



Salicylic Acid and Biochar-Biofertilizer Improve Soil Fertility, Drought Tolerance, and Fig Yield in a Semi-Arid Region

Mohammad Saeed Tadayon¹ · Seyed Majid Mousavi² · Seyed Mashaallah Hosseini³

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Abstract

Aims: Prolonged drought and low rainfall have severely affected the rain-fed fig groves (*Ficus carica* L. ‘Sabz’) in the semi-arid Estahban region of Iran. Depletion of soil organic matter, exacerbated by rapid decomposition under hot, dry conditions, has reduced soil fertility and water retention, ultimately limiting fig productivity. This four-year field study (2021–2024) evaluated the effects of foliar-applied salicylic acid (SA), biochar, and their combination with biofertilizers on soil fertility, plant nutrition, water status, and yield in *F. carica* ‘Sabz’ orchards. **Methods:** A randomized complete block design was used with four SA concentrations (0, 0.5, 1.0, and 1.5 mM) and three biochar-biofertilizer treatments: control, biochar alone (10 kg tree⁻¹), and biochar combined with biofertilizers (10 kg biochar+500 g mycorrhizal fungi+500 mL bacterial inoculant+100 mL fulvic acid and amino acids per tree). Biochar was produced by slow pyrolysis in a solar-powered stainless-steel chamber and applied via vertical trenching around each tree. **Results:** Biochar significantly improved soil water retention at 0–40, 40–80, and 80–120 cm depths. The 1.0 mM SA+biochar+biofertilizer treatment markedly enhanced leaf nutrient concentrations (N, P, K, Ca, Mg, Fe, Zn, B), chlorophyll content, leaf area, stomatal conductance, and net CO₂ assimilation, leading to a significant increase in fruit yield. Mycorrhizal colonization exceeded 70% in inoculated treatments. These findings underscore the synergistic benefits of integrating biochemical and organic amendments to enhance drought resilience and sustain productivity in rain-fed fig orchards. **Conclusions:** The combined application of 1.0 mM SA and biochar-based biofertilizers enriched with fulvic acid and amino acids was the most effective and economically viable strategy for improving soil moisture, nutrient uptake, and overall plant performance under semi-arid, rain-fed conditions.

Keywords Biochar · Biofertilizer · Fig Trees · Plant Nutrition · Soil Water Content

1 Introduction

Iran ranks as the fifth-largest producer of figs (*Ficus carica* L.) globally, with an annual output of 86,372 tons, highlighting the crop’s significance in the country’s agricultural landscape. The ‘Sabz’ fig cultivar, widely cultivated in Estahban’s rain-fed orchards in the semi-arid Fars province, is recognized for its inherent drought tolerance (Sedaghat and Rahemi 2018). However, ongoing climate change has introduced severe threats to sustainable fig production, particularly in the form of prolonged droughts, erratic precipitation, and increasing frequency of wet–dry cycles.

Drought stress is a primary constraint to productivity in semi-arid orchards. In these regions, soil organic carbon is often depleted due to chronic rainfall shortages and sustained drought. Severe water deficits lead to leaf abscission, branch dieback, and substantial declines in fruit yield and

✉ Mohammad Saeed Tadayon
m.tadayon@areeo.ac.ir

Seyed Majid Mousavi
majid62mousavi@gmail.com

Seyed Mashaallah Hosseini
m.hosseini@areeo.ac.ir

¹ Water Research Department, Agricultural Research, Education and Extension Organization (AREEO), Shiraz, Iran

² Soil and Water Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran

³ Associate professors of Soil and Water Research Department, Agricultural Research, Education and Extension Organization (AREEO), Shiraz, Iran

quality, with extended drought periods potentially resulting in tree mortality (Zare et al. 2019). Furthermore, inconsistent precipitation and poor deep-soil recharge aggravate water stress, even for deep-rooted trees such as figs (Ding et al. 2021). Long-term drought depletes deep soil moisture reserves, while elevated temperatures and increased solar radiation intensify physiological stress, leading to wilting, reduced photosynthetic rates, impaired stomatal conductance, and decreased water use efficiency (Ahluwalia et al. 2021).

Effective strategies to address these challenges must focus on improving soil moisture conservation and optimizing water use. Enhancing soil organic matter is crucial, as it improves soil structure, fertility, water retention, erosion resistance, and microbial activity. Among the promising approaches is the application of biochar, a carbon-rich byproduct of biomass pyrolysis under limited oxygen conditions (Iwuzor et al. 2024). Biochar enhances soil water retention, increases microbial biomass, and improves nutrient cycling, especially in drought-prone Aridisols (Naorem et al. 2023). Its high porosity reduces bulk density, increases total porosity, and boosts water-holding capacity during hydrological extremes (Toková et al. 2020; Wang et al. 2019). When combined with beneficial microbes such as *Pseudomonas koreensis* and *Bacillus coagulans*, biochar can alleviate water and salinity stress in degraded soils (Hafez et al. 2019).

As a stable carbon reservoir, biochar sequesters carbon for extended periods, helping reduce greenhouse gas emissions (Wang et al. 2023b). It also stimulates enzyme activities, promotes nutrient cycling, and offers slow-release properties for plant nutrients, thereby enhancing soil health and crop performance (Bhattacharyya et al. 2024). Moreover, biochar supports microbial biodiversity and root colonization, fostering healthier plant growth (Haider et al. 2022).

In fig orchards, strategic pruning, typically removing around 75% of one-year-old lateral shoots, is a traditional practice for improving drought resilience (Abdolahipour et al. 2019; Zare 2021). However, pruning waste is often discarded or burned. Converting this biomass into biochar via solar-powered pyrolysis offers a sustainable and eco-friendly strategy. Biochar derived from fig pruning residues exhibits high organic carbon content, low H: C ratios, and high chemical stability, with its properties influenced by pyrolysis temperature (Kammann et al. 2015; Su et al. 2023).

