After 15 min, absorbance was recorded at 560 nm using a UV–Vis spectrophotometer. One unit of SOD activity was defined as the enzyme amount causing 50% inhibition of NBT reduction and expressed as U mg^{-1} protein.

Peroxidase Activity Measurement

Peroxidase (POD) activity was determined by monitoring guaiacol oxidation following the formation of tetraguaiacol. Fresh leaf tissue (0.5 g) was extracted in 50 mM sodium phosphate buffer (pH 7.0) supplemented with 1% PVP, and the extract was obtained after centrifugation (12,000 × g, 15 min, 4 °C). Enzyme activity was assayed using a mixture containing phosphate buffer, guaiacol, H_2O_2, and enzyme extract. The change in absorbance at 470 nm was monitored for 3 min with a spectrophotometer. POD activity was calculated using an extinction coefficient of 26.6 mM^{-1} cm^{-1} and expressed as U mg^{-1} protein, with one unit defined as a 0.01 increase in absorbance per minute under the assay conditions [25].

Plant Sampling and Yield Determination

At physiological maturity, plants were harvested from the inner rows of each plot to avoid border effects. Aboveground biomass was oven-dried at 70 °C until a constant weight was achieved, and biological yield was recorded. EO was extracted from dried aerial tissues, and EO yield was calculated by integrating EO content with biological yield according to Afshari *et al*. [5].

Statistical Analysis

The experiment was arranged as a split-plot design within an RCBD with three replications and was conducted over two growing seasons. Year was considered a random factor in the statistical model to account for seasonal and environmental variation between growing seasons. Data were analyzed using SAS software (Version 9.4; SAS Institute Inc., Cary, NC, USA). The assumptions of normality and variance homogeneity were assessed using the Shapiro–Wilk and Levene's tests, respectively. Significant treatment effects were further evaluated using Duncan's multiple range test at the 5% significance level ($P \leq 0.05$).

RESULTS

Phenolic and Flavonoids Content

The interaction between irrigation regime and foliar treatments significantly affected TPC and TFC. In untreated plants, moderate drought increased TPC and TFC by 23 and 27%, respectively, compared with normal irrigation. Under severe drought, these increases were limited to 8 and 6%, respectively. However, compared with moderate drought, severe drought reduced TPC by 12% and TFC by 17%.

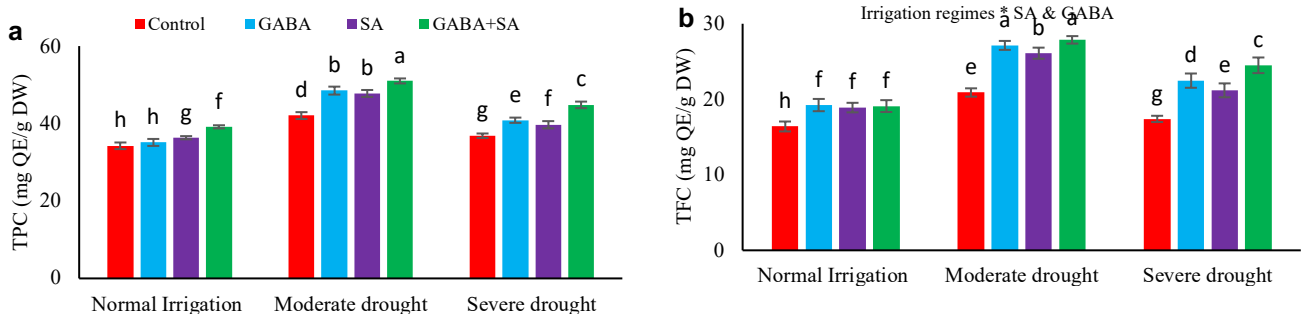

Fig. 1 Total phenolic content (TPC) (a) and total flavonoid content (TFC) (b) of coriander plants subjected to foliar treatment of salicylic acid (SA) and γ-aminobutyric acid (GABA) under different irrigation regimes. Values are presented as means ± standard error (SE) of three replicates. Different lowercase letters indicate significant differences among treatment means according to Duncan's multiple range test at $P \leq 0.05$.

