



Article

Synergistic Role of Encapsulated *Lelliottia amnigena* MSR-M49 and Salicylic Acid in Enhancing Growth, Yield, and Essential Oil of Fennel (*Foeniculum vulgare* Mill.) under Water Stress Conditions

Maie, Mohsen M. A.^{1,*}, Hanaa A. Abo-Koura² and Abd El-Latif Kh.M.²



¹ Medicinal & Aromatic plants. Res. Dept., Hort. Research Institute, Agricultural Research Center Giza, Egypt.

² Soils, Water and Environment Research Institute, Agricultural Research Center, Giza 12619, Egypt

<https://doi.org/10.37229/fsa.fja.2025.12.05>

*Corresponding author: maie1972@hotmail.com

Future Science Association

Available online free at
www.futurejournals.org

Print ISSN: 2687-8151

Online ISSN: 2687-8216

Received: 2 October 2025

Accepted: 9 December 2025

Published: 5 December 2025

Publisher's Note: FA stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Abstract: In Egypt, water scarcity represents a primary constraint on sustainable crop production. To address this challenge, the present study examined eco-friendly mitigation approaches for fennel (*Foeniculum vulgare* L.) subjected to water stress, focusing on the synergistic and individual effects of bio-encapsulated *Lelliottia amnigena* MSR-M49 and salicylic acid (SA). Two-year factorial field experiments using a split-plot design were conducted during the 2019/2020 and 2020/2021 growing seasons at the Agricultural Research Centre (ARC), Giza, Egypt. Fennel plants were subjected to three irrigation regimes: normal (15-day intervals; I₁), moderate water deficit (21-day intervals; I₂), and severe water deficit (30-day intervals; I₃). The results indicated that co-application of SA and encapsulated *L. amnigena* significantly enhanced boosted vegetative growth, flowering parameters, total chlorophyll (a and b), total carbohydrates, NPK nutrient uptake, and essential oil yield compared to the untreated control. This combination significantly boosted phytohormones in both seasons. While drought stress severely reduced total phenolic content by 44% under moderate stress (I₂, 80% ETc) and 70% under severe stress (I₃, 60% ETc), the combined treatment effectively restored phenolic levels, proline accumulation, and relative water content (RWC). Notably, abscisic acid (ABA) content decreased by 48.0% and 48.6% in the first and second seasons, respectively, under moderate stress (80% ETc). Furthermore, applying SA alone or combined with microencapsulated bacteria strongly reduced antioxidant enzyme activities. Under moderate water deficit, co-inoculation with *L. amnigena* and foliar SA demonstrated the strongest synergistic effect. Additionally, the 21-day irrigation interval proved to be the optimal regime, requiring the lowest seasonal irrigation water (mean = 2048 m³ fed⁻¹) and reducing water use by 5.8 % and 9.7% relative to the 15- and 30-day intervals, respectively, through the first season without compromising crop growth, flowering, or essential oil

production. Consequently, integrating encapsulated *L. amnigena* with foliar SA under a 21-day irrigation schedule offers a viable agronomic strategy to optimize fennel production and water-use efficiency in arid environments.

Key words: *Foeniculum vulgare* Mill, *Lelliottia amnigena* MSR-M4, salicylic acid, drought stress, essential oil.

1. Introduction

Worsening water scarcity poses a critical challenge to agricultural sustainability in Egypt, where climate-driven droughts amplify an annual water deficit of over 54 billion cubic meters (FAO, 2024). Drought is a multifaceted abiotic stress (Farooqi *et al.*, 2020) found that lowers cellular turgor and water potential, compromising plant development through impaired water retention and efficiency (Kapoor *et al.*, 2020). Drought stress disrupts gas exchange and photosynthetic machinery by lowering stomatal conductance, electron transport rates, and carboxylation efficiency. This leads to diminished chlorophyll (a and b) levels and relative water content (RWC). The resulting oxidative stress increases reactive oxygen species (ROS) and H₂O₂ leading to membrane damage, electrolyte leakage, and elevated MDA levels (Zhu *et al.*, 2021). Although antioxidant enzymes (CAT, APX, POX) accumulate to mitigate this damage, total proteins, carotenoids, and root biomass decline. Furthermore, elevated ABA accumulation alters thylakoid and chloroplast architecture (Liu *et al.*, 2022). Drought also restricts soil nutrient availability—notably decreasing nitrogen mineralization and K⁺ retention. Reduced intracellular CO₂ inhibits the Calvin cycle, depleting electron acceptors (NADP⁺, NAD⁺, and FAD) and promoting ROS generation (Gupta *et al.*, 2020).

Foeniculum vulgare Mill., commonly known as fennel, is an aromatic member of the Apiaceae family native to the Mediterranean region and now cultivated worldwide. Egypt ranks as the fifth-largest producer globally, accounting for approximately 3.1% of international exports (ITC, 2019). It is a resilient umbelliferous herb characterized by feathery leaves, hollow stems, and bright yellow blooms. Due to their distinct anise-like aroma, its seeds are widely utilized as flavoring agents in baked goods, seafood, confectioneries, and beverages (Vincenzo and Angelo, 2021). Beyond its culinary applications, fennel exhibits well-documented carminative, diuretic, and galactagogue properties (Telci *et al.*, 2019). Rich in potent bioactive compounds such as quercetin, limonene, and chlorogenic acid, fennel offers broad therapeutic benefits, including antimicrobial, anti-inflammatory, and antioxidant activities (Akhbari *et al.*, 2019). Additionally, it contains significant dietary fiber and essential minerals (K, Mg and Ca), making it a traditional remedy for gastrointestinal conditions such as heartburn, flatulence, bloating, anorexia, and infant colic. Ethnobotanically, it has also been used to treat respiratory ailments, backaches, ocular disorders, and snakebite wounds via topical powdered poultices (Making Chinese Medicine Series 03, 2021). Mature fennel fruits yield between 3% and 6% essential oil, rich in volatile compounds such as *trans*-anethole, fenchone, and estragole (methyl chavicol). These constituents impart strong hepatoprotective, antimicrobial, and antioxidant properties. Owing to anethole's proven anti-inflammatory, antiviral, and anti-carcinogenic qualities, fennel essential oil is widely applied across the pharmaceutical, cosmetic, and confectionery industries (Rezaei-Chiyaneh *et al.*, 2020).

Over the past few decades, plant growth-promoting rhizobacteria (PGPR) have drawn substantial interest as sustainable bio-inoculants capable of enhancing crop productivity and tolerance to biotic and abiotic stresses. PGPR mitigate drought stress through diverse direct and indirect mechanisms, including the alteration of root architecture, production of phytohormones and extracellular polymeric substances (EPS), activity of 1-aminocyclopropane-1-carboxylate (ACC) deaminase, release of volatile organic compounds, and intracellular osmolyte accumulation. Furthermore, these beneficial microbes bolster the plant's antioxidant defense systems and up regulate stress-responsive gene expression (Singh *et al.*, 2021). The efficacy of PGPR inoculation hinges on the effective colonization, metabolic activity, and persistence of bacterial populations within the rhizosphere (Fanai *et al.*, 2024). Owing to their colonization capacity and intimate associations with host plants—both on the root surface (rhizoplane) and endophytically within plant tissues—PGPR represent a viable, long-term biological approach to

counter severe drought impacts (Cherif-Silini *et al.*, 2022). Compared to conventional liquid formulations, microencapsulation provides superior protection and physical stability, ensuring sustained bacterial survival and localized release in the root zone over extended periods (Mushtaq *et al.*, 2025). Notably, the encapsulated strain *L. amnigena* has demonstrated strong potential in enhancing plant resilience under moisture-deficit conditions (Abo-Koura *et al.*, 2025). Encapsulated PGPR promote growth and drought endurance by improving nitrogen, potassium, and essential mineral acquisition, expanding the root absorptive surface for enhanced water uptake, and modulating endogenous phytohormone balances (including indole-3-acetic acid [IAA], abscisic acid [ABA], cytokinins [CK], and gibberellins [GA] (Asif *et al.*, 2023).

Salicylic acid (SA) is an endogenous phenolic phytohormone that functions as a critical signaling molecule in regulating plant growth and development. It has gained widespread recognition for its capacity to enhance plant tolerance against abiotic stresses, particularly drought. Under moisture-deficit conditions, SA modulates key physiological processes, including photosynthetic efficiency, water relations, and nitrogen metabolism. Furthermore, SA plays an indispensable role in controlling stomatal closure, transpiration rates, protein biosynthesis, root nutrient and water uptake, and the inhibition of ethylene synthesis (Gulfam *et al.*, 2021, b). It mitigates abiotic stress damage by inducing glycine betaine accumulation and activating the enzymatic and non-enzymatic antioxidant defense systems (Wang *et al.*, 2019). Additionally, SA can trigger mitochondrial alternative oxidase (AOX) pathways, which serve a protective role in maintaining metabolic stability under stress (Fernandes *et al.*, 2022). Beyond vegetative resilience, SA significantly influences floral development and reproductive yield, likely by maintaining cellular turgor, preserving enzymatic activity under stress, and optimizing overall metabolic efficiency (Hassoun and Abdel-Jabbar, 2019). Because water scarcity is a primary abiotic threat to Egyptian agriculture, identifying sustainable solutions to alleviate drought damage is essential. Therefore, the present study was conducted to investigate the response of fennel (*Foeniculum vulgare* Mill.) to co-inoculation with encapsulated *Lelliottia amnigena* MSR-M49 and salicylic acid (SA) under water-stress conditions.

2. Materials and Methods

2.1. Site description and Experimental design

Field experiments were carried out in clay loam soil at the Agricultural Research Centre (ARC), Giza, Egypt (31° 11' longitude (30° 02' N, 31° 13' E) over two consecutive seasons (2019/2020 and 2020/2021) to assess the impact of encapsulated *Lelliottia amnigena* MSR-M49 and salicylic acid (SA) on drought-stressed fennel (*Foeniculum vulgare* Mill.). Fennel seeds (obtained from the Medicinal and Aromatic Plants Research Department, Dokki) were sown on November 4th and 8th in the respective seasons. Sowing was performed at 30 cm intra-row hill spacing and 60 cm inter-row spacing, later thinned to two plants per hill. The trial utilized a split-plot design with three replicates and 12 treatment combinations. Plot dimensions were 3 x 1.5 m (4.5 m²), housing 24 plants (Main plots received three irrigation regimes starting at the three-leaf stage: 15-day (normal condition I₁), 21 days (moderate water deficit stress I₂) and 30 days (severe water deficit stress I₃) intervals. Sub-plots comprised four soil/foliar treatments: control, SA, bacterial microcapsules, and SA + bacterial microcapsules. Recommended doses of NPK fertilizers were applied per Egyptian Ministry of Agriculture recommendations.

2.2. Initial Soil Sampling and Analysis

Prior to sowing in each season, composite soil samples were collected from the experimental field at a depth of 0–30 cm using a soil auger. The samples were air-dried, crushed, and passed through a 2-mm sieve for physical and chemical analyses. Soil particle size distribution was determined according to the method of (Piper, 1950), while physical properties were evaluated following (Klute, 1986) and (Page *et al.*, 1982). Chemical characteristics were analyzed as described by (Ryan *et al.*, 1996). The initial physical and chemical properties of the experimental soil and irrigation water across both growing seasons are summarized in Tables A and B.

Table (A). Soil physical and chemical properties at the experimental site

Season	Particle size distribution			Textural class	Chemical properties					
	Clay	Silt	Sand		O.M. (%)	EC dSm ⁻¹ (1:5)	Available (ppm)			pH (1:2.5)
							N	P	K	
2019/2020	40.8	35.4	23.8	Clay loam	1.84	0.99	45.00	12.5	191.90	7.75
2020/2021	40.7	36.2	23.1		1.82	0.89	41.02	10.00	194.80	7.75

Table (B). Soil water constants and bulk density at the experimental site

Depths (cm)	Field capacity (%)	Wilting point (%)	Available moisture (%)	Bulk density (g cm ⁻³)	Available moisture (mm/layer)	
0-15	35.8	18.8	17.0	1.21	31.0	59.1
15-30	33.4	17.3	16.1	1.18	28.1	
30-45	31.9	15.1	16.8	1.25	31.5	65.5
45-60	31.7	16.8	14.9	1.52	34.0	

2.3. Bacterial Strain Growth and Encapsulation

The bacterial strain *Lelliottia amnigena* MSR-M49 (GenBank Accession No. MN494098) was obtained from the Department of Agricultural Microbiology, Soils, Water and Environment Research Institute (SWERI), Agricultural Research Centre (ARC), Giza, Egypt. The strain was cultured in 100 mL of Luria-Bertani (LB) broth medium and incubated at 28°C for 48h with continuous shaking to achieve a cell density of approximately 10⁷ CFU mL⁻¹. Bacterial microcapsules were subsequently prepared according to the protocol described by (Abo-Koura *et al.*, 2025).