Plant growth-promoting rhizobacteria (PGPR) further enhance plant tolerance to abiotic stress. These microbes improve root growth through mechanisms such as ACC-deaminase activity, nitrogen (N) fixation, phosphate solubilization, and phytohormone (e.g., IAA) production (Danish et al. 2020; Karnwal et al. 2023; Wang et al. 2023a).

However, the efficacy of free-living PGPR in dry soils is limited due to poor root colonization. Biochar serves as an effective microbial carrier, improving bacterial survival and promoting favorable microbial communities (Waqar et al. 2022).

Salicylic acid (SA), a key phytohormone synthesized via the phenylalanine or isochorismate pathway, regulates plant responses to abiotic stresses such as drought. SA modulates antioxidant defenses, photosynthesis, and osmotic regulation, enhancing plant resilience under adverse conditions (Paul et al. 2024; Roychowdhury et al. 2024; Sedaghat et al. 2020). Despite growing interest, the mechanisms of SA in perennial woody crops under drought stress remain underexplored.

Integrated strategies combining biochemical (e.g., SA) and organic (e.g., biochar and biofertilizers) approaches are essential to sustaining fig productivity under semi-arid, rain-fed conditions. While SA, biochar, and PGPR-based biofertilizers individually improve stress tolerance and soil fertility, their synergistic effects in fig orchards have yet to be comprehensively studied.

This study investigated the four-year (2021–2024) effects of foliar-applied SA and soil-applied biochar, alone and in combination with biofertilizers enriched with fulvic acid and amino acids, on the physiological performance, soil fertility, and yield of rain-fed fig trees (*Ficus carica* L. ‘Sabz’) in a semi-arid region. We hypothesize that biochar improves soil moisture and nutrient availability, while SA and biofertilizers enhance plant water status, nutrient uptake, and photosynthetic capacity. This integrated approach aims to develop cost-effective and sustainable solutions for mitigating drought-induced productivity losses in dryland fig cultivation.

2 Materials and methods

2.1 Site Description and Climate

This four-year field study (2021–2024) was conducted in a rain-fed fig orchard located in Estahban, Fars Province, Iran (29°07'64"N, 54°04'18"E; 1769 m elevation), characterized by a semi-arid climate. The site included mature *Ficus carica* L. ‘Sabz’ fig trees, 42 years old, grown on a 10–12% slope. Meteorological data (2021–2024) were obtained from local weather stations, showing considerable seasonal and interannual variability in temperature, humidity, and precipitation (Supplementary Table S1). Summers are characterized by high temperatures and low humidity, intensifying drought stress, while most precipitation occurs during winter months.

2.2 Initial Soil Properties

In February 2021, composite soil samples were collected at depths of 0–40, 40–80, and 80–120 cm beneath the canopy edge. Samples were analyzed using standard procedures outlined by Estefan et al. (2013) at the Zarghan Soil and Water Research Laboratory (Supplementary Table S2). The soil is classified as loamy skeletal, carbonate, thermic Typic Xerorthents with neutral to slightly alkaline pH. Bulk density increased slightly with depth, suggesting mild compaction in subsoil layers. Organic carbon content declined significantly with depth, affecting fertility and microbial activity. Similarly, field capacity decreased with depth, highlighting the importance of improving soil water retention.

2.3 Experimental Design

Seventy-two uniform fig trees were selected in August 2020, spaced 10 × 10 m (100 trees/ha). Annual pruning (~65% of one-year-old lateral shoots) was performed in March, and caprification was conducted thrice per season using the ‘Pouzdonbaly’ caprifig cultivar.

A factorial experiment was arranged in a randomized complete block design (RCBD) with two factors and three replications. The first factor was SA foliar application at four levels: 0 (SA0), 0.5 (SA0.5), 1.0 (SA1.0), and 1.5 mM (SA1.5). The second factor included three biochar-biofertilizer treatments: no application (B0), biochar alone (B1), and biochar combined with biofertilizers (B2). The B2 treatment included biochar, mycorrhizal fungi (*Glomus* spp.), beneficial bacteria (*Bacillus subtilis* and *Pseudomonas fluorescens*), fulvic acid, and amino acids.

All amendments were incorporated into vertical mulching trenches (80 cm deep × 30 cm wide) along the canopy edge. Each treatment was applied to six trees.

2.4 Biochar Preparation and Characterization

Biochar was produced by slow pyrolysis of fig pruning waste in a solar-powered stainless-steel chamber at 500 °C for 4 h under limited oxygen. The biochar’s physicochemical properties were assessed based on International Biochar Initiative (IBI) guidelines (Supplementary Table S3).

2.5 Biofertilizer Composition

The biofertilizer included a liquid bacterial inoculant containing *P. fluorescens* (1.7×10^8 cells/mL) and *B. subtilis* (2×10^8 cells/mL), as well as a solid mycorrhizal inoculum (10^5 propagules/g). The full B2 treatment consisted of 10 kg biochar + 500 g mycorrhizal fungi + 250 mL each of the

bacterial inoculants (500 mL total) + 100 mL fulvic acid and amino acids per tree.

Mycorrhizal root colonization was assessed at the end of each growing season using the grid-line intersect method (Giovannetti and Mosse 1980). Roots were cleared, stained, and evaluated microscopically, confirming colonization > 70% in B2-treated trees.

2.6 Measurements

2.6.1 Soil Moisture Monitoring

Soil moisture was measured monthly using time-domain reflectometry (TDR) probes (TRIME[®]-PICO IPH/T3) installed 60 cm upslope from each tree trunk at depths of 0–40, 40–80, and 80–120 cm.