Under normal irrigation, GABA, SA, and GABA + SA increased TPC by 3, 6, and 14%, respectively, compared with the untreated control. The increase caused by GABA was not statistically significant, whereas SA and the combined treatment significantly enhanced TPC. Under moderate drought, GABA, SA, and GABA + SA increased TPC by 15, 14, and 21%, respectively. Similarly, under severe drought, these treatments enhanced TPC by 11, 8, and 22%, respectively (Fig. 1a). For TFC, GABA, SA, and GABA + SA increased the values by 17, 15, and 16%, respectively, under normal irrigation. Under moderate drought, the corresponding increases were 30, 25, and 33%, whereas under severe drought, TFC increased by 29, 22, and 41%, respectively. The highest TPC and TFC were obtained from plants treated with GABA + SA under moderate drought. Overall, the combined treatment was particularly effective under severe drought, where it increased TPC and TFC by 22 and 41%, respectively, compared with untreated plants (Fig. 1b).

Malondialdehyde and Hydrogen Peroxide

Irrigation regime and foliar application with SA and GABA significantly affected MDA content. In untreated plants, moderate and severe drought increased MDA by 51 and 153%, respectively, compared with normal irrigation. Under normal irrigation, GABA, SA, and GABA + SA reduced MDA by 7, 8, and 13%, respectively, compared with the control. The corresponding reductions under moderate drought were 17, 12, and 26%, while under severe drought they were 30, 28, and 34%, respectively (Fig. 2a). H_2O_2 content increased progressively with drought severity. In untreated plants, moderate and severe drought increased H_2O_2 by 71 and 127%, respectively, compared with normal irrigation. Foliar application effectively reduced H_2O_2 accumulation. Under normal irrigation, GABA, SA, and GABA + SA decreased H_2O_2 by 6, 10, and 13%, respectively, relative to the control. The corresponding reductions under moderate drought were 28, 18, and 32%, while under severe drought they were 26, 28, and 33%, respectively. The combined GABA + SA treatment consistently produced the lowest H_2O_2 content under all irrigation regimes and exhibited pronounced benefits under stress circumstance (Fig. 2b).

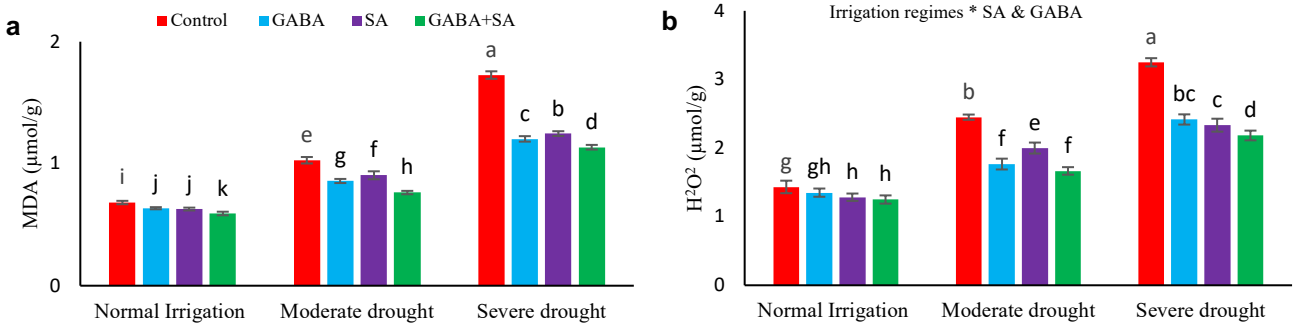

Fig. 2 Malondialdehyde (MDA) (a) and hydrogen peroxide (H_2O_2) (b) contents of coriander plants subjected to foliar treatment of salicylic acid (SA) and γ-aminobutyric acid (GABA) under different irrigation regimes. Values are presented as means ± standard error (SE) of three replicates. Different lowercase letters indicate significant differences among treatment means according to Duncan's multiple range test at $P \leq 0.05$.