2.4. Inoculation with Encapsulated *Lelliottia amnigena*

The wet bacterial microcapsules were manually blended with fennel seeds immediately prior to sowing to ensure uniform seed mixed, following the method described by (Saad *et al.*, 2020).

2.5. Salicylic Acid (SA) Application

Salicylic acid (SA) was obtained from the (Aldrich Chemical Co., Egypt) was dissolved in distilled water to prepare a 100 ppm (100 mg L⁻¹) solution for foliar application. Plants were sprayed until runoff using a calibrated hand sprayer, with Nestapon added as a surfactant/wetting agent at a concentration of 1.0 mL L⁻¹. Foliar applications were carried out three times during each growing season: the first spray was applied at 14 days after sowing, followed by subsequent applications at 21 and 30 days after sowing. All foliar sprays were performed early in the morning (1h after sunrise) to cover both the adaxial and abaxial surfaces of the leaves (Abd El-Mageed *et al.*, 2016).

2.6. Recorded Data

Fennel plant responses to the tested irrigation intervals in conjunction with the use of capsules *Lelliottia amnigena* MSR-M49 and salicylic acid were monitored over the two experimental seasons by recording the following data:

2.6.1. Vegetative Growth Parameters

Across both experimental seasons, vegetative growth parameters were evaluated prior to the onset of flowering. Three representative plants per row were sampled to determine plant height (cm), branch number per plant, and fresh and dry weights per plant (g).

2.6.2. Fruit Yield and its Components

Plants were harvested on May 18th across both experimental seasons. The number of umbels per plant and the seed index (weight of 100 seeds, expressed in grams) were recorded. Individual fruit yield per plant (g) and total fruit yield per feddan were mathematically calculated and reported.

2.6.3. Quantification and Chemical Profiling of Essential Oil

Volatile oil was extracted from fruit tissues across treatments using distillation as detailed by (British, 1963). The essential oil content (%) was determined, and mathematical calculations were applied to estimate essential oil yield per plant and per feddan. Furthermore, essential oil samples collected during the first growing season (2019/2020) underwent gas-liquid chromatographic (GC) analysis following the protocols of (Hoftman, 1967) and (Bunzen *et al.*, 1969) to resolve and quantify the dominant chemical components.

2.6.4. Physiological and Biochemical Parameters

Chlorophyll concentration in fennel foliage was quantified using the methodology outlined by (Nornai, 1982). Total carbohydrate content in dried leaf samples was quantified in accordance with the method of (Herbert *et al.*, 1971). Total nitrogen (N) content was determined using the modified micro-Kjeldahl method as outlined by (Pregl, 1945). Phosphorus (P) content was evaluated according to the protocol described by (Allen *et al.*, 1974), while potassium (K) content was quantified via atomic absorption spectrometry in accordance as pronounced by (Jackson, 1973).

2.6.5. Osmotic parameters

Total phenolic content was quantified using the Folin-Ciocalteu colorimetric assay, following the protocol described by (Barka *et al.*, 2006). Absorbance was recorded at 750 nm, with gallic acid serving as the standard reference. Results were expressed as mM gallic acid equivalents per gram of fresh weight (mM GA eq/g FW). Proline accumulation was measured after 30 days from sowing following the colorimetric procedure described by (Bates *et al.*, 1973). For antioxidant enzyme profiling, catalase (CAT) activity was measured according to (Aebi, 1983), ascorbate peroxidase (APX) activity was evaluated following (Nakano and Asada, 1981), and superoxide dismutase (SOD) activity was determined using the method outlined by (Donahue, 1997). Relative Water Content (RWC %) of the shoots was evaluated 60 days post-sowing. To determine RWC, the fresh mass (FM) of shoot samples was recorded immediately upon harvest. Samples were subsequently placed in an environment with 100% relative humidity at 40°C in the dark for 4 hours to record their turgid mass (TM). Finally, the tissues were oven-dried at 70°C until a constant mass was reached to obtain the dry mass (DM). Shoot RWC % was calculated using the equation established by (Sharp *et al.*, 1990):

$$\text{RWC \%} = (\text{FM-DM} / \text{TM-DM}) \times 100$$

2.6.6. Phytohormone Analysis in Fennel

To quantify endogenous phytohormone levels (IAA, GA and ABA) 60 days after sowing; 10 g of fresh tissue per sample was homogenized in 70% (v/v) methanol and stirred continuously at 4 °C overnight. The extract was filtered through a Millipore membrane filter and analyzed using high-performance liquid chromatography (HPLC) following the method described by (Wurst *et al.*, 1984).

2.6.7. Dehydrogenase enzyme

The dehydrogenase activity was also determined according to (Skujins and Burns, 1976) at 60 days from sowing.

2.6.9. Soil-water relations

2.6.9.1. Applied irrigation water (AIW)

A furrow surface irrigation method was used to conduct this treatment. An experimental plot of 4.5 m². 3x1.5 m with furrows spaced at 0.6m was used. The depth of applied irrigation water (AIW) to the experimental plots was calculated according to the following equation:

$$AIW = ET_c / E_a$$

Where:

ET_c = water consumptive use (CU, mm/d), or actual evapotranspiration (ET_c).

E_a = application efficiency (fraction) = 0.6 for surface system at the site.

A submerged flow orifice with fixed dimensions was used to measure the amount of water applied to the experimental plots. The discharge of the orifice was calculated according to the following equation (Michael, 1978).

$$Q = CA \sqrt{2gh}$$

where:

Q = discharge through orifice, (cm³/sec)

C = coefficient of discharge (0.6 up to 0.8).

A = cross-sectional area of the orifice (cm²)

g = acceleration of gravity (981 cm/sec²).

h = head of water causing discharge through the orifice (cm).

2.6.9.2. Crop water productivity (WP)

WP is defined as crop yield per unit applied irrigation water that is looking into the efficient use of applied irrigation water (Zhang, 2003) and is given as follow:

$$WP = \frac{\text{Fruit yield (kg/fed)}}{\text{Applied irrigation water (m}^3\text{/fed)}}$$

2.7. Statistical Analysis

The collected data were subjected to statistical analysis according to (Little and Hills, 1978). Mean separation was done using the least significant difference test at 5% level (LSD 0.05).

3. Results

3.1. Vegetative growth characteristics

Results represented effects of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interactions under irrigation intervals on vegetative parameters of fennel plant during the two tested seasons are recorded in (Table 1).

Acknowledging that the application of salicylic acid or encapsulated *Lelliottia amnigena* MSR-M49 had a significant impact on the various vegetative growth characteristics of the fennel (*Foeniculum vulgare*, Mill) plant, as measured by plant height (cm), number of branches per plant, and fresh and dry plant weights (g). When compared to the untreated plants, the inoculation with *Lelliottia amnigena* MSR-M49 or foliar salicylic acid (SA) treatments generally increased the values of these traits and

encouraged vegetative growth. Plants treated with salicylic acid (SA) and inoculated with *Lelliottia amnigena* MSR-M49 in both seasons showed gradual increases in the aforementioned features, which were followed by treatments inoculated with *Lelliottia amnigena* MSR-M49 individually. Lowest growth parameters were recorded in fennel plants which treated by salicylic acid (SA) individually.

Data on irrigation intervals were entered into (Table 1). According to the findings, vegetative growth indicators gradually and significantly decreased when irrigation intervals increased (i.e., from every 15 days to every 21 days, and finally to every 30 days) in both seasons. Plants that received irrigation every 15 days had the highest average vegetative attributes when compared to those that received irrigation every 30 days.

Significant effects on vegetative growth parameters were noted throughout the two tested seasons with regard to the interaction effects of irrigation intervals, salicylic acid (SA), and *Lelliottia amnigena* MSR-M49 inoculation (Table 1). In general, these characteristics increased significantly when salicylic acid (SA) and capsules of bacteria inoculation were combined under the irrigation intervals used. Plants treated with both salicylic acid (SA) and capsules of bacteria inoculation under I₁ interval showed the greatest results. Conversely, under conditions of severe water stress I₃, the control group experienced a sharp decline, reaching its lowest levels. However, the application of the combination treatment using salicylic acid (SA) in addition to inoculation of capsules of bacteria under the same drought conditions (30 days) improved these vegetative parameters. This was true during the two seasons.

3.2. Flowering growth characteristics

The effects of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interactions under Irrigation intervals on flowering parameters of fennel plant, during the two tested seasons are recorded in (Table 2).

The data in (Table 2) demonstrate the impact of *Lelliottia amnigena* MSR-M49 or/and salicylic acid treatments in both seasons. In comparison to the control, these treatments significantly increased the number of umbels/plant, the weight of 100 fruit (g), the fruit yield/plant (g), and the fruit yield/faddan (tonne). Plants treated with salicylic acid (SA) and inoculated with capsules of bacteria yielded the highest results, followed by treatments inoculated with capsules of bacteria alone. Fennel plants treated with salicylic acid (SA) alone showed the lowest values of that characteristic.

The data in (Table 2) further demonstrates that, in comparison to the control group, plants that received irrigation every 15 and 21 days had a substantial impact on the number of umbels per plant, 100-fruit weight (g), fruit yield per plant (g), and fruit output per faddan (tonnes) in both seasons. Plants that received irrigation every 30 days, on the other hand, had the lowest values for the flowering parameters tested in both seasons.

Data in (Table 2) show that the irrigation intervals from 21 and 30 days significantly decreased no. of umbels/plant, 100-fruit weight (g), fruit yield /plant (g), and fruit yield /faddan (tons). Whereas salicylic acid (SA) application or/ and inoculated with *Lelliottia amnigena* MSR-M49 under different irrigation intervals significantly enhancement these flowering parameters. Generally, the combination treatment between salicylic acid (SA) and capsules of bacteria under irrigated I₁ had the highest effect on these parameters. On the other hand, the combined application of salicylic acid (SA) and inoculated with *Lelliottia amnigena* MSR-M49 under the long irrigation interval (30 days) caused an increasing of flowering parameters in first and second season compared to the control and individual treatments under the same irrigation interval.

Table (1). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on plant vegetative parameters of fennel plant under water stress conditions during two seasons

Irrigation intervals	First season 2019/2020					Second season 2020/2021				
	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.
Plant height (cm)										
15 days	125.14	135.75	141.30	147.00	137.30	121.65	132.17	138.34	144.82	134.25
21 days	122.18	132.07	138.72	144.25	134.31	118.22	129.88	135.45	141.55	131.28
30 days	114.65	118.25	128.45	129.83	122.80	112.45	115.64	123.75	126.63	119.62
Mean of SA&PGPR	120.66	128.69	136.16	140.36		117.44	125.90	132.51	137.67	
L.S.D.5% Irr	2.103					2.087				
L.S.D.5% SAxPGPR	3.412					3.110				
Interaction	1.547					1.230				
No. of branches/plant										
15 days	7.10	9.94	11.25	14.16	10.59	6.25	8.50	10.86	13.00	9.65
21 days	6.25	8.82	10.15	12.54	9.44	5.50	7.37	9.70	11.25	8.46
30 days	4.17	5.24	7.86	8.30	6.39	3.09	4.45	6.18	7.05	5.19
Mean of SA&PGPR	5.84	8.00	9.75	11.63		4.95	6.77	8.91	10.43	
L.S.D.5% Irr	0.412					0.347				
L.S.D.5% SAxPGPR	1.003					0.988				
Interaction	0.247					0.213				
Fresh weight of plant (gm)										
15 days	365.12	465.20	500.45	586.70	479.37	348.15	446.44	485.73	535.40	453.93
21 days	337.33	439.82	486.15	545.22	452.13	327.45	428.25	460.05	502.66	429.60
30 days	285.45	320.16	383.75	417.91	351.82	277.80	315.63	361.70	406.22	340.34
Mean of SA&PGPR	329.30	408.39	456.78	516.61		317.80	396.77	435.83	481.43	
L.S.D.5% Irr	12.354					11.201				
L.S.D.5% SAxPGPR	15.427					13.875				
Interaction	11.552					9.569				
Dry weight of plant (gm)										
15 days	54.77	69.78	75.07	88.01	71.91	52.22	66.97	72.86	80.31	68.09
21 days	50.60	65.97	72.92	81.78	67.82	49.12	64.24	69.01	75.40	64.44
30 days	42.82	48.02	57.56	62.69	52.77	41.67	47.34	54.26	60.93	51.05
Mean of SA&PGPR	49.40	61.26	68.52	77.49		47.67	59.52	65.38	72.21	
L.S.D.5% Irr	3.574					3.126				
L.S.D.5% SAxPGPR	6.542					5.722				
Interaction	3.222					3.047				

Salicylic acid (SA)

Lelliottia amnigena MSR-M49 (Capsules PGPR)

Irrigation intervals (Irr.)