2.6.2 Fruit Quality Assessment

Between late July and September, 20 randomly selected fruits per tree were evaluated. Total soluble solids (TSS) were measured using a refractometer (VBR 80 S) from juice extracted by homogenizing 5 g of neck tissue in 5 mL distilled water (Sugiura et al. 1983). Titratable acidity (TA) was determined by titrating fig juice with 0.1 N NaOH using phenolphthalein (Samee et al. 2006).

Fruit color was visually classified into light yellow, light brown, and dark brown. Diameter-based grading followed commercial standards: < 17 mm (Grade B), 17–22 mm (Grade A), and > 22 mm (Grade AA).

2.6.3 Vegetative Growth Parameters

During the full vegetative stage each season, current-year shoot length, diameter, leaf number, and sunburn incidence were recorded on 10 tagged one-year-old shoots per tree.

2.6.4 Leaf Physiological Traits

Measurements were conducted during late June on fully expanded leaves. Leaf temperature was recorded on the south-facing side of the canopy using an infrared thermometer (Testo 830-T2) between 12:00–13:00 (Nielsen and Anderson 1989).

Chlorophyll content index was determined using a calibrated SPAD-502 m (Minolta Inc., USA) at five points along the midrib of leaves from 10 tagged shoots. Leaf area was measured using a CI-203 handheld laser scanner.

Stomatal conductance, transpiration, and net CO₂ assimilation were measured using a LI-6400 portable gas exchange system under standardized conditions: ~25 °C air

temperature, 40% humidity, 400 ppm CO₂, and > 1500 μmol m⁻² s⁻¹ PPFD, between 09:00 and 11:00.

Leaf water potential (Ψ_{leaf}) was measured using a pressure chamber following the method of Boyer (1967). One leaf per tree was enclosed in plastic and aluminum foil for two hours before measurement (13:00–15:00). The pressure required to express the first drop of sap from the petiole indicated the Ψ_{leaf} (Boyer 1967).

2.6.5 Leaf Nutrient Analysis

Fully expanded leaves from non-fruiting shoots were collected in late August, washed, and oven-dried at 70 °C. Total N was determined by micro-Kjeldahl method using a Kjeltex analyzer. Phosphorus (P) was analyzed colorimetrically, potassium (K) via flame photometry, and calcium (Ca)/magnesium (Mg) by complexometric titration (Estefan et al. 2013). Micronutrients (Zn, Mn, Fe, Cu) were determined by atomic absorption spectroscopy (PerkinElmer), following dry ashing and HCl digestion. Boron (B) was measured using the Azomethine-H method.

2.7 Statistical Analysis

The experiment followed an RCBD factorial design with three replications. Data from 2021 to 2024 were subjected to combined ANOVA using SAS software. Percentage data were arcsine square-root transformed. Means were compared using Duncan's multiple range test ($p < 0.05$). Principal Component Analysis (PCA) was performed in Minitab 14. Significant loadings in the first four PCs were identified using the selection criterion (SC) of Collins and Ovalles (1988):

$$SC = \frac{0.5}{\sqrt{PC \text{ eigenvalues}}}$$

2.8 Economic Analysis

Economic performance was evaluated using Net Present Value (NPV) and Benefit-Cost Ratio (BCR). Cost estimation included material and labor costs for SA sprays, biochar, and biofertilizers over four years (2021–2024). Benefit estimation calculated from increased dry fig yield relative to control and market price (\$2.5 USD/kg). NPV > 0 and BCR > 1 were interpreted as economically viable outcomes (Gittinger 1981).

3 Results

3.1 Soil Water Content

The application of biochar (B1) significantly improved soil volumetric water content at all measured depths (0–40 cm, 40–80 cm, and 80–120 cm) compared to the control treatment (B0). Specifically, at 0–40 cm depth, water content increased from 17.28% in B0 to 22.73% in B1. Similarly, water content at 40–80 cm increased from 15.50% (B0) to 23.43% (B1), and at 80–120 cm from 14.28% (B0) to 19.95% (B1). The combined treatment of biochar and biofertilizers (B2) showed a slightly higher water content than B1 at all depths; however, the differences between B1 and B2 were not statistically significant (Table 1).

These results suggest that biochar was the primary factor responsible for improving soil moisture retention, while the addition of biofertilizers did not further enhance water content under the given experimental conditions. The enhanced soil moisture in biochar-treated plots is particularly valuable for sustaining fig trees under rain-fed, drought-prone conditions.

3.2 Soil Moisture Dynamics

Figure 1 illustrates the monthly trend in soil moisture content (%) from February to January, averaged across four

Table 1 Effect of Biochar and biofertilizer treatments on soil volumetric water content (%) at different depths in *Ficus carica* L. 'Sabz' orchards under rainfed conditions (four-year average: 2021–2024)

Soil depth (cm)	Volumetric soil water content (%)		
	0–40	40–80	80–120
II- Biochar-Biofertilizer (B)			
No application (B ₀) (Ctrl.)	17.28 ± 1.05b	15.50 ± 1.32b	14.28 ± 1.30b
Biochar (B ₁)	22.73 ± 1.26a	23.43 ± 1.18a	19.95 ± 1.28a
Biochar + Biofertilizer (B ₂)	22.95 ± 1.40a	23.63 ± 1.36a	20.43 ± 1.34a
F. test	**	**	**

† Values represent means ± standard error

Means within each column followed by the same letter are not significantly different at the 0.05 probability level according to Duncan's Multiple Range Test

F-test: **, * indicate significance at $P < 0.01$ and $P < 0.05$, respectively. "ns" denotes non-significant differences