Antioxidant Enzyme Activity

Drought stress markedly increased SOD activity. In untreated plants, moderate and severe drought increased SOD activity by 316 and 596%, respectively, compared with normal irrigation. Under normal irrigation, GABA, SA, and GABA + SA increased SOD activity by 37, 27, and 79%, respectively, relative to the untreated plants. Conversely, under moderate drought, these treatments reduced SOD activity by 34, 36, and 41%, respectively, while under severe drought the corresponding reductions were 27, 33, and 37%. Co-applied GABA and SA produced the highest activity under normal irrigation but the greatest reduction under drought conditions (Fig. 3a).

POD activity increased considerably with increasing drought severity. In untreated plants, moderate and severe drought increased POD activity by 260 and 362%, respectively, compared with normal irrigation. Under normal irrigation, GABA, SA, and GABA + SA increased POD activity by 29, 8, and 104%, respectively. In contrast, under moderate drought, these treatments reduced POD activity by 31, 21, and 41%, respectively, whereas under severe drought the corresponding reductions were 20, 18, and 25%. Overall, the combined application of GABA and SA was the most effective treatment in modulating drought-induced changes in POD activity (Fig. 3b).

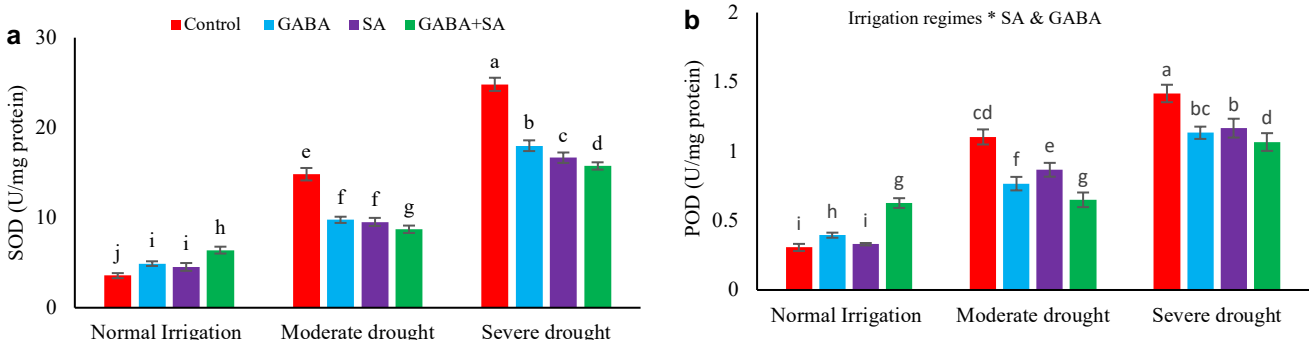

Fig. 3 Superoxide dismutase (SOD) (a) and peroxidase (POD) (b) activities of coriander plants subjected to foliar treatment of salicylic acid (SA) and γ-aminobutyric acid (GABA) under different irrigation regimes. Values are presented as means ± standard error (SE) of three replicates. Different lowercase letters indicate significant differences among treatment means according to Duncan's multiple range test at $P \leq 0.05$.

Biological Yield and Essential Oil Yield

The significant interaction observed between irrigation management and foliar application revealed that changes in water supply modified the effectiveness of foliar treatments in affecting biological yield. In the absence of foliar treatment, moderate and severe drought caused 17 and 39% reductions in biological yield, respectively, relative to normal irrigation. Foliar application partly alleviated these losses. Under normal irrigation, GABA, SA, and their combined application enhanced biological yield by 3, 6, and 12%, respectively, compared with the untreated control. These treatments increased biological yield by 12, 11, and 14% under moderate drought and by 19, 17, and 27% under severe drought, respectively (Fig. 4a).

EO yield showed a different response to drought intensity. In untreated plants, moderate drought increased EO yield by 10%, whereas severe drought reduced it by 31% compared with normal irrigation. Under normal irrigation, GABA, SA, and GABA + SA increased EO yield by 14, 12, and 28%, respectively. Under moderate drought, the respective increases were 25, 19, and 33%, while under severe drought they reached 29, 22, and 51% (Fig. 4b).