Table (2). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on plant flowering parameters of fennel plant under water stress conditions during two seasons

Irrigation intervals	First season 2019/2020					Second season 2020/2021				
	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.
No. of umbels/plant										
15 days	39.12	60.70	72.50	84.31	64.16	37.08	58.30	70.50	80.66	61.64
21 days	34.45	52.33	66.17	77.15	57.53	32.47	49.08	64.10	75.45	55.28
30 days	28.06	30.88	42.82	47.98	37.44	25.18	28.45	40.22	45.72	34.89
Mean of SA&PGPR	33.88	47.97	60.50	69.81		31.58	45.28	58.27	67.28	
L.S.D.5% Irr	5.233					3.536				
L.S.D.5% SAxPGPR	7.332					5.854				
Interaction	2.687					2.009				
Weight of 100 fruit (gm)										
15 days	0.90	1.32	1.66	2.08	1.49	0.80	1.24	1.52	1.97	1.38
21 days	0.86	1.20	1.45	1.88	1.35	0.74	1.09	1.34	1.72	1.22
30 days	0.68	0.76	0.96	1.03	0.86	0.55	0.63	0.85	0.98	0.75
Mean of SA&PGPR	0.81	1.09	1.36	1.66		0.70	0.99	1.24	1.56	
L.S.D.5% Irr	0.102					0.065				
L.S.D.5% SAxPGPR	0.255					0.207				
Interaction	0.087					0.034				
Fruit yield/ plant (gm)										
15 days	55.25	60.34	64.33	70.05	62.49	51.46	55.40	60.38	67.42	58.67
21 days	46.65	54.55	61.25	66.75	57.30	40.80	50.83	57.75	60.81	52.55
30 days	40.17	47.76	50.91	60.48	49.83	36.25	41.07	45.33	52.62	43.82
Mean of SA&PGPR	47.36	54.22	58.83	65.76		42.84	49.10	54.49	60.28	
L.S.D.5% Irr	3.024					2.741				
L.S.D.5% SAxPGPR	4.412					3.631				
Interaction	2.327					2.107				
Fruit yield/ fed (ton)										
15 days	1.238	1.352	1.441	1.569	1.400	1.153	1.241	1.353	1.510	1.314
21 days	1.045	1.222	1.372	1.495	1.284	0.914	1.139	1.294	1.362	1.177
30 days	0.900	1.070	1.140	1.355	1.116	0.812	0.920	1.015	1.179	0.982
Mean of SA&PGPR	1.061	1.215	1.318	1.473		0.960	1.100	1.221	1.350	
L.S.D.5% Irr	0.144					0.136				
L.S.D.5% SAxPGPR	0.115					0.104				
Interaction	0.098					0.084				

Salicylic acid (SA)

Lelliottia amnigena MSR-M49 (Capsules PGPR)

Irrigation intervals (Irr.)

3.3. Quantification and Chemical Profiling of Essential Oil

Recorded data representing quantification and chemical profiling of essential oil are in (Tables 3 and 4).

3.3.1. Effect of *Lelliottia amnigena* MSR-M49 or/ and salicylic acid treatments

In comparison to control plants over the course of the two seasons, the results in (Table 3) show that inoculation of capsules of bacteria or/and salicylic acid treatments considerably enhanced the percentage of essential oil in fruits. In the first season, the fruit essential oil percentage mean was 2.154, 2.134, and 2.107% compared to 2.077% in control plants; in the second season, it was 2.144, 2.124, and 2.098% compared to 2.066% in control plants for plants treated with capsules of bacteria plus salicylic acid, followed by those treated with capsules of bacteria individually then salicylic acid individually, respectively. From the previously discussed results of such research, it could be noticed that capsules of bacteria or/ and salicylic acid treatments which improved plant height, branches No/ plant, umbels No/ plant, and fruit yield per plant also increased fruit essential oil percentage.

According to data in (Table 3), the application of encapsulated of bacteria or/and salicylic acid treatments considerably boosted the essential oil yield/plant (ml) during the course of the two seasons when compared to the control. Additionally, unfertilized (control) plants produced much lower oil yields (0.985 and 0.886 ml/plant in the first and second seasons, respectively), whereas capsules of bacteria and salicylic acid treatment produced the highest oil yield/plant (1.418 and 1.294 ml/plant in the first and second seasons, respectively). Similarly, for oil yield /faddan (L), the results in (Table 3) followed the same trend as for oil yield / plant in both seasons, with plants treated with capsules of bacteria and salicylic acid recording the highest oil yield /faddan (L), followed by plants inoculated with capsules of bacteria alone, and then plants treated with salicylic acid alone, compared to untreated plants.

The capsules of bacteria or/and salicylic acid influence on the primary constituents of the extracted essential oil was demonstrated by the data in (Table 4). When compared to control plants or plants treated with other treatments, it is evident that the inoculation with capsules of bacteria and foliar salicylic acid (SA) produced the highest percentages of the primary identified essential oil constituents. However, the largest amounts of α -pinene (3.10%), β -pinene (3.81%), anethole (24.53%), anise aldehyde (9.85%), and fenchone (30.55%) were found in the essential oil generated under that treatment. Conversely, compared to 39.20% of control plants, the estragole produced the lowest percentage (26.38%).

3.3.2. Effect of Irrigation intervals treatment

The results in (Table 3) show the effect of different irrigation intervals on the percentage of oil in fennel fruits in both seasons. Plants which irrigated every 15 and 21 days recorded the highest oil percentage (2.142% and 2.129% for the first season and 2.131% and 2.119% for the second season, respectively) compared to plants which irrigated every 30 days.

As for essential oil/plant production, the data in (Table 3) in both seasons showed that plants which suffered from a lack of irrigation water (30 days) gave the lowest oil yield/fennel plant (1.040 and 0.911 ml/plant for the first and second seasons, respectively) compared to those plants were irrigated every 15 or 21 days. It was observed that the plants which irrigated every 15 days recorded the highest oil yield /plant (1.340 and 1.252 ml/plant for the first and second seasons, respectively).

Regarding essential oil yield /faddan, the data in (Table 3) for both seasons showed the same trend for oil yield /plant. Plants were irrigated I_1 or I_2 days recorded a higher oil yield /faddan compared to plants under water stress (I_3). Plants irrigated every 15 days recorded the highest oil yield /faddan (30.016 and 28.045 liters for the first and second seasons, respectively). Conversely, plants irrigated every 30 days gave the lowest oil yield /faddan (23.291 and 20.401 liters for the first and second seasons, respectively).

Data represented the main components of the obtained essential oil as affected by irrigation intervals treatments (Table 4) revealed that the highest percentages of α - pinene, anethole, anise aldehyde, and fenchone (2.36 %, 22.40 %, 9.36 % and 27.72%, respectively) were recorded in essential oil extracted from plants were irrigated every 15 days, comparing to the other irrigation intervals. On the

contrary, the same treatment resulted in the lowest percentages of estragole 28.09% compared to 36.72% of the plants irrigated every 30 days.

Table (3). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on oil determinations of fennel plant under water stress conditions during two seasons

Irrigation intervals	First season 2019/2020					Second season 2020/2021				
	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.	Control	Salicylic acid (SA)	Capsule PGPR	SA+ PGPR	Mean of Irr.
Essential oil (%)										
15 days	2.095	2.132	2.152	2.188	2.142	2.085	2.124	2.140	2.174	2.131
21 days	2.087	2.122	2.144	2.164	2.129	2.074	2.117	2.133	2.152	2.119
30 days	2.048	2.066	2.105	2.111	2.083	2.040	2.052	2.100	2.106	2.075
Mean of SA&PGPR	2.077	2.107	2.134	2.154		2.066	2.098	2.124	2.144	
L.S.D.5% Irr	0.011					0.009				
L.S.D.5%PGP R	0.018					0.015				
Interaction SA&PGPR	0.020					0.010				
Essential oil yield/plant (mL)										
15 days	1.157	1.286	1.384	1.533	1.340	1.073	1.177	1.292	1.466	1.252
21 days	0.974	1.158	1.313	1.445	1.223	0.846	1.076	1.232	1.309	1.116
30 days	0.823	0.987	1.072	1.277	1.040	0.740	0.843	0.952	1.108	0.911
Mean of SA&PGPR	0.985	1.144	1.256	1.418		0.886	1.032	1.159	1.294	
L.S.D.5% Irr	0.140					0.128				
L.S.D.5%PGP R	0.123					0.120				
Interaction SA&PGPR	0.087					0.072				
Essential oil yield/faddan (L)										
15 days	25.917	28.806	31.002	34.339	30.016	24.035	26.365	28.941	32.838	28.045
21 days	21.818	25.939	29.411	32.368	27.384	18.950	24.102	27.597	29.322	24.993
30 days	18.435	22.109	24.013	28.605	23.291	16.576	18.883	21.325	24.819	20.401
Mean of SA&PGPR	22.057	25.618	28.142	31.771		19.854	23.117	25.954	28.993	
L.S.D.5% Irr	2.854					2.254				
L.S.D.5%PGP R	2.095					1.742				
Interaction SA&PGPR	1.661					1.153				

Salicylic acid (SA)

Lelliottia amnigena MSR-M49 (Capsules PGPR)

Irrigation intervals (Irr.)

3.3.3. Effect of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interactions under irrigation intervals

It is evident that the oil percentage in fennel fruits throughout both seasons was significantly impacted by the interaction between capsules of bacteria and salicylic acid under various watering intervals (Table 3). When compared to all other interaction treatments over both seasons, the plants that inoculated with capsules of bacteria plus salicylic acid during irrigation interval (I₁) had the highest essential oil percentages in their fruits. In this regard, the mean recorded 2.188% and 2.174% in the first and second seasons, respectively, followed by plants which treated by the same treatment under irrigation (I₂) (giving values of 2.164% and 2.152% in the first and second seasons, respectively),

whereas the least effective treatment was using salicylic acid (SA) individually under irrigation (I₃) which recorded (2.066% and 2.052% in the first and second seasons, respectively).

The combination treatments of capsules of bacteria and salicylic acid under different irrigation intervals application treatments caused considerable effects on essential oil yield per plant (Table 3). In general, the above 2 mentioned interaction treatments which caused significant increases in essential oil %; *i.e.* capsules of bacteria plus salicylic acid under irrigation interval (15 days) and with capsules of bacteria individually under irrigation (15 days) also caused significant increases in essential oil yield per plant as compared to the most of the other interaction treatments. On the other hand, inoculated with capsules of bacteria combined with foliar of salicylic acid resulted in a slight increase in oil yield/fennel plants under water stress (irrigation every 30 days) compared to the other treatments under the same irrigation interval (30 days).

It is clear that both seasons' oil output and faddan were significantly impacted by the interaction between capsules of bacteria and salicylic acid under various watering intervals (Table 3). When compared to all other interaction treatments during both seasons, plants that inoculated with capsules of bacteria + salicylic acid during irrigation interval (15 days) had the highest essential oil yield/faddan. In this regard, the average was 34.339 L and 32.838 L in the first and second seasons, respectively, followed by plants which treated by the same treatment under irrigation (21 days) yielded values of 32.368 L and 29.322 L in the first and second seasons, respectively. The least successful treatment was applied salicylic acid (SA) separately under irrigation for 30 days which recorded (22.109 L and 18.883 L in the first and second seasons, respectively).

The data in (Table 4) state that, the combined between capsules of bacteria and salicylic acid gave the highest values of the α - Pinene, β - Pinene, anethole, anise aldehyde, and fenchone contents (3.65%, 4.07%, 29.40%, 11.02%, and 36.18% respectively), under irrigation interval (15 days). comparing to the other treatments under different irrigation intervals. On the contrary, the same treatment resulted in the lowest percentages of estragole 21.82% compared to 36.72% of the plants irrigated every 30 days. Notably, even under severe water stress (30 days interval), the same treatment provided a robust protective effect, enhancing the main components of the obtained essential oil the untreated plants.