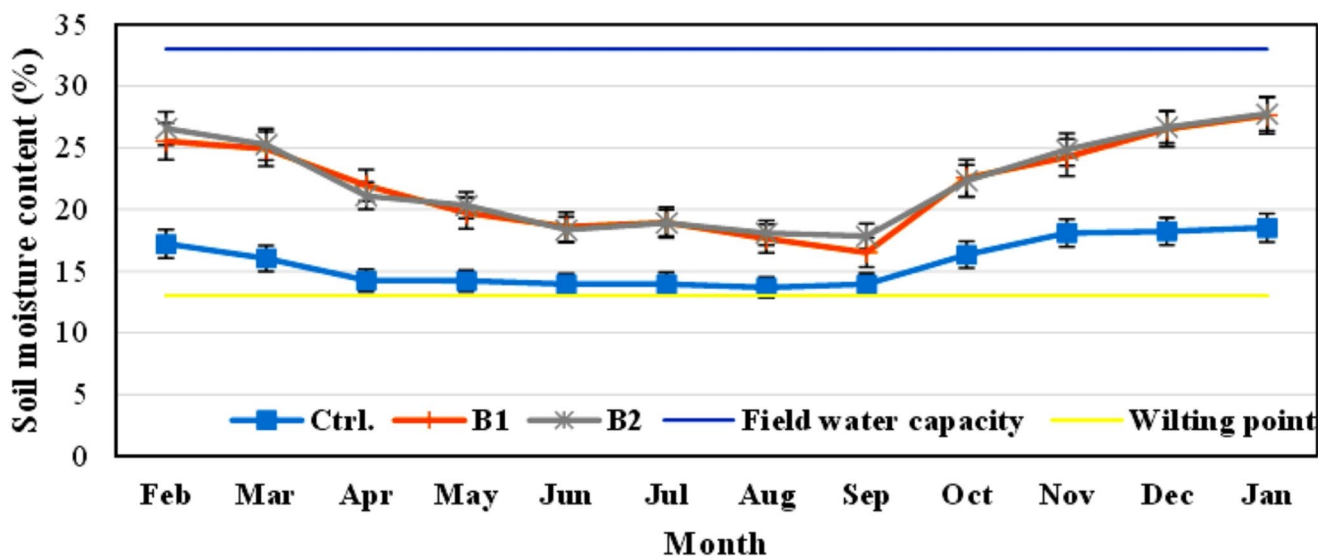


Fig. 1 Monthly variation in soil moisture content (0–120 cm depth) under three treatments: B0 (control, no biochar), B1 (biochar alone), and B2 (biochar + biofertilizers) applied within vertical mulching trenches beneath the canopy of fig trees (*Ficus carica* L. ‘Sabz’), aver-

aged from February 2019 to January 2023. The field capacity and permanent wilting point are shown as reference lines. Error bars represent standard error of the mean

years, under three treatments: control (B0), biochar alone (B1), and biochar combined with biofertilizers (B2). The control treatment consistently showed the lowest soil moisture content throughout the year. A gradual decline from February to August indicates limited water-holding capacity and high evaporative loss under rainfed conditions. A slight recovery in moisture from September to January is attributed to seasonal rainfall. However, moisture levels in the control treatment remained below optimal levels and approached the permanent wilting point during peak summer, indicating potential stress for fig trees.

In contrast, B1 and B2 treatments maintained significantly higher soil moisture content across the year. Initial values in February and March were near field capacity, reflecting either higher residual moisture or enhanced retention due to biochar. Although moisture content decreased during the summer, it remained well above the wilting point and rebounded in the post-summer months, likely due to natural precipitation. Moisture levels in B1 and B2 remained close to the field capacity line for extended periods, supporting improved water availability for plant growth.

No significant differences were observed between B1 and B2, suggesting that biochar was the dominant factor in enhancing water retention. These results reinforce the role of biochar in maintaining favorable soil moisture regimes under semi-arid, rainfed conditions.

3.3 Leaf Nutrient Content

The combined application of biochar and biofertilizers (B2) significantly improved the concentration of macro- and

micronutrients in fig leaves compared to the control (B0). Specifically, the B2 treatment resulted in increased concentrations of N (55.86%), P (54.55%), K (60.20%), Ca (50.42%), Mg (82.61%), S (72.73%), Fe (32.50%), Mn (41.18%), Zn (60.00%), Cu (30.00%), and B (23.08%) (Table 2).

The interaction of SA with the B2 treatment had a synergistic effect, particularly at the SA1.0 mM + B2 level, which produced the highest nutrient concentrations. Notably, leaf N concentration in this treatment reached 1.88%, consistent with sufficiency thresholds for *Ficus carica* under well-managed rainfed conditions.

These findings suggest that the integration of SA with biochar and biofertilizer improves nutrient uptake and accumulation in fig trees under drought stress.

3.4 Shoot Growth and Leaf Physiological Characteristics

Foliar application of SA and soil application of biochar-biofertilizers significantly enhanced shoot growth and leaf physiological traits in fig trees (*Ficus carica* L. ‘Sabz’) under rainfed conditions. The highest shoot lengths were observed in SA0.5 mM and SA1.0 mM treatments (10.29 cm and 10.41 cm, respectively), significantly exceeding the control (6.81 cm). The SA1.0 mM + B2 treatment achieved the highest shoot length (13.90 cm), shoot diameter (8.30 mm), and number of leaves per shoot (9.20) (Table 3).