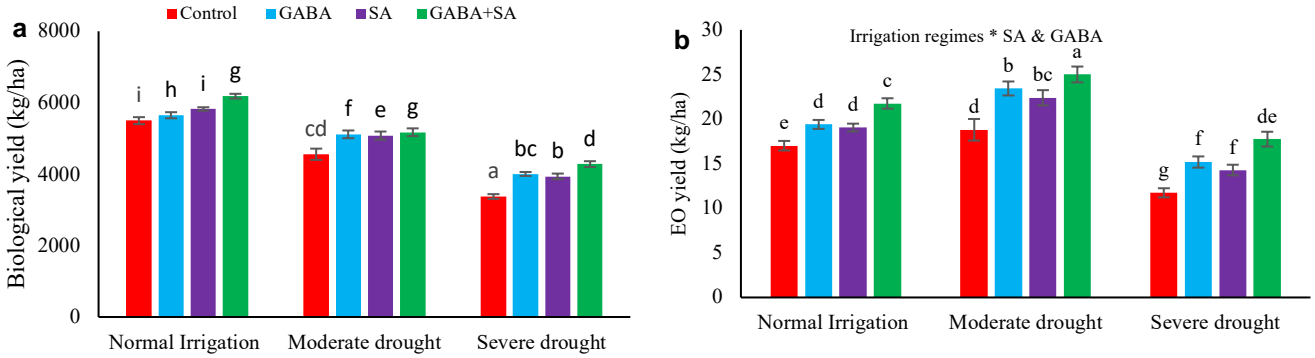

Fig. 4 Biological yield (a) and essential oil (EO) yield (b) of coriander plants subjected to foliar treatment of salicylic acid (SA) and γ-aminobutyric acid (GABA) under different irrigation regimes. Values are presented as means ± standard error (SE) of three replicates. Different lowercase letters indicate significant differences among treatment means according to Duncan's multiple range test at $P \leq 0.05$.

Principal Component Analysis

The PCA biplot for irrigation regimes explained 100% of the total variation, with F1 and F2 contributing 69.94% and 30.06% of the variance, respectively (Fig. 5). Moderate drought was closely associated with TPC and TFC, indicating higher accumulation of these secondary metabolites under moderate stress. Severe drought was positioned near MDA and SOD and, to a lesser extent, H_2O_2 and POD, reflecting greater oxidative damage and antioxidant enzyme activity. Normal irrigation was located on the negative side of F1 and was more closely related to biological yield and EO yield. The narrow angles between TPC and TFC, between MDA and SOD, and between POD and H_2O_2 indicated strong positive relationships within these groups of traits.

The PCA biplot for foliar treatments explained 99.06% of the total variation, of which F1 and F2 accounted for 95.17 and 3.89%, respectively. The GABA + SA treatment was positioned near biological yield, EO yield, and TPC, indicating its favorable association with yield and phenolic accumulation. GABA and SA were located close to TFC, suggesting a stronger relationship with flavonoid accumulation. In contrast, the untreated control was closely associated with MDA and H_2O_2, demonstrating greater oxidative stress in the absence of foliar application. POD and SOD also showed positive loadings on F1 but were separated from MDA and H_2O_2 along F2. Overall, GABA + SA was associated with improved productive and biochemical traits, whereas the control was primarily related to oxidative stress indicators.