Table (4). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on the components (%) of essential oil of fennel plant under water stress conditions in the first season

Irrigation intervals	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.	Control	Salicylic acid (SA)	Capsules PGPR	SA+ PGPR	Mean of Irr.
α- Pinene						β- Pinene				
15 days	1.12	1.95	2.70	3.65	2.36	1.55	2.17	3.26	4.07	2.76
21 days	0.96	1.72	2.33	3.18	2.05	1.87	2.80	3.70	3.82	3.05
30 days	1.44	2.17	2.28	2.48	2.09	1.27	2.66	3.02	3.54	2.62
Mean PGP&SA	1.17	1.95	2.44	3.10		1.56	2.54	3.33	3.81	
Anise aldehyde						Fenchone				
15 days	6.87	9.23	10.33	11.02	9.36	19.12	25.43	30.14	36.18	27.72
21 days	6.51	8.60	9.74	10.71	8.89	18.80	23.44	27.85	33.72	25.95
30 days	6.08	6.23	7.15	7.82	6.82	17.53	18.07	19.92	21.76	19.32
Mean PGP&SA	6.49	8.02	9.07	9.85		18.48	22.31	25.97	30.55	
Anethole						Estragole				
15 days	16.00	20.70	23.51	29.40	22.40	36.90	28.44	25.20	21.82	28.09
21 days	14.74	19.46	21.82	26.57	20.65	39.52	31.10	26.73	23.07	30.11
30 days	13.51	16.36	17.02	17.63	16.13	41.17	35.00	36.45	34.25	36.72
Mean PGP&SA	14.75	18.84	20.78	24.53		39.20	31.51	29.46	26.38	

Salicylic acid (SA)

Lelliottia amnigena MSR-M49 (Capsules PGPR)

Irrigation intervals (Irr.)

3.4. Biochemical and Physiological Parameters

The results in (Figs. 1 and 2) obtained the effects of encapsulated *Lelliottia amnigena*, salicylic acid and their interactions under Irrigation intervals on total Chlorophyll (A&B) content, total Carbohydrates and mineral contents of Fennel plant.

Regarding the effects of capsules of bacteria or/and salicylic acid treatments on the chemical analysis of fennel plants, it is evident from the data in (Figs. 1 and 2) that all treatments at the two tested seasons increased the chemical analysis of fennel plants expressed as total chlorophyll (A&B), total carbohydrates, nitrogen, phosphorus, and potassium. Plants treated with capsules of bacteria plus salicylic acid showed the highest values, followed by those treated with capsules of bacteria alone. The combined treatment (SA + microencapsulated bacteria) yielded the highest total Chlorophyll concentrations, reaching 6.3 mg/g f.w. and 6.8 mg/g f.w. in the first and second seasons, respectively, compared to 5.1 mg/g f.w. and 5.5 mg/g f.w. for SA alone.

Data on irrigation intervals were documented in (Figs 1 and 2). Total chlorophyll (a and b), total carbohydrates, nitrogen, phosphate, and potassium all gradually and significantly decreased with increased irrigation intervals (i.e., from every 15 days to 21 days, and finally to 30 days) in both seasons, according to the data. Plants that received irrigation every 15 days had the highest average values for the aforementioned chemical analysis when compared to plants that received irrigation every 30 days.

During the two tested seasons, the combined treatments of salicylic acid and capsules of bacteria with different watering intervals had a substantial impact on the chemical analysis of fennel plants (Figs. 1 and 2). In comparison to the control group and all other reactive treatments, the interaction between capsules of bacteria and salicylic acid under a 15 days irrigation interval was most successful in raising the chemical analysis parameters recorded in fennel plants. This was followed by the same treatment under a 21 days irrigation interval. Although, the fennel plants were subjected to drought stress with irrigation every 30 days, the use of capsules of bacteria with salicylic acid mitigated the effects of drought and improved the measured chemical analysis results compared to the control plants.

3.5. Osmotic parameters

3.5.1. Leaf Phenolic Content, Proline Accumulation, and Relative Water Content (RWC)

According to data in (Fig. 3), drought stress significantly altered the concentration of phenolics, leaf proline, and relative water content (R.W.C.%). Plants treated with either salicylic acid or capsules of bacteria increased phenolic content, proline content, and relative water content (R.W.C%) in both seasons. When paired with salicylic acid and capsules of bacteria. In first season, severe water deficit reduced phenolics in untreated controls by 44% (I₂) and 70% (I₃). Co-application of SA and encapsulated bacteria restored phenolic levels to 3.7 mg GAE/g (I₂) and 3.3 mg GAE/g (I₃), compared to 1.5 mg GAE/g (I₂) and 0.8 mg GAE/g (I₃) in untreated controls. In comparison to plants treated with salicylic acid and *Lelliottia amnigena* capsules, untreated plants showed the maximum proline accumulation under watering circumstances of I₂ or I₃ days. All treatments salicylic acid or capsules bacteria saw a notable rise in proline content. In comparison to plants grown in regular irrigation water (15 days), plants treated with microcapsules alone showed the maximum proline accumulation recorded (6.1 mg/g d.w.) followed by plants treated with SA alone (5.8 mg/g d.w. under I₂) and the dual SA + bacteria treatment (5.1 mg/g d.w.). Leaf RWC % declined under water deficit, but bacterial encapsulation with or without SA significantly reduced drought-induced damage (Fig. 3). Under I₂, RWC increased by 21% (dual treatment) and 18% (bacteria alone). Under I₃, RWC improved by 21.4% (dual treatment) and 12% (bacteria alone).

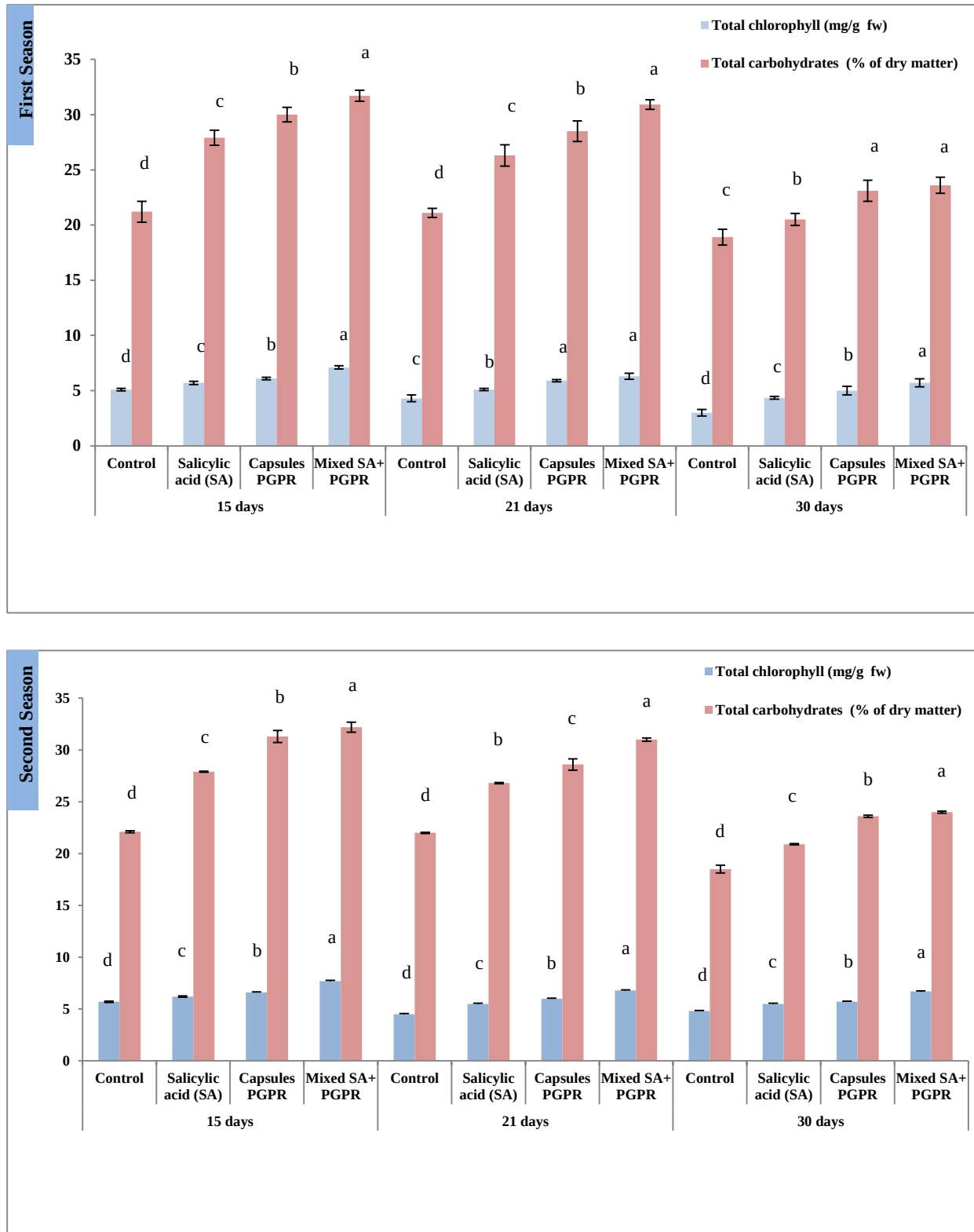


Fig (1). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on total chlorophyll (A&B) content and total carbohydrates content in leaves of fennel plant under water stress conditions during two seasons

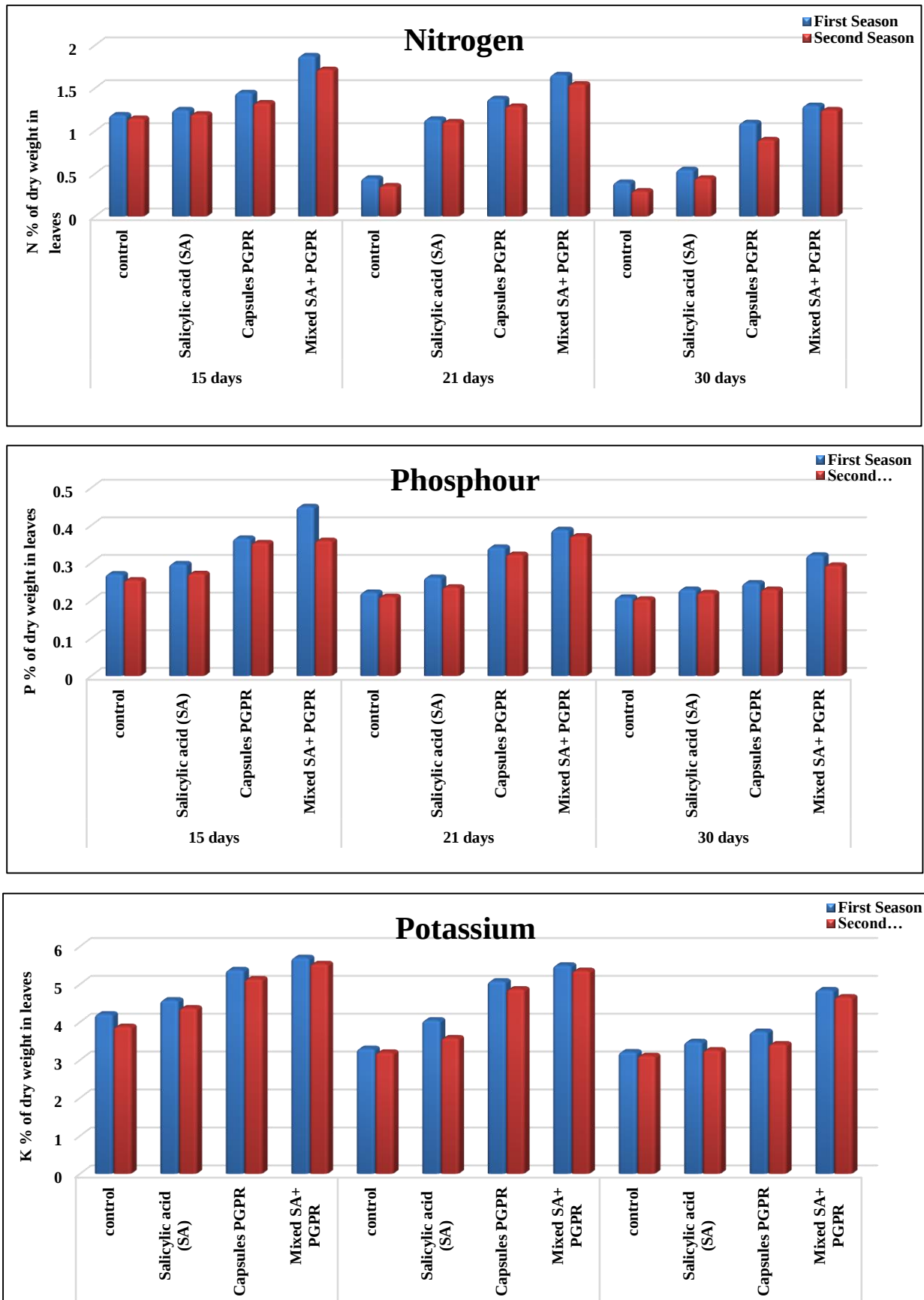


Fig (2). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on percentage of nitrogen, phosphorous and potassium in leaves of fennel plant under water stress conditions during two seasons