This combined treatment also significantly reduced leaf temperature to 29.78 °C, compared to 37.41 °C in the control, suggesting improved thermal regulation. SA0.5

Table 2 Effects of foliar-applied Salicylic acid and soil-applied Biochar and biofertilizers on leaf nutrient concentrations in Fig trees (*Ficus carica* L. 'Sabz') under rainfed conditions (average values from 2021–2024)

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	B (mg kg ⁻¹)
I- Salicylic acid (SA)											
(SA _{0.0} mM) (Ctrl.)	1.31 ± 0.05c	0.12 ± 0.006c	1.17 ± 0.12b	1.45 ± 0.11ab	0.28 ± 0.02b	0.15 ± 0.011ab	73.57 ± 5.3b	30.41 ± 2.5b	7.48 ± 0.55a	3.33 ± 0.23b	32.44 ± 2.5b
SA _{0.5} mM	1.43 ± 0.05ab	0.15 ± 0.007a	1.42 ± 0.13a	1.64 ± 0.12a	0.33 ± 0.02a	0.16 ± 0.012a	87.73 ± 6.1a	37.97 ± 2.4a	7.93 ± 0.57a	3.81 ± 0.21a	36.40 ± 2.6ab
SA _{1.0} mM	1.48 ± 0.06a	0.14 ± 0.007ab	1.32 ± 0.12ab	1.45 ± 0.11ab	0.35 ± 0.02a	0.13 ± 0.010ab	92.53 ± 6.5a	29.41 ± 2.2b	8.07 ± 0.62a	3.70 ± 0.23ab	40.47 ± 2.8a
SA _{1.5} mM	1.35 ± 0.05bc	0.13 ± 0.006b	1.17 ± 0.10b	1.33 ± 0.10b	0.32 ± 0.02ab	0.13 ± 0.010ab	85.60 ± 6.2ab	29.30 ± 2.3b	7.81 ± 0.56a	3.91 ± 0.22a	38.74 ± 2.4a
F. test	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
II- Biochar-Bio-fertilizer (B)											
No application (B ₀) (Ctrl.)	1.11 ± 0.05c	0.11 ± 0.006c	0.98 ± 0.10c	1.19 ± 0.10c	0.23 ± 0.02c	0.11 ± 0.010b	73.70 ± 5.4b	26.51 ± 2.3b	5.30 ± 0.53c	2.79 ± 0.21c	29.95 ± 2.3c
Biochar (B ₁)	1.35 ± 0.06b	0.13 ± 0.006b	1.27 ± 0.11b	1.43 ± 0.11b	0.31 ± 0.02b	0.13 ± 0.011b	83.45 ± 5.3b	31.10 ± 2.5b	7.76 ± 0.57b	3.80 ± 0.21b	36.64 ± 2.4b
Biochar + Bio-fertilizer (B ₂)	1.73 ± 0.07a	0.17 ± 0.008a	1.57 ± 0.12a	1.79 ± 0.12a	0.42 ± 0.03a	0.19 ± 0.012a	97.43 ± 5.7a	37.72 ± 2.8a	10.41 ± 0.61a	4.48 ± 0.23a	44.45 ± 2.5a
F. test	**	**	**	**	**	**	**	**	**	**	**
Inter-action (SA+B)											
SA _{0.0} mM + B ₀ (Ctrl.)	0.94 ± 0.04 g	0.09 ± 0.005f	0.86 ± 0.10 g	1.12 ± 0.10e	0.22 ± 0.02f	0.12 ± 0.010ef	63.51 ± 4.2e	25.60 ± 2.5ef	5.64 ± 0.50f	2.24 ± 0.22f	24.32 ± 2.2 g
SA _{0.0} mM + B ₁	1.31 ± 0.06de	0.12 ± 0.005 cd	1.21 ± 0.11def	1.39 ± 0.11d	0.28 ± 0.02de	0.13 ± 0.011de	72.29 ± 5.6de	28.68 ± 2.4de	7.32 ± 0.56e	3.65 ± 0.21de	32.49 ± 2.4f
SA _{0.0} mM + B ₂	1.68 ± 0.06bc	0.16 ± 0.006b	1.45 ± 0.12bc	1.84 ± 0.12ab	0.35 ± 0.02c	0.19 ± 0.012ab	84.91 ± 5.5c	36.95 ± 2.6bc	9.48 ± 0.64bc	4.10 ± 0.23bc	40.50 ± 2.3bcd
SA _{0.5} mM + B ₀	1.13 ± 0.05f	0.12 ± 0.005 cd	1.15 ± 0.11f	1.36 ± 0.11d	0.23 ± 0.02	0.13 ± 0.011de	78.11 ± 5.4 cd	31.71 ± 2.3d	5.32 ± 0.57f	3.26 ± 0.22e	27.57 ± 2.3 g
SA _{0.5} mM + B ₁	1.41 ± 0.07d	0.15 ± 0.007b	1.44 ± 0.12c	1.67 ± 0.12bc	0.32 ± 0.02 cd	0.15 ± 0.012 cd	86.73 ± 5.5c	37.63 ± 2.4b	7.71 ± 0.53de	3.58 ± 0.23de	36.25 ± 2.5def
SA _{0.5} mM + B ₂	1.75 ± 0.08ab	0.18 ± 0.007a	1.68 ± 0.13ab	1.89 ± 0.12ab	0.45 ± 0.03ab	0.21 ± 0.012a	98.40 ± 6.2b	44.57 ± 3.1a	10.76 ± 0.65ab	4.59 ± 0.24a	45.37 ± 2.6ab
SA _{1.0} mM + B ₀	1.22 ± 0.05ef	0.10 ± 0.006ef	0.95 ± 0.10 fg	1.14 ± 0.11e	0.23 ± 0.02f	0.09 ± 0.010 g	74.00 ± 5.4d	23.11 ± 2.0f	4.90 ± 0.49	2.40 ± 0.20f	33.10 ± 2.3f
SA _{1.0} mM + B ₁	1.35 ± 0.05d	0.13 ± 0.006c	1.28 ± 0.10cdef	1.29 ± 0.11de	0.34 ± 0.02c	0.11 ± 0.011ef	88.69 ± 5.5bc	28.39 ± 2.2de	7.36 ± 0.55de	3.89 ± 0.21 cd	38.70 ± 2.4cde