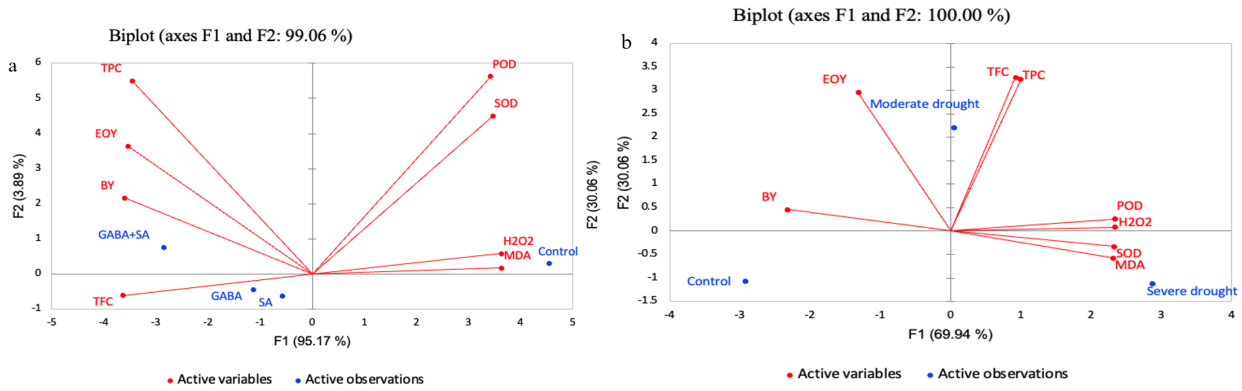

Fig. 5 Principal component analysis (PCA) of coriander plants under different irrigation regimes (a) and foliar treatment of salicylic acid (SA) and γ-aminobutyric acid (GABA) treatments (b). Values are presented as means ± standard error (SE) of three replicates. Different lowercase letters indicate significant differences among treatment means according to Duncan's multiple range test at $P \leq 0.05$.

DISCUSSION

The enhancement of TPC and TFC under moderate drought suggests that mild water limitation stimulated the accumulation of phenolic-based and flavonoid metabolites as part of the plant's protective response against drought-induced oxidative stress [5]. These secondary metabolites can contribute to ROS scavenging and membrane protection; however, their lower accumulation under severe drought compared with moderate drought indicates

that intense water deficit may have restricted carbon assimilation, enzyme activity, and the regulation of secondary metabolite pathways [16]. Foliar application of GABA and SA further promoted phenolic and flavonoid accumulation, likely by activating antioxidant defense pathways and enzymes involved in phenylpropanoid metabolism. The greater effectiveness of GABA + SA may result from coordinated regulation of redox signaling and phenylpropanoid metabolism. GABA may improve osmotic adjustment, carbon–nitrogen balance, and antioxidant capacity [12], whereas SA can activate defense-related pathways and stimulate phenylalanine ammonia-lyase [9, 17, 26]. Their combined action may reduce oxidative damage, preserve membrane integrity, and maintain the metabolic substrates required for phenolic and flavonoid production. Similar increases in phenolic and flavonoid accumulation following SA application under drought have been reported by Khalil *et al.* [9] and Jayathilaka *et al*. [17], supporting the role of SA in stimulating secondary metabolite biosynthesis and strengthening antioxidant protection under water-deficit conditions.

The simultaneous increases in H_2O_2 and MDA with increasing drought severity indicate enhanced ROS accumulation, membrane lipid peroxidation, and loss of membrane stability under water deficit [11]. The reductions in both oxidative stress markers following GABA and SA application demonstrate their protective roles in limiting drought-induced oxidative damage. GABA may alleviate oxidative stress by regulating the GABA shunt, improving osmotic adjustment and carbon–nitrogen balance, and strengthening antioxidant metabolism [12, 14]. Similarly, SA may activate stress-signaling pathways and enhance enzymatic and non-enzymatic antioxidant defenses [11, 15]. The combined GABA + SA treatment produced the lowest H_2O_2 and MDA contents, which suggests a complementary effect on ROS detoxification and membrane protection. Therefore, their combined application may improve drought tolerance by maintaining redox homeostasis, restricting lipid peroxidation, and preserving cellular membrane integrity [14, 15, 27]. The present findings corroborate previous reports demonstrating that GABA and SA reduced drought-induced H_2O_2 accumulation and oxidative damage by enhancing antioxidant defenses in rice, faba bean, maize, and marjoram [11, 12, 14, 15].