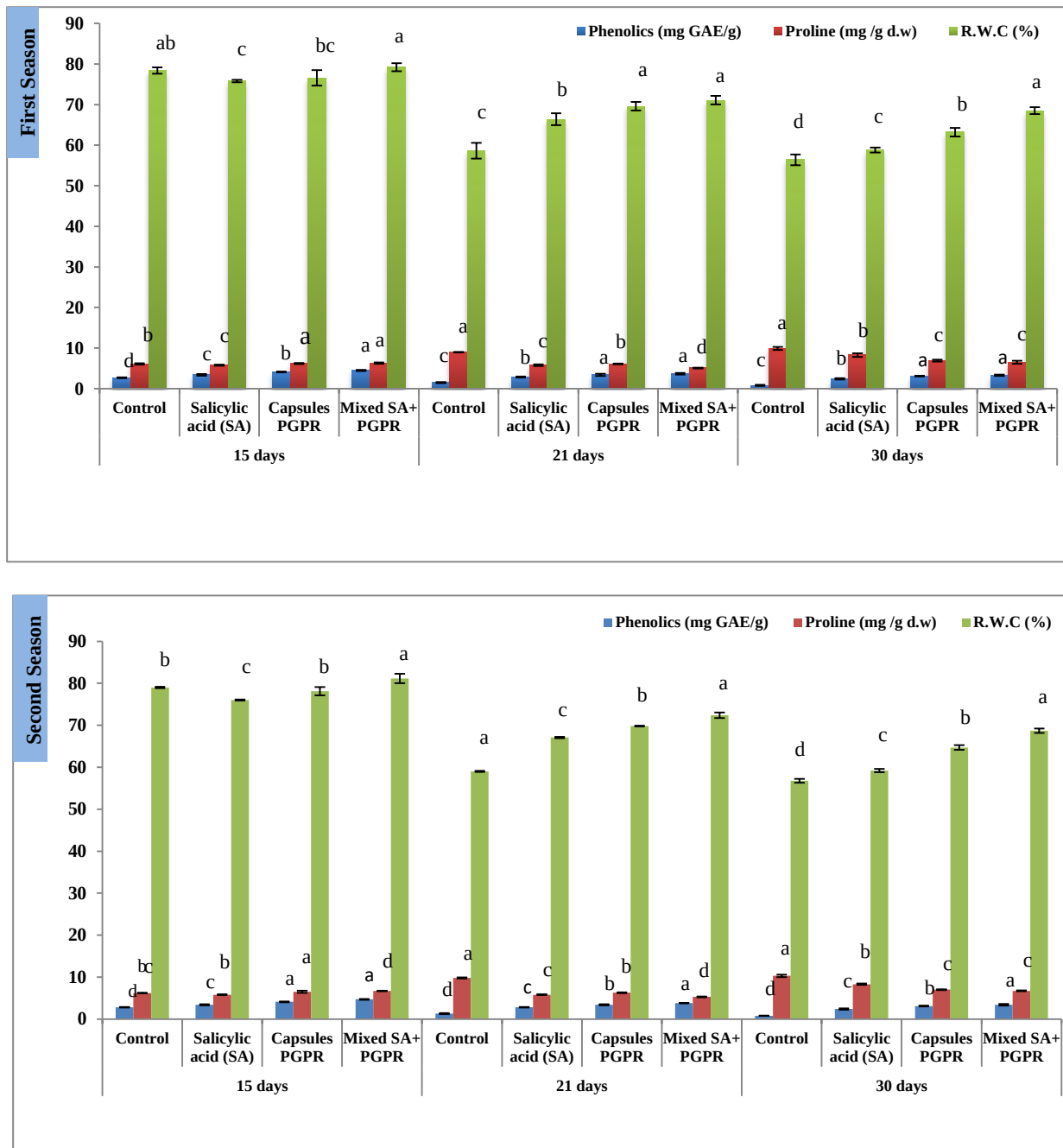


Fig (3). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on phenolic content, shoot proline content and relative water content (R.W.C.) in leaves of fennel plant under water stress conditions during two seasons

3.5.2. Leaf Antioxidant Enzyme Activities

In comparison to the control group, the results obtained in (Fig. 4) during the two experimental seasons show that the use of salicylic acid or capsules containing *Lelliottia amnigena* bacteria greatly increased the capacity of fennel leaves to scavenge free radicals caused by water stress. Furthermore, because there was less moisture available in both seasons, longer irrigation times (21 and 30 days) greatly boosted the antioxidant enzyme activity in fennel leaves. The leaves of untreated plants showed the biggest increases in the activity of the enzymes catalase (CAT), acetyl peroxidase (APX), and superoxide dismutase (SOD) at the irrigation intervals of I₂ and I₃ days. However, the use of (SA) alone or with capsules *Lelliottia amnigena* led to significant reductions in the concentrations of catalase (CAT), acetyl peroxidase (APX), and superoxide dismutase (SOD) enzymes, and mitigated the damaging effects of oxidative stress regardless of the irrigation interval. Under moderate drought stress

(I₂), untreated plants exhibited the highest peak activities for (CAT), APX, SOD, recording 5.8, 9.0, and 19.6 U mg⁻¹ protein in Season 1 (Fig. 4), and 6.0, 9.4, and 19.9 U mg⁻¹ protein in Season 2 (Fig. 4). Conversely, treating plants with SA alone or co-applying SA with microencapsulated bacteria significantly suppressed CAT, APX, and SOD activities relative to untreated stress controls across all irrigation intervals. This attenuation of enzyme activity indicates that the bio-inoculant and SA treatments effectively mitigated oxidative stress damage, reducing the plant's baseline requirement for high antioxidant enzyme synthesis even under severe water deficit (I₃).

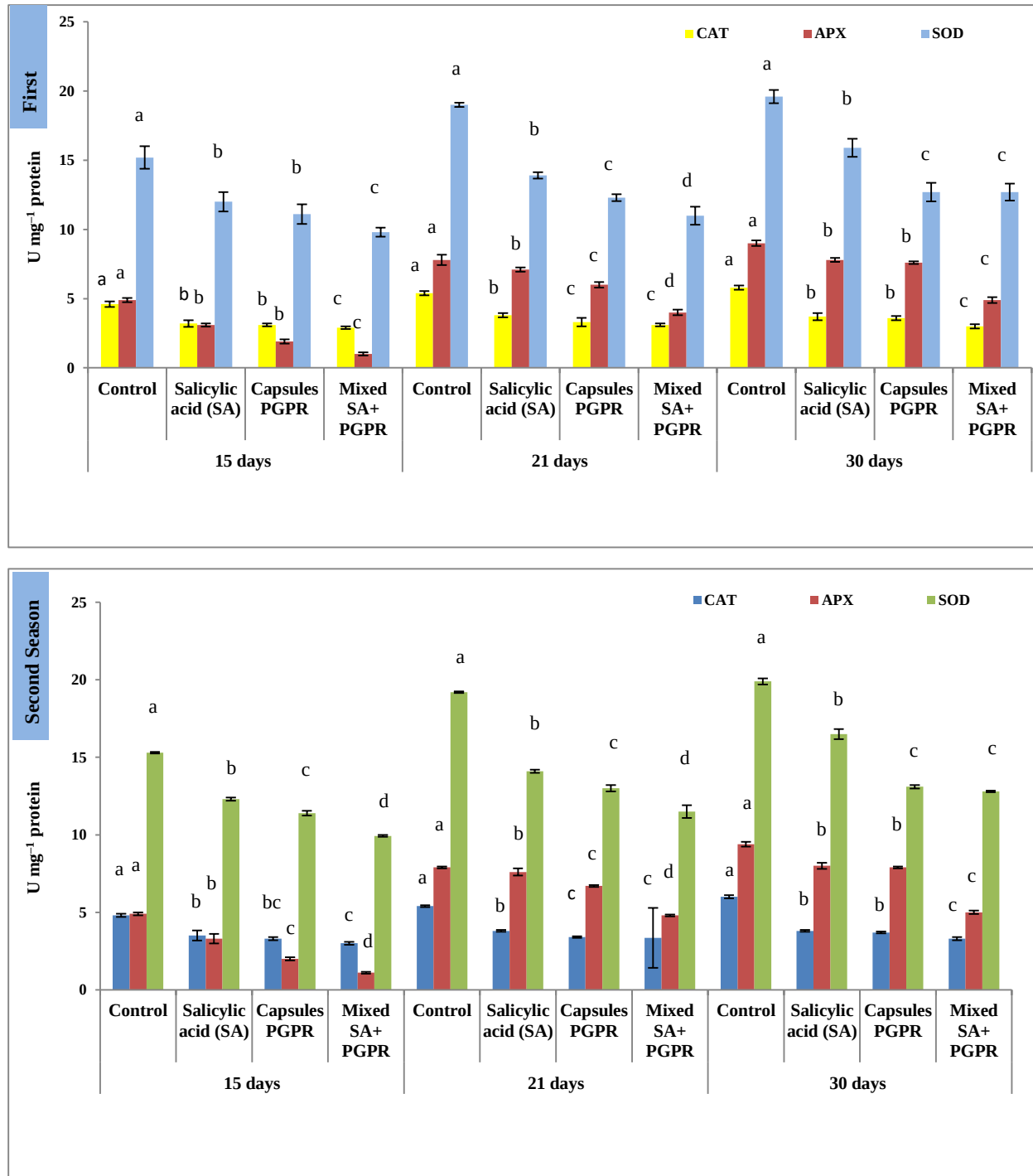


Fig (4). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on antioxidant enzymes in leaves of fennel plant under water stress conditions during two seasons

3.6. Phytohormones

Endogenous phytohormone levels were significantly enhanced by all applied treatments across both growing seasons compared to untreated drought-stressed controls (Fig. 5). Co-application of microencapsulated *L. amnigena* and (SA) markedly elevated (IAA), (GA), and (CK) concentrations in fennel leaves. Plants that received irrigation every 15 days showed the best results. In contrast to plants that were irrigated every 15 days, plants that were subjected to water stress (irrigation every 21 or 30 days) showed a drop in phytohormones across all treatments. However, under moderate drought stress (I_2), the combined treatment increased IAA by 69%, GA by 9.6% and CKs by 21.5% in the first season, and by 29% (IAA), 13% (GA), and 17% (CKs) in the second season relative to untreated, un-inoculated plants. Conversely, severe water deficit (I_3) led to a sharp drop in IAA, GA, and CK concentrations compared to well-watered conditions (I_1). Foliar application of SA alone produced slight increases in GA content, recording gains of 1.6% and 1.2% in the first and second seasons, respectively. Additionally, in both seasons, fennel leaves under water stress (21 or 30 days) had higher levels of abscisic acid (ABA) than plants that received irrigation every 15 days. Under I_2 , the combined application of encapsulated bacteria and SA reduced ABA levels by 48.0% in Season 1 and 48.6% in Season 2 compared to untreated controls, demonstrating greater efficacy than either single treatment. On the other hand, under non-stressed conditions (I_1), no significant differences in leaf ABA content were observed between treated and untreated plants.

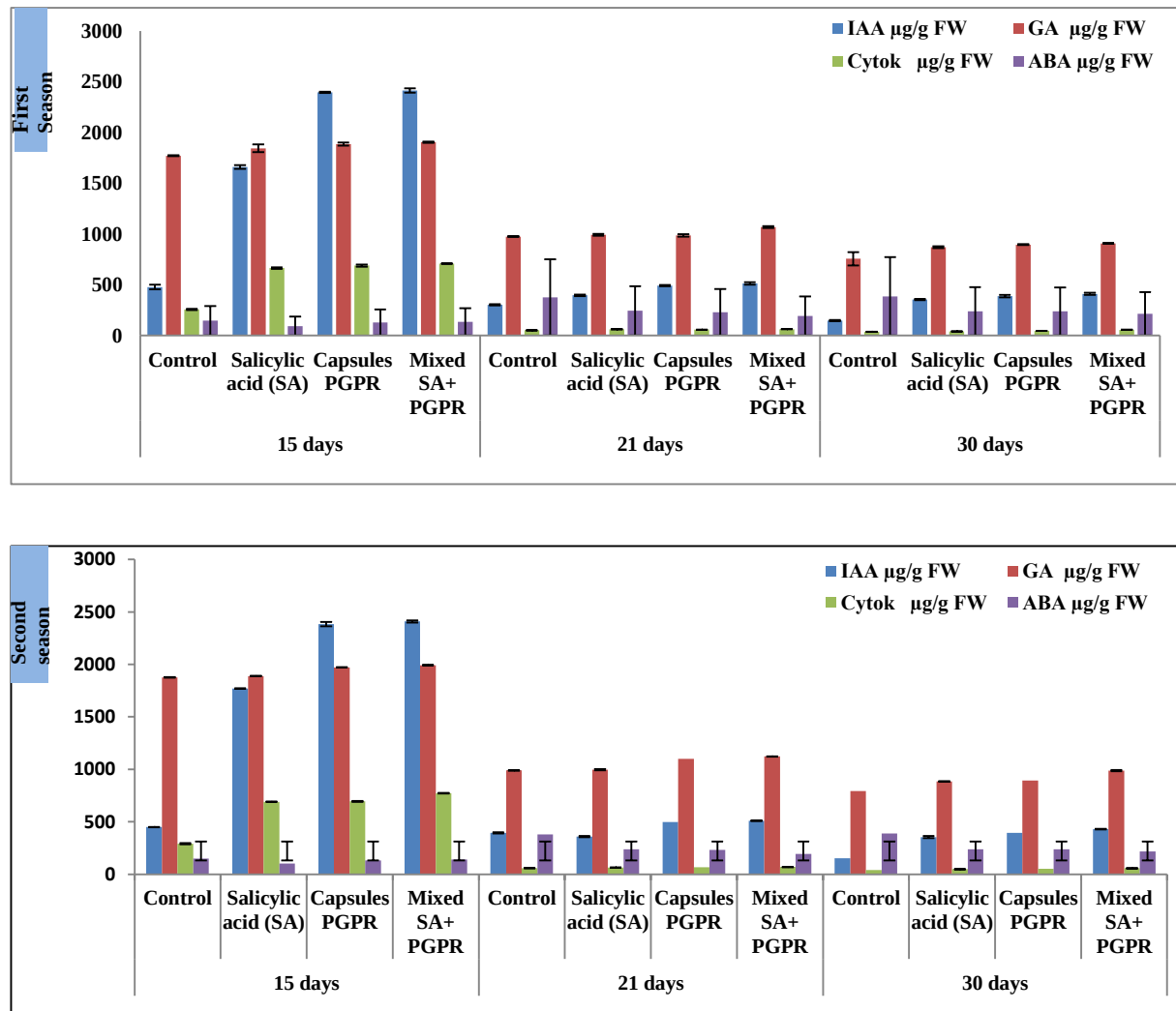


Fig (5). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on Phytohormone content in leaves of fennel plant under water stress conditions during two seaso