Table 2 (continued)

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	B (mg kg ⁻¹)
SA _{1.0} mM + B ₂	1.88 ± 0.07a	0.19 ± 0.008a	1.73 ± 0.13a	1.93 ± 0.12a	0.47 ± 0.03a	0.20 ± 0.012a	114.87 ± 5.8a	36.74 ± 2.4bc	11.94 ± 0.64a	4.82 ± 0.22a	49.61 ± 2.5a
SA _{1.5} mM + B ₀	1.15 ± 0.04f	0.11 ± 0.005de	0.95 ± 0.10 fg	1.14 ± 0.10e	0.25 ± 0.02ef	0.10 ± 0.010 fg	79.19 ± 5.3 cd	25.61 ± 2.2ef	5.32 ± 0.52f	3.25 ± 0.23e	34.80 ± 2.4ef
SA _{1.5} mM + B ₁	1.32 ± 0.06de	0.13 ± 0.006c	1.14 ± 0.11e	1.37 ± 0.11d	0.31 ± 0.02 cd	0.12 ± 0.011ef	86.09 ± 6.1c	29.70 ± 2.3de	8.65 ± 0.62 cd	4.08 ± 0.23bc	39.10 ± 2.3cde
SA _{1.5} mM + B ₂	1.59 ± 0.07c	0.16 ± 0.007b	1.43 ± 0.11 cd	1.49 ± 0.12 cd	0.40 ± 0.02b	0.17 ± 0.011bc	91.48 ± 5.7b	32.58 ± 2.5 cd	9.46 ± 0.61c	4.39 ± 0.22ab	42.33 ± 2.5bc
F. test	**	**	**	**	**	**	**	**	**	**	**

† Values represent means ± standard error ($n=6$)

Means within the same column followed by the same letter are not significantly different at the 0.05 level, based on Duncan's Multiple Range Test

F-test significance levels: $P < 0.05$ (*), $P < 0.01$ (**), and ns = not significant

mM and SA_{1.0} mM treatments significantly enhanced the chlorophyll content index (35.60 and 35.67) and leaf area (66.33 and 67.03 cm²), compared to the control (30.87 and 47.03 cm²). Both SA levels also improved stomatal conductance and gas exchange parameters, including the highest net CO₂ assimilation rate (16.63 and 16.57 μmol. m⁻².s⁻¹) and transpiration rates (6.47 and 6.60 mmol. m⁻².s⁻¹), while improving leaf water potential.

The application of biochar alone (B₁) improved growth and physiological traits compared to the control; however, the combined treatment with biofertilizers (B₂) produced the greatest improvements. B₂ treatment increased chlorophyll content by 22.4%, leaf area by 56%, stomatal conductance by 64%, transpiration by 28%, CO₂ assimilation by 41%, and improved water potential from -1.65 MPa (B₀) to -1.32 MPa.

The SA_{1.0} mM + B₂ interaction produced the most pronounced benefits across all measured traits: chlorophyll index (39.48), leaf area (85.52 cm²), stomatal conductance (0.42 mol. m⁻².s⁻¹), transpiration (7.84 mmol. m⁻².s⁻¹), CO₂ assimilation (20.4 μmol. m⁻².s⁻¹), and improved leaf water potential (-1.14 MPa). Compared to the control (SA_{0.0} mM + B₀), this treatment increased chlorophyll by 40%, leaf area by 107%, stomatal conductance by 121%, assimilation by 96%, transpiration by 52%, and improved water potential by 35%.

3.5 Fruit Characteristics

SA application significantly influenced fruit size distribution and yield. SA_{1.0} mM reduced the number of small fruits (<17 mm, Grade B) to 60.70 per tree (from 74.13 in the control), while increasing medium-sized (17–22 mm, Grade A) and large-sized fruits (>22 mm, Grade AA) to 24.57 and 14.73 per tree, respectively (Table 4). SA_{1.0} mM also resulted in the highest dry fruit yield (16.49 kg/tree), more than double that of the control (7.93 kg/tree). The overall trend showed that increasing SA concentration decreased small fruit numbers and improved both fruit size and yield quality.

Biochar and biofertilizer treatments also significantly affected fruit traits. B₂ (biochar + biofertilizer) resulted in the fewest small fruits (56.63), the highest numbers of Grade A (26.63) and Grade AA (16.75) fruits, and the highest dry yield (16.70 kg/tree), nearly doubling that of the control (8.06 kg/tree). In contrast, the control (B₀) had the highest number of small fruits (76.48) and the lowest proportion of larger fruits and yield.

The SA × B₂ interaction showed significant synergistic effects. The SA_{1.0} mM + B₂ combination resulted in the highest number of Grade A (33.90) and Grade AA (22.22) fruits, the highest dry fruit yield (23.61 kg/tree), and the

Table 3 Effects of foliar application of Salicylic acid and soil application of biochar-biofertilizer treatments on shoot growth and leaf physiological characteristics of Fig tree (*Ficus carica* L. 'Sabz') under rainfed conditions averaged over 2021–2024