The notable increases in SOD and POD activities in untreated plants under drought conditions indicate activation of the enzymatic antioxidant system in response to drought-induced ROS accumulation. SOD constitutes the first line of enzymatic defense by catalyzing the dismutation of superoxide anions to H_2O_2, which is subsequently detoxified by enzymes such as POD [28]. Under well-watered conditions, GABA + SA application may have enhanced antioxidant preparedness through GABA-mediated metabolic regulation and SA-dependent redox signaling, resulting in increased SOD and POD activities. Under drought conditions, GABA may contribute to mitochondrial metabolism, osmotic adjustment, and ROS homeostasis [29], whereas SA may regulate stress-responsive signaling and antioxidant defense [10]. The combined application of GABA + SA may therefore have alleviated drought-induced oxidative pressure by limiting excessive ROS accumulation, thereby reducing membrane lipid peroxidation and helping to maintain cellular redox balance. Importantly, the lower SOD and POD activities observed in GABA + SA-treated plants under drought were not lower than those of the well-watered control plants; rather, they were lower than the activities observed under the corresponding drought-stress conditions. Thus, the reduced enzyme activities likely reflected a lower oxidative demand resulting from improved stress mitigation rather than a weakening of antioxidant capacity [10, 23]. This interpretation is consistent with the concept that effective biostimulant application can reduce ROS accumulation and consequently decrease the requirement for strong antioxidant enzyme activation [30]. A similar stress-dependent modulation of POD activity by SA was reported by Torun *et al.* [31]. In contrast, increased antioxidant enzyme activities following SA or GABA application have been reported in tomato, wheat, and faba bean [10, 13, 14], indicating that the direction and magnitude of antioxidant enzyme responses may depend on stress intensity, plant species, and the physiological status of the plants.

The decline in biological yield under drought can be attributed to reduced cell expansion, photosynthetic activity, and assimilate production caused by limited water availability. The greater effectiveness of GABA + SA, particularly under severe drought, suggests that their combined application improved plant growth by supporting osmotic adjustment, protecting cellular membranes, and maintaining metabolic activity [19]. The changes in essential oil yield appeared to be associated with both biomass production and essential oil content. The increase in essential oil yield under moderate drought may have resulted from enhanced essential oil content, which compensated for the moderate reduction in biomass and reflected the stimulation of secondary metabolism as an adaptive response. In contrast, the reduction in essential oil yield under severe drought was likely driven mainly by the pronounced decrease in biomass production, which limited the amount of plant material available for essential oil accumulation and the carbon substrates required for essential oil biosynthesis [5]. Foliar application of GABA and SA enhanced essential oil yield under all irrigation regimes, probably by improving redox balance, preserving photosynthetic capacity, and supporting pathways involved in terpenoid production [12, 32]. Thus, the pronounced improvement in essential oil yield under severe drought following GABA + SA application may have resulted from the combined preservation of biomass and enhancement of essential oil accumulation [18, 32].

CONCLUSION

The present study highlights that the evaluated treatment can serve as an effective strategy for enhancing stress resilience and phytochemical accumulation in coriander under drought conditions. Beyond improving plant adaptation to water deficit, the treatment promoted the accumulation of antioxidant metabolites that may contribute to the medicinal and functional value of coriander. These findings suggest considerable potential for the sustainable production of high-quality medicinal plants with enhanced bioactive properties under water-limited conditions. From an industrial perspective, improving the accumulation of valuable phytochemicals while maintaining plant performance could increase the commercial value of coriander as a source of natural antioxidants and functional ingredients. However, a limitation of the present study is that essential oil composition and the profiles of its individual constituents were not determined; therefore, the effects of the treatment on essential oil quality could not be fully assessed. Future studies should characterize essential oil composition using gas chromatography–mass spectrometry and/or gas chromatography–flame ionization detection, together with metabolomics profiling, to provide a more comprehensive understanding of treatment-induced changes in secondary metabolism. Further investigations under large-scale field

conditions are also recommended to validate the consistency and practical applicability of this strategy for sustainable coriander production in water-limited environments.

Consent for Publication

All authors agree to the publication of this manuscript in JMPB.

Data Availability

The data are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no conflict of interests.

Funding

Not Applicable.

Authors' Contributions

All authors contributed to the conception and design of the study, data analysis, drafting, reviewing, and editing of the manuscript. All authors read and approved the final version of the manuscript.

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