3.7. Dehydrogenase activity (DHA)

The effects of salicylic acid, encapsulated *Lelliottia amnigena* MSR-M49, and their interactions during irrigation intervals on the dehydrogenase enzyme (DHA) in the soil of fennel plants over the two tested seasons are shown in (Fig. 6). The findings demonstrate that, in comparison to the untreated control, all applied treatments showed a significant increase in soil dehydrogenase (DH) activity throughout all irrigation intervals. As the watering intervals increased from 15 days to 21 and 30 days, a gradual decrease in DH activity was noted. All treatments showed peak dehydrogenase (DH) activity during the 15 days irrigation interval, with the synergistic treatment a combination of salicylic acid and *Lelliottia amnigena* MSR-M49 achieving the highest total level of enzymatic activity. The different treatments utilizing SA and *Lelliottia amnigena* MSR-M49 capsules followed in descending sequence, with the control plants exhibiting the lowest amount of dehydrogenase (DH) activity. When compared to the 15 days interval, extending the irrigation interval caused a relative decrease in DH activity across all investigated treatments. The mixture of *Lelliottia amnigena* MSR-M49 and salicylic acid maintained the highest activity levels despite the moisture shortage, followed in order by *Lelliottia amnigena* MSR-M49 capsules, SA, and the control therapy. This shows that using these materials together successfully reduced mild water stress, maintaining high levels of microbial metabolic activity.

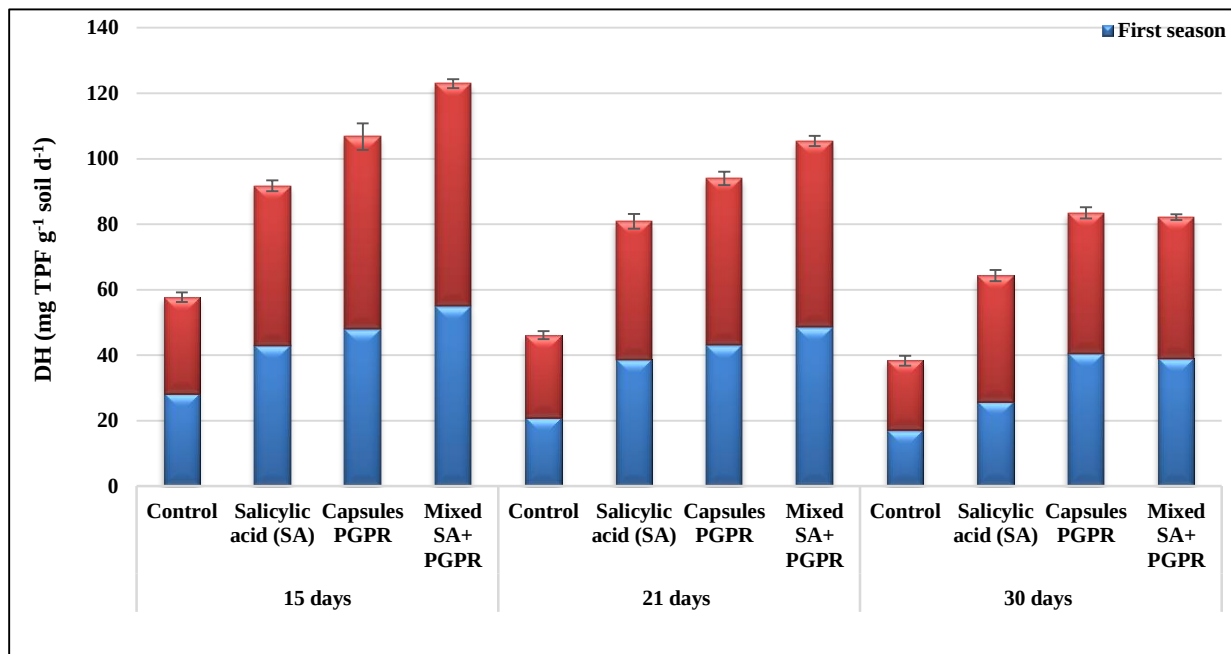


Fig (6). Synergistic role of encapsulated *Lelliottia amnigena* MSR-M49, salicylic acid and their interaction on dehydrogenase activity in soil of fennel plant under water stress conditions during two seasons

3.8. Soil–Water Relations

3.8.1. Applied Irrigation Water (AIW)

The total volume of applied irrigation water (AIW) for fennel across three irrigation regimes during the 2019/2020 and 2020/2021 growing seasons is presented in (Table 5). The results indicate that AIW varied depending on the irrigation frequency and seasonal climate variations. During the first season (2019/2020), total AIW ranged from 2.048 to 2.269 m³ fed⁻¹, whereas in the second season (2020/2021), it ranged from 2.102 to 2.325 m³ fed⁻¹. Overall, the 2019/2020 growing season required less irrigation water than the 2020/2021 season under all corresponding irrigation intervals.

Table (5). Total seasonal applied irrigation water (m³ fed⁻¹) as influenced by varying irrigation schedules across two consecutive growing seasons (2019/2020 and 2020/2021)

Irrigation intervals	Applied irrigation water (m ³ fed ⁻¹)		Mean
	2019/20	2020/21	
15 days	2177	2232	2205
21 days	2048	2102	2075
30 days	2269	2325	2297
Mean	2165	2219	

The reduced irrigation water requirement recorded during the 2019/2020 season can be attributed to inter-annual climatic variations, such as lower atmospheric evaporative demand, decreased reference evapotranspiration (ET_o), and fluctuations in ambient air temperature, relative humidity, wind speed, and precipitation patterns. These microclimatic variables govern crop water requirements, directly altering the overall volume of applied irrigation water required to maintain optimal soil moisture.

3.8.2. Water productivity, (kg/m³)

The results shown in (Table 6) show that irrigation at different intervals (15, 21 and 30 days) had a highly significant impact on the fennel crop's quantitative yield and irrigation water productivity (IWP) over the course of the two subsequent seasons, in addition to the total seasonal water applied (m³/fed). The total volume of water applied per feddan (m³/fed) was significantly reduced during both growing seasons when the irrigation intervals were extended from 15 days to 21 days.

Table (6). Water productivity (WP m³ fed⁻¹) of fennel (*Foeniculum vulgare* Mill.) as influenced by different treatments during the two seasons

Irrigation Interval	The total water applied, (m ³ /fed.)	The yield, kg/fed	The irrigation Water Productivity, kg/m ³	Water saved (m ³ /fed.)
	2019/2020			
(15 Days)	2177	1400	0.643	-----
(21 Days)	2048	1284	0.627	129
(30 Days)	2269	1116	0.492	----
	2020/2021			
(15 Days)	2232	1314	0.589	-----
(21 Days)	2102	1177	0.560	130
(30 Days)	2325	982	0.422	----

Specifically, the amount of water used dropped from 2232 to 2102 m³/fed in the second season and from 2177 to 2048 m³/fed in the first. In comparison to the regular, well-irrigation treatment (15 days interval), the fruit/herb yield per feddan gradually decreased when fennel (*Foeniculum vulgare* Mill.) plants were subjected to progressive water shortage stress (by irrigating every 21 and 30 days). The maximum yield was recorded under the 15 days irrigation interval, yielding 1400 kg/fed. and 1314 kg/fed. for the two successive seasons, respectively. Although the 15 days irrigation interval produced the highest absolute crop yield, the maximum Irrigation Water Productivity (IWP) was significantly achieved under the moderate irrigation interval (21 days). It recorded the highest values of 0.727 kg/m³ in the first season and 0.560 kg/m³ in the second season. Whereas the intensive irrigation treatment (15 days) exhibited the lowest water use efficiency. A satisfactory physiological balance is demonstrated by the increase in IWP during the 21 days interval. The significant decrease in the overall amount of water applied did not cause a significant decline in crop output at this intermediate interval. plants under mild-

to-moderate drought stress maximize their gas exchange and retain high photosynthetic water-use efficiency per m³ of water. The effectiveness of the applied *Lelliottia amnigena* MSR-M49 capsules actively maintained crop productivity through several growth-promoting mechanisms in the root zone, as evidenced by the lack of a significant decrease in fruit output under water deficit conditions (21days interval). Additionally, the exogenous injection of salicylic acid served as an essential physiological buffer; its function as a signaling molecule and antioxidant effectively mitigated the osmotic and oxidative stress brought on by the prolonged watering intervals.

The results presented in (Table 6) clearly demonstrate the water-saving potential of adjusting irrigation intervals. Extending the irrigation frequency from 15 to 21 days in the first season yielded significant water savings of 129 m³/fed (5.9% reduction in total applied water). A consistent trend was observed in the second season, achieving 5.8% reduction in irrigation volume for the same 21-day regime. Crucially, evaluating these water savings alongside agronomic performance revealed that the 21-day irrigation interval was particularly effective. It conserved nearly 6% of irrigation water while preserving vegetative growth, flowering performance, and essential oil yield. This optimal balance was enabled by a strong biological synergy with the combined application of encapsulated *Lelliottia amnigena* and (SA), which successfully mitigated drought stress and prevented yield losses under the extended watering schedule.

4. Discussion

Abiotic stresses including drought, salinity, and temperature extremes severely impair plant growth and agricultural productivity, leading to substantial global economic losses. Most abiotic stressors trigger oxidative stress within plant tissues, causing a rapid accumulation of cellular reactive oxygen species (ROS) (Kerchev *et al.*, 2020). Among these, drought remains a critical global environmental challenge, severely limiting crop yield and threatening international food security. Consequently, developing viable strategies to improve crop resilience and sustain plant growth under water-limited conditions is an urgent priority for modern agriculture (Chukwuneme *et al.*, 2020). Water deficit suppresses cell elongation, turgor pressure, and cellular volume, directly restricting overall plant height. The observed decline in shoot and root fresh and dry biomass under moisture stress is largely driven by diminished photosynthetic rates. In drought-affected fennel foliage, reduced carbon assimilation restricts carbohydrate accumulation within mature leaves, thereby limiting assimilate transport to actively developing sinks and ultimately depressing overall yield (Ahluwalia *et al.*, 2023). Under water stress, plants typically close their stomata to minimize transpiration water loss, which concurrently restricts CO₂ diffusion into the leaf mesophyll. This decline in stomatal conductance restricts CO₂ assimilation, directly impairing photosynthetic efficiency while simultaneously promoting reactive oxygen species (ROS) accumulation within plant tissues (Sachdev *et al.*, 2021). The decline in relative water content (RWC) under drought conditions is primarily driven by restricted internal water transport. Reduced water movement accelerates protoplasmic dehydration, triggers oxidative damage within chloroplasts, compromises membrane stability index (MSI), forces stomatal closure, and diminishes both mesophyll CO₂ concentration and photo assimilate production (Khatun *et al.*, 2021). Furthermore, moisture deficits physically extract water from the cellular membrane, disrupting and displacing the lipid bilayer structure, which directly reduces MSI (Panda *et al.*, 2021).