Treatment	Shoot length (cm)	Shoot diameter (mm)	No. of leaves per shoot	No. of sunburned leaves per shoot	Leaf temperature (°C)	Leaf chlorophyll content index	Leaf areas (cm ²)	Stomatal conductance (mol·m ⁻² ·s ⁻¹)	Leaf transpiration (mmol·m ⁻² ·s ⁻¹)	Light-saturated net CO ₂ assimilation (μmol·m ⁻² ·s ⁻¹)	Leaf water potential (MPa)	
I- Salicylic acid (SA)												
(SA _{0.0} mM) (Ctrl.)	6.81±0.6c	5.55±0.3b	4.96±0.4b	1.25±0.13a	35.87±0.33a	30.87±1.0b	47.03±2.3c	0.23±0.02b	5.46±0.1c	12.90±0.6c	-1.65±0.05a	
SA _{0.5} mM	10.29±0.7a	6.78±0.3a	7.46±0.5a	0.77±0.10b	33.37±0.32c	35.60±1.1a	66.33±2.5a	0.33±0.03a	6.47±0.2a	16.63±0.7a	-1.33±0.04b	
SA _{1.0} mM	10.41±0.7a	6.81±0.3a	7.37±0.5a	0.71±0.10b	32.57±0.32d	35.67±1.2a	67.03±2.6a	0.32±0.03a	6.60±0.2a	16.57±0.7a	-1.40±0.04b	
SA _{1.5} mM	8.36±0.6b	5.93±0.3b	5.35±0.4b	1.20±0.11a	34.07±0.30b	31.53±1.0b	55.00±2.1b	0.26±0.02b	6.02±0.1b	14.53±0.6b	-1.61±0.05a	
F, test	**	**	**	**	**	**	**	**	**	**	**	
II- Biochar-Bio-fertilizer (B)												
No application (B ₀) (Ctrl.)	7.38±0.6b	5.61±0.3b	5.02±0.4c	1.32±0.12a	35.93±0.32a	30.90±1.0c	46.60±2.7c	0.22±0.02c	5.46±0.1c	12.70±0.6c	-1.65±0.05a	
Biochar (B ₁)	8.29±0.6b	6.08±0.3b	5.93±0.4b	0.97±0.11b	34.40±0.31b	33.25±1.1b	57.20±2.5b	0.29±0.02b	5.95±0.2b	14.90±0.7b	-1.52±0.04b	
Biochar+ Biofertilizer (B ₂)	11.24±0.7a	7.12±0.3a	7.91±0.5a	0.66±0.10c	31.58±0.31c	36.10±1.2a	72.75±2.6a	0.36±0.03a	6.99±0.2a	17.88±0.7a	-1.32±0.04c	
F, test	**	**	**	**	**	**	**	**	**	**	**	
Interaction (SA+B)												
SA _{0.0} mM + B ₀ (Ctrl.)	5.58±0.5 h	5.13±0.3e	3.61±0.4e	1.89±0.13a	37.41±0.33a	28.30±1.0 g	41.32±2.2 g	0.19±0.02f	5.14±0.1 g	10.4±0.5 g	-1.78±0.06a	
SA _{0.0} mM + B ₁	6.41±0.6gh	5.62±0.3cde	4.32±0.4e	1.04±0.11 cd	35.80±0.32b	31.59±1.1e	47.71±2.2de	0.24±0.02e	5.41±0.1f	13.3±0.6e	-1.62±0.04b	
SA _{0.0} mM + B ₂	8.45±0.6e	5.91±0.3bcd	6.95±0.5b	0.82±0.10d	34.38±0.32d	32.72±1.2de	52.10±2.3d	0.27±0.02de	5.83±0.2de	15.0±0.7d	-1.54±0.04c	
SA _{0.5} mM + B ₀	8.61±0.6de	6.04±0.3bc	6.73±0.4bc	0.93±0.11d	35.11±0.32c	33.61±1.2cde	51.48±2.4d	0.26±0.02de	5.79±0.1e	14.6±0.6d	-1.43±0.04de	
SA _{0.5} mM + B ₁	9.87±0.7 cd	6.44±0.3b	7.29±0.5b	0.84±0.11d	34.10±0.31d	35.42±1.1bc	69.82±2.7c	0.34±0.03bc	6.37±0.2c	16.5±0.6c	-1.32±0.04f	
SA _{0.5} mM + B ₂	12.40±0.7b	7.86±0.4a	8.35±0.5a	0.55±0.10e	30.88±0.29f	37.78±1.3ab	77.71±2.6b	0.40±0.03ab	7.24±0.2b	18.8±0.7b	-1.23±0.03 g	
SA _{1.0} mM + B ₀	8.37±0.7e	5.84±0.3bcd	5.96±0.4 cd	0.88±0.11d	34.79±0.31 cd	32.41±1.1de	50.68±2.1d	0.23±0.03ef	5.73±0.1e	14.1±0.6de	-1.57±0.05bc	
SA _{1.0} mM + B ₁	8.95±0.6de	6.28±0.3b	6.94±0.5b	0.83±0.11d	33.11±0.32e	34.81±1.2 cd	64.90±2.5c	0.31±0.03 cd	6.22±0.2 cd	15.2±0.6d	-1.48±0.04 cd	
SA _{1.0} mM + B ₂	13.90±0.7a	8.30±0.4a	9.20±0.5a	0.41±0.09e	29.78±0.30 g	39.48±1.3a	85.52±3.0a	0.42±0.03a	7.84±0.2a	20.4±0.7a	-1.14±0.03 h	
SA _{1.5} mM + B ₀	6.96±0.6 fg	5.42±0.3de	3.76±0.4e	1.57±0.12b	36.42±0.33b	29.02±1.0 fg	42.89±2.3 fg	0.18±0.02f	5.18±0.1 g	11.7±0.6f	-1.83±0.06a	
SA _{1.5} mM + B ₁	7.91±0.6ef	5.97±0.3bcd	5.16±0.4d	1.18±0.11c	34.61±0.33 cd	31.21±1.3ef	46.40±2.5ef	0.26±0.02de	5.81±0.1e	14.6±0.6d	-1.64±0.04b	
SA _{1.5} mM + B ₂	10.20±0.6c	6.40±0.3b	7.12±0.5b	0.86±0.10d	31.18±0.31f	34.39±1.4 cd	75.67±2.8b	0.34±0.03bc	7.06±0.2b	17.3±0.6c	-1.35±0.04ef	
F, test	**	**	**	**	**	**	**	**	**	**	**	

† Values represent means ± standard error (*n* = 6)

Means within the same column followed by the same letter are not significantly different at the 0.05 level, based on Duncan's Multiple Range Test

F-test significance levels: *P* < 0.05 (*), *P* < 0.01 (**), and *ns* = not significant

highest total soluble solids (TSS, 19.12 °Brix) and flavor index (91.0), indicating significantly improved fruit quality and marketability.