Soil microorganisms serve as vital, dynamic components of sustainable agricultural systems. To mitigate drought stress and improve crop productivity, these beneficial bacteria exhibit disease-suppressive traits and stimulate growth by synthesizing essential phytohormones and solubilizing soil minerals (Reddy *et al.*, 2024). Furthermore, plant growth-promoting rhizobacteria (PGPR) modify root system architecture, expanding total soil contact area by promoting main root development and prolific root hair formation (Zhang and Wang, 2025). This improves nutrient uptake by the host plant. Furthermore, by secreting low-molecular-weight signaling molecules such as 2, 4-diacetylphloroglucinol (DAPG), encapsulated PGPR can alter root morphology and system architecture (Vedulla, 2025). Plants inoculated with (PGPR) exhibited higher relative water content (RWC) than uninoculated controls. This elevated hydration status is largely attributed to the microbial synthesis of osmo-protectants such as proline, which preserve cell membrane integrity, mitigate electrolyte leakage, and restrict water loss under stress. Additionally, PGPR facilitate plant adaptation by producing

phytohormones like indole-3-acetic acid (IAA). IAA stimulates lateral root expansion and overall root architecture, thereby augmenting water and nutrient uptake, regulating stomatal conductance, moderating transpirational water loss, and sustaining essential metabolic and physiological functions. PGPR facilitate osmotic regulation in plants by driving the accumulation of compatible solutes, including soluble sugars, trehalose, glycine betaine, soluble proteins, and proline. This solute enrichment steepens the cellular water potential gradient, thereby enhancing water uptake and sustaining plant growth during moisture stress (**Shahid *et al.*, 2023**). Furthermore, phytohormone production by PGPR represents a key mechanism underlying plant tolerance to both biotic and abiotic stressors. Among these signaling molecules, auxins, gibberellins, abscisic acid, and cytokinins play predominant roles. Specifically, microbial synthesis of indole-3-acetic acid (IAA) loosens plant cell walls and stimulates root exudation, which subsequently fuels microbial proliferation and rhizosphere colonization. Together, these root-zone dynamics significantly bolster plant resilience against drought stress. Inoculation with PGPR assists plants in counteracting reactive oxygen species (ROS)-induced oxidative stress by upregulating both enzymatic and non-enzymatic antioxidant defense systems. Consequently, this enhances plant membrane stability and physiological integrity while reducing hydrogen peroxide H_2O_2 accumulation, electrolyte leakage, and malondialdehyde (MDA) content (**Chiappero *et al.*, 2019**). Furthermore, PGPR confer drought tolerance by increasing the activities of key antioxidant enzymes, including superoxide dismutase (SOD), ascorbate peroxidase (APX), peroxidase (POD), and catalase (CAT) (**Batool *et al.*, 2020**).

Salicylic acid (SA) is a ubiquitous phenolic phytohormone that plays a pivotal role in plant defense mechanisms and regulates diverse physiological processes (**Raza *et al.*, 2023**). By enhancing stomatal conductance, SA promotes net carbon dioxide (CO_2) assimilation (**Zulfikar *et al.*, 2024**). Furthermore, SA application mitigates lipid peroxidation under drought conditions, supports plant height and dry biomass accumulation, and limits toxic ion accumulation and electrolyte leakage (**Ahmad *et al.*, 2024**). Salicylic acid (SA) alleviates drought-induced oxidative stress by regulating key enzymatic and non-enzymatic defense mechanisms, including the glyoxalase pathway (**Bhardwaj *et al.*, 2023**). Furthermore, SA enhances drought tolerance by stimulating root cell division and expansion within the apical meristem (**Pasternak *et al.*, 2019**). Additionally, SA contributes to osmotic adjustment by enhancing root water uptake capacity (**Hussain *et al.*, 2024**). Optimizing soil moisture extraction facilitates transpiration flow and stomata conductance, which elevates carbon dioxide (CO_2) fixation, thereby driving biomass accumulation and crop yield. Furthermore, SA enhances photosynthetic capacity by increasing total leaf area and expansion rate (**Bagautdinova *et al.*, 2022**). Additionally, salicylic acid (SA) enhances nitrogen absorption and assimilation efficiency, elevates photosynthetic performance, and significantly increases endogenous cytokinin levels within both leaves and reproductive structures (**Saleem and Rehman 2025**). Furthermore, SA application preserves leaf turgor pressure, maintains chlorophyll and carotenoid concentrations, and optimizes stomatal conductance, all of which are critical factors conferring drought tolerance (**Bhardwaj *et al.*, 2023**). Furthermore, under water deficit conditions, exogenous application of salicylic acid (SA) significantly elevates relative water content (RWC) as well as the accumulation of proline, soluble sugars, and starch. This response indicates that SA facilitates cellular rehydration and tissue water status recovery, thereby protecting plants against osmotic stress. Additionally, SA application enhances root water uptake capacity, which promotes nutrient availability and sustains photosynthetic activity a process further supported by the accumulation of osmotic solutes and storage carbohydrates (**Hussain *et al.*, 2024**). At the molecular level, SA up regulation of proline biosynthesis occurs via the activation of pyrroline-5-carboxylate synthetase (P5CS) alongside the simultaneous suppression of the proline dehydrogenase (PDH) gene (**Bhardwaj *et al.*, 2023**). Moreover, SA mitigates oxidative damage in drought-stressed plants by enhancing the activities of key enzymatic antioxidants including catalase (CAT), ascorbate peroxidase (APX), glutathione peroxidase (GPX), and superoxide dismutase (SOD) thereby lowering hydrogen peroxide and malondialdehyde (MDA) concentrations across diverse plant species (**Bagautdinova *et al.*, 2022**).

Our findings demonstrate that the combined application of plant growth-promoting rhizobacteria (PGPR) inoculation and exogenous salicylic acid (SA) foliar spray significantly enhances fennel essential oil yield under moderate water stress conditions. This increase in essential oil accumulation under moderate drought intervals (e.g., 21 days) is primarily attributed to modified carbon partitioning

and the upregulation of secondary metabolite biosynthetic pathways, which typically coincide with acclamatory reduction in vegetative biomass (**Chiappero *et al.*, 2022**). Under reduced soil moisture availability, plants elevate secondary metabolite production as an adaptive mechanism to scavenge reactive oxygen species, minimize cellular oxidative damage, and optimize water use efficiency (WUE). Both signaling molecules (SA) and biological elicitors (PGPR) have been widely documented to increase essential oil percentage and total yield in various aromatic and oilseed crops subjected to drought stress. Furthermore, these dual interventions promote essential oil synthesis and mitigate stress-induced physiological damage by modulating key biochemical pathways, enhancing the development and density of secretory structures (oil glands), and up regulating antioxidant defense networks (**Rizvi *et al.*, 2022**). The significant decrease in total applied water did not lead to a notable decline in crop yield at this intermediate interval. This indicates that while over-irrigation (e.g., a 15-day cycle) induces nutrient leaching and root zone hypoxia, mild-to-moderate drought stress prompts plants to maximize gas exchange and maintain high photosynthetic water-use efficiency per cubic meter of water. The effectiveness of the applied *Lelliottia amnigena* capsules actively maintained crop productivity through several growth-promoting mechanisms in the root zone, as evidenced by the lack of a significant decrease in fruit output under water deficit conditions (21days interval). Additionally, the exogenous injection of salicylic acid served as an essential physiological buffer; its function as a signaling molecule and antioxidant effectively mitigated the osmotic and oxidative stress brought on by the prolonged watering intervals. Those data are in agreement with the conclusions reached by **Parashar *et al.*, (2023)**

5. Conclusion

In conclusion, this study demonstrates a significant positive synergy between salicylic acid (SA) application and encapsulated *Lelliottia amnigena* MSR-M4 inoculation. This biostimulatory combination effectively mitigates the adverse impacts of drought stress in fennel (*Foeniculum vulgare* Mill.) by promoting endogenous phytohormone biosynthesis, enhancing vegetative growth parameters, increasing essential oil yield and composition, and optimizing overall plant nutritional and chemical profiles relative to un-treated controls. Furthermore, combining encapsulated bio inoculation with foliar SA application achieved significant water savings of 129 m³/ fed (5.9% reduction in total applied water) under drought conditions

References

- Abd El-Mageed, T.A.; Semida, W.M.; Mohamed, G.F. and Rady, M.M. (2016).** Combined effect of foliar-applied salicylic acid and deficit irrigation on physiological–anatomical responses, and yield of squash plants under saline soil. *South African Journal of Botany*, 106, pp 8–16.
- Abo-Koura, H.A.; Abd El-Latif, K.M.; Ismael, R.R. and Saad El-Dein, A. (2025).** Enhancing Drought Tolerance in Wheat Using Encapsulated *Lelliottia amnigena* MSR-M49. *International Journal of Plant & Soil Science*, 37(1), pp 208–230.
- Aebi, H.E. (1983).** Catalase. In: *Methods of Enzymatic Analysis*, VCH, Weinheim, pp 273–286.
- Ahluwalia, O.; Singh, P.C. and Bhatia, R. (2023).** A review on drought stress in plants: Implications, mitigation, and the role of plant growth-promoting rhizobacteria. *Plant Stress*, 10, 100282.
- Ahmad, P.; Ahanger, M.A. and Alyemeni, M.N. (2024).** Mitigation of drought-induced oxidative damage in crops: Role of salicylic acid in lipid peroxidation control and ion homeostasis. *Journal of Plant Growth Regulation*, 43(2), pp 511–528.
- Akhbari, M.; Kord, R.; Nodooshan, S.J. and Hamedi, S. (2019).** Analysis and evaluation of the antimicrobial and anticancer activities of the essential oil isolated from *Foeniculum vulgare* from Hamedan, Iran. *Natural Product Research*, 33(11), pp 1629–1632.
- Allen, S.E.; Grimshaw, H.M.; Parkinson, J.A. and Quarmby, C. (1974).** *Chemical analysis of ecological materials*. Blackwell Scientific, Oxford.
- Asif, R.; Yasmin, R.; Mustafa, M.; Ambreen, A.; Mazhar, M.; Rehman, A.; Ayazi, M.; Ehsanzadeh, P. and El-Mallah, M.H. (2023).** Growth, seed yield, and essential oil composition of

fennel (*Foeniculum vulgare* Mill.) genotypes as affected by irrigation intervals and deficit water regimes. *Industrial Crops and Products*, 197, 116540.

Bagautdinova, Z.Z.; Omelyanchuk, N.; Tyapkin, A.V.; Kovrizhnykh, V.V.; Lavrekha, V.V. and Zemlyanskaya, E.V. (2022). Salicylic acid in root growth and development. *International Journal of Molecular Sciences*, 23(4), 2228.

Barka, E.A.; Nowak, J. and Clément, C. (2006). Enhancement of chilling resistance of inoculated grapevine plantlets with a plant growth-promoting rhizobacterium, *Burkholderia phytofirmans* strain PsJN. *Applied and Environmental Microbiology*, 72(11), pp 7246–7252.

Bates, L.S.; Waldrem, R.P. and Tear, I.D. (1973). Rapid determination of free proline for water stress studies. *Plant and Soil*, 39(1), pp 205–207.

Batool, T.; Ali, S.; Seleiman, M.F.; Naveed, N.H.; Ali, A.; Ahmed, K.; Mohamed, A.; Khan, G. and Al-Dhumri, S.A. (2020). Plant growth promoting rhizobacteria alleviates drought stress in potato in response to suppressive oxidative stress and antioxidant enzymes activities. *Scientific Reports*, 10, 16975.

Bhardwaj, R.; Sharma, A. and Ramakrishna, B. (2023). Salicylic acid signaling in plants: Mechanisms of oxidative stress tolerance and glyoxalase system regulation under drought. *Plant Physiology and Biochemistry*, 196, pp 384–397.

British Pharmacopoeia. (1963). Determination of Volatile Oils in Drugs. The Pharmaceutical Press, 17 Bloomsbury Square, London, WC1.

Bunzen, J.N.; Guichard, J.; Labbe, P.; Prevot, J.; Sperpinet, J. and Tranchant, J. (1969). Practical Manual of Gas Chromatography. Tranchant, J. (Ed.), Elsevier Publishing Co., Amsterdam – London.

Cherif-Silini, H.; Silini, A.; Chenari Bouket, A.; Alenezi, F.N.; Luptakova, L.; Chiappero, J.; Cappellari, L.d.R.; Palermo, T.B.; Giordano, W. and Banchio, E. (2022). Influence of drought stress and PGPR inoculation on essential oil yield and volatile organic compound emissions in *Mentha piperita*. *Horticulturae*, 8(12), 1120.

Chiappero, J.; Cappellari, L.d.R.; Palermo, T.B.; Giordano, W. and Banchio, E. (2022). Influence of drought stress and PGPR inoculation on essential oil yield and volatile organic compound emissions in *Mentha piperita*. *Horticulturae*, 8(12), 1120.

Chiappero, J.; del Rosario Cappellari, L.; Alderete, L.G.S.; Palermo, T.B. and Banchio, E. (2019). Plant growth promoting rhizobacteria improve the antioxidant status in *Mentha piperita* grown under drought stress leading to an enhancement of plant growth and total phenolic content. *Industrial Crops and Products*, 139, 111553.

Chukwuneme, C.F.; Babalola, O.O.; Kutu, F.R. and Ojuederie, O.B. (2020). Characterization of actinomycetes isolates for plant growth promoting traits and their effects on drought tolerance in maize. *Journal of Plant Interactions*, 15(1), pp 93–105.

Donahue, J.L.; Okpodu, C.M.; Cramer, C.L.; Grabau, E.A. and Alscher, R.G. (1997). Responses of antioxidants to paraquat in pea leaves. *Plant Physiology*, 113(1), pp 249–257.

Fanai, A.; Bohia, B.; Lalremruati, F.; Lalhriatpuii, N.; Lalrokimi; Lalmuanpuii, R.; Singh, P.K. and Zothanpuia. (2024). Plant growth promoting bacteria (PGPB)-induced plant adaptations to stresses: an updated review. *PeerJ*, 12, e17882.

FAO - Food and Agriculture Organization of the United Nations. (2024). Water Stress and its Impacts on Agriculture in the Near East and North Africa Region. FAO, Rome.

Farooqi, Z.u.R.; Ayub, M.A.; Ziaur Rehman, M.; Sohail, M.I.; Usman, M.; Khalid, H. and Al-Wabel, M.I. (2020). Regulation of drought stress in plants. In: *Plant Life Under Changing Environment*, Elsevier, pp 77–104.

Fernandes, C.; De Oliveira, J.R. and Santos, M. (2022). Phytohormonal signaling and mitochondrial enzyme regulation under abiotic stress mitigation. *Frontiers in Plant Science*, 13, 812340.

- Gulfam, A.; Shahbaz, M. and Hussain, M. (2021).** Salicylic acid mediated regulation of stomatal movement, water relations, and nitrogen metabolism in plants under abiotic stress. *Acta Physiologiae Plantarum*, 43(8), 114.
- Gupta, A.; Rico-Medina, A. and Caño-Delgado, A.I. (2020).** The physiology of plant responses to drought. *Science*, 368(6488), pp 266–269.
- Hassoun, S.A. and Abdel-Jabbar, A.M. (2019).** Activation of alternative oxidase pathway in plant mitochondria by salicylic acid application under abiotic stress conditions. *Iraqi Journal of Agricultural Sciences*, 50(4), pp 1105–1114.
- Herbert, D.; Phipps, P.J. and Strange, R.E. (1971).** Determination of total carbohydrates. *Methods in Microbiology*, 5, pp 290–344.
- Heftman, E. (1967).** Chromatography. 2nd Ed., Reinhold Publishing Corp., New York, pp 208–515.
- Hussain, I.; Iqbal, M. and El-Esawi, M.A. (2024).** Salicylic acid promotes root hydraulic conductance and osmotic adaptation via upregulation of aquaporins and compatible solutes in drought-stressed plants. *Acta Physiologiae Plantarum*, 46(3), 34.
- International Trade Centre (ITC). (2019).** Trade statistics for international trade of essential oils. ITC Trade Map, Geneva.
- Jackson, M.L. (1973).** Soil Chemical Analysis. Prentice-Hall of India Pvt. Ltd., New Delhi, India.
- Kapoor, D.; Bhardwaj, S.; Landi, M.; Sharma, A.; Ramakrishnan, M. and Sharma, A. (2020).** The impact of drought in plant metabolism: How to exploit tolerance mechanisms to increase crop production. *Applied Sciences*, 10(16), 5692.
- Kerchev, P.; van der Meer, T.; Sujeeth, N.; Verlee, A.; Stevens, C.V.; Van Breusegem, F. and Gechev, T. (2020).** Molecular priming as an approach to induce tolerance against abiotic and oxidative stresses in crop plants. *Biotechnology Advances*, 40, 107503.
- Khatun, M.; Sarkar, S.; Era, F.M.; Islam, A.K.M.M.; Anwar, M.P.; Fahad, S.; Datta, R. and Islam, A.K.M.A. (2021).** Drought Stress in Grain Legumes: Effects, Tolerance Mechanisms and Management. *Agronomy*, 11(12), 2374.
- Klute, A. (1986).** Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods. 2nd ed., ASA and SSSA, Madison, Wisconsin, USA.
- Little, T.M. and Hills, F.J. (1978).** Agricultural Experimentation-Design and Analysis. John Wiley and Sons, Inc., New York, pp 53–60, 63–66.
- Liu, C.; Duan, N.; Chen, X.; Li, H.; Zhao, X.; Duo, P.; Wang, J. and Li, Q. (2022).** Modulation of secondary metabolic machinery in Lamiaceae and Apiaceae species. *Phytochemistry*, 218, 113940.
- Making Chinese Medicine Series 03: Fennel (*Foeniculum vulgare*). (2021).** Purplecloudinstitute.com. Available at: <https://purplecloudinstitute.com> (Accessed: 26 February 2021).
- Michael, Schudson. (1978).** Discovering the News. Basic Books, New York.
- Mushtaq, N.; Iqbal, A.; Batool, S.; Janiad, S.; Ahmed, M.; Al-Asmari, F.; Rahim, M.A.; Ramadan, M.F. and Zongo, E. (2025).** Alginate beads encapsulated auxin-producing PGPR as a biofertilizer promotes *Triticum aestivum* growth. *ACS Omega*, 10(6), pp 4303–4314.
- Nakano, Y. and Asada, K. (1981).** Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. *Plant and Cell Physiology*, 22(5), pp 867–880.
- Nornai, R. (1982).** Formulae for determination of chlorophyll pigments extracted with N,N-dimethylformamide. *Plant Physiology*, 69(6), pp 1376–1381.
- Page, A.L.; Miller, R.H. and Keeney, D.R. (1982).** Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. 2nd ed., American Society of Agronomy Monograph No. 9, Madison, Wisconsin, USA.

- Panda, D.; Mishra, S.S. and Behera, P.K. (2021).** Drought tolerance in rice: Focus on recent mechanisms and approaches. *Rice Science*, 28(2), pp 119–132.
- Parashar, M.; Dhar, S.K.; Kaur, J.; Sharma, A.; Kumar, R. and Rastogi, N. (2023).** Two novel plant-growth-promoting *Lelliottia amnigena* isolates enhance the overall productivity of wheat and tomato under abiotic stress. *Plants*, 12(17), 3081.
- Pasternak, T.; Groot, E.P.; Kazantsev, F.V.; Teale, W.; Omelyanchuk, N.; Kovrizhnykh, V.; Palme, K. and Mironova, V.V. (2019).** Salicylic acid affects root meristem patterning via auxin distribution in a concentration-dependent manner. *Plant Physiology*, 180(3), pp 1725–1739.
- Piper, C.S. (1950).** *Soil and Plant Analysis*. The University of Adelaide Press, Adelaide, Australia.
- Pregl, F. (1945).** *Quantitative Organic Microanalysis*. 4th ed., J. and A. Churchill Ltd., London.
- Raza, A.; Tabassum, J.; Kudapa, A. and Varshney, R.K. (2023).** Salicylic acid: A key player in regulating plant growth, physiological processes, and defense mechanisms under climate change. *Plant Growth Regulation*, 101(2), pp 245–267.
- Reddy, P.P.; Kumar, G.S. and Srinivas, C. (2024).** Soil microorganisms as bio-inoculants: Mechanisms of plant growth promotion and biocontrol under abiotic stress. *Acta Physiologiae Plantarum*, 43(8), 114.
- Rezaei-Chiyaneh, E.; Seyyedi, S.M.; Ebrahimi, A. and Jamali Asl, H. (2020).** Evaluation of essential oil composition and bioactivity of fennel (*Foeniculum vulgare* Mill.) under different intercropping patterns and organic fertilizer applications. *Industrial Crops and Products*, 154, 112634.
- Rizvi, A.; Ahmed, B.; Khan, M.S.; El-Beltagi, H.S.; Umar, S. and Lee, J. (2022).** Bioprospecting plant growth promoting rhizobacteria for enhancing the biological properties and phytochemical composition of medicinally important crops. *Molecules*, 27(4), 1407.
- Ryan, R.M.; Sheldon, K.M.; Kasser, T. and Deci, E.L. (1996).** All goals are not created equal. In: Gollwitzer, P.M. and Bargh, J.A. (Eds.), *The Psychology of Action: Linking Cognition and Motivation to Behavior*, Guilford Press, New York, pp 7–26.
- Saad, M.M.; Abo-Koura, H.A.; Abd El-Latif, K.M. and Aly, M.M. (2020).** Application of alginate bead encapsulated N-fixing bacteria in improving wheat yield under drought stress. *Plant Archives*, 20(1), pp 1735–1747.
- Sachdev, S.; Ansari, S.A.; Ansari, M.I.; Fujita, M. and Hasanuzzaman, M. (2021).** Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms. *Antioxidants*, 10(2), 277.
- Saleem, M.H.; Ali, S. and Rehman, M. (2025).** Salicylic acid application enhances nitrogen metabolism, carbon dioxide assimilation, and protects photosynthetic apparatus under abiotic stress. *Journal of Plant Growth Regulation*, 44(3), pp 712–729.
- Shahid, M.; Khan, M.S. and Ahmed, B. (2023).** Plant growth-promoting rhizobacteria (PGPR): Sustainable approach for plant growth promotion and mitigating biotic and abiotic stresses. *Journal of Plant Growth Regulation*, 42(7), pp 4125–4145.
- Sharp, R.E.; Hsiao, T.C. and Silk, W.K. (1990).** Growth of the maize primary root at low water potentials II: Role of growth and deposition of hexose and potassium in osmotic adjustment. *Plant Physiology*, 93(4), pp 1337–1346.
- Singh, A.D.; Kour, J.; Dhiman, S.; Khanna, K.; Kumar, P.; Kaur, R.; Kapoor, N. and Bhardwaj, R. (2021).** Prospects of PGPR-mediated antioxidants and S and P metabolism in plants under drought stress. In: Singh, H.B.; Vaishnav, A. and Sayyed, R. (Eds.), *Antioxidants in Plant-Microbe Interaction*, Springer, Singapore.
- Skujins, J. and Burns, R.G. (1976).** Extracellular enzymes in soil. *CRC Critical Reviews in Microbiology*, 4(4), pp 383–421.

- Telci, I.; Dirican, A.; Elmastas, M.; Akşit, H. and Demirtas, I. (2019).** Chemical diversity of wild fennel populations from Turkey. *Journal of Applied Research on Medicinal and Aromatic Plants*, 13, 100201.
- Vedulla, M. (2025).** Plant Growth-Promoting Rhizobacteria (PGPR) and Genetic Resistance: A Dual Approach to Crop Protection. *Microbiology Archives*, 12(3), pp 115–132.
- Vincenzo, I. and Angelo, T. (2021).** Re-evaluation and typification of *Foeniculum piperitum* (Apiaceae), an underknown medicinal plant and crop wild relative. *Phytotaxa*, 508(2), pp 197–204.
- Wang, Y.Y.; Wang, Y.; Li, G.Z. and Hao, L. (2019).** Salicylic acid-altering *Arabidopsis* plant response to cadmium exposure: Underlying mechanisms affecting antioxidation and photosynthesis-related processes. *Ecotoxicology and Environmental Safety*, 169, pp 645–653.
- Wurst, M.; Semerdzieva, M. and Vokoun, J. (1984).** Analysis of psychotropic compounds in fungi of the genus *Psilocybe* by reversed-phase liquid chromatography. *Journal of Chromatography A*, 286, pp 229–235.
- Zhang, L. and Wang, H. (2025).** Study on the isolation of rhizosphere bacteria and the mechanism of growth promotion in response to drought stress: The role of root exudate modulation. *Frontiers in Plant Science*, 16, pp 1595–1610.
- Zhang, X.; Pei, D. and Hu, C. (2003).** Conserving groundwater for the North China Plain. *Irrigation Science*, 21, pp 159–166.
- Zhu, G.; Gu, L.; Shi, Y. and Wang, Y. (2021).** Plant hydraulic conductivity determines photosynthesis in rice under PEG-induced drought stress. *Pakistan Journal of Botany*, 53(2), pp 409–417.
- Zulfiqar, F.; Nafees, M. and Hancock, J.T. (2024).** Modulating stomatal conductance and photosynthetic efficiency via exogenous salicylic acid application under environmental extremes: A review. *Environmental and Experimental Botany*, 218, 105612.