3.6 Principal Component Analysis (PCA)

The principal component analysis revealed that the first principal component (PC1) explained 82.7% of the total variance, accounting for most of the variation in soil moisture, physiological parameters, growth traits, and fruit quality attributes in *Ficus carica* L. ‘Sabz’ trees under rain-fed conditions. PC1 was positively associated with shoot length, shoot diameter, leaf chlorophyll content, leaf area, CO₂ assimilation, stomatal conductance, transpiration, fruit size, and yield. In contrast, PC1 showed negative loadings for sunburned leaves, small fruit number (<17 mm), and leaf temperature (Table 5).

These findings emphasize that treatments improving water retention and physiological performance contributed most to enhancing fruit quality and yield. Variables contributing significantly to PC1 (above the selection criterion [SC]=0.093) were identified in bold (Table 5).

The PCA score plot (Fig. 2) clearly separated treatments based on their effectiveness. Treatments with higher concentrations of SA (0.5, 1.0, and 1.5 mM) combined with biochar (B1) or biochar+biofertilizer (B2) were grouped on the right side of PC1, reflecting superior performance. The control treatment (SA0.0 mM+B0) clustered in the bottom-left quadrant, indicating poor performance across most variables.

The interaction of SA1.0 mM+B2 showed the most favorable position in the PCA biplot, contributing most to the overall improvement in plant growth, physiological traits, fruit size, quality, and yield. It was followed by SA0.5 mM+B2, SA1.5 mM+B2, and SA0.5 mM+B1, confirming the synergistic impact of combined biochemical and organic treatments in mitigating drought stress under rain-fed conditions.

3.7 Economical Survey and Benefit-Cost Analysis of Experimental Treatments

The economic analysis demonstrated that the SA1.0 mM+B2 treatment had the highest Benefit-Cost Ratio (BCR) of 3.99, indicating exceptional economic viability under rainfed fig production systems (Table 6). This treatment produced the greatest increase in fruit yield and quality while providing the highest return on investment.

Although other treatments such as SA0.5 mM+B2 (BCR=1.93) and SA0.5 mM+B1 (BCR=1.44) also yielded favorable economic outcomes, the SA1.0 mM+B2 combination was clearly superior. In contrast, the control

(SA0.0 mM+B0) had a low BCR (0.29) and a negative Net Present Value (NPV), reflecting poor profitability due to low productivity.

4 Discussion

This four-year field study confirmed the hypothesis that integrating SA foliar application with biochar and microbial-enriched soil amendments significantly improves drought resilience, nutrient acquisition, and yield performance of *Ficus carica* L. ‘Sabz’ under rain-fed semi-arid conditions. Our findings align with the objective to determine whether biochar enhances soil moisture retention and nutrient availability, and whether SA, in synergy with biofertilizers, optimizes plant physiological responses under environmental stress. The SA1.0 mM+B2 treatment emerged as the most effective, consistently improving water status, nutrient content, photosynthetic efficiency, and fruit yield and quality.

Biochar application significantly enhanced soil water content at all measured depths (0–120 cm), consistent with its known porous architecture and capacity to improve water retention through increased surface area and soil aggregation (Haider et al. 2022; Toková et al. 2020; Wang et al. 2019). Notably, no significant differences were observed in soil moisture between the biochar-only (B1) and biochar+biofertilizer (B2) treatments. This suggests that the direct physical effects of biochar on bulk soil water holding capacity may have overshadowed the more subtle biological influences of biofertilizers, at least at the scale and resolution of measurement used. The improvement in subsoil water reserves, however, was essential for sustaining deep-rooted fig trees during extended dry periods, which supports prior observations in similar systems (Tadayon and Hosseini 2022; Zare et al. 2019).

Despite limited impact on soil moisture, biofertilizer application in the B2 treatment markedly enhanced leaf nutrient concentrations, emphasizing its role in promoting nutrient availability and uptake rather than directly affecting bulk water retention. This reflects the known function of mycorrhizal fungi in extending root access to nutrient pools and the role of PGPR (e.g., *Bacillus subtilis*, *Pseudomonas fluorescens*) in phosphate solubilization and N fixation (Karnwal et al. 2023; Wang et al. 2023a). These microbial benefits were likely facilitated by biochar, which provided a stable habitat that enhanced microbial colonization and survival (Waqar et al. 2022). The observed increase in leaf N concentration (up to 1.88%) within sufficiency ranges further confirms the success of this integrated nutrient delivery system. Moreover, biochar’s influence on nutrient retention was enhanced by its alkaline pH and cation exchange

Table 4 Effects of foliar application of Salicylic acid and soil application of biochar-biofertilizer treatments on fruit characteristics of Fig (*Ficus carica* L. 'Sabz') tree under rainfed conditions averaged over 2021–2024

Treatment	No. of fruits with diameters < 17 mm (grade B)	No. of fruits with diameters 17–22 mm (grade A)	No. of fruits with diameters > 22 mm (grade AA)	Dry fruit yield per fig tree (kg/tree)	No. of fruits with dark brown skin	No. of fruits with light brown skin	No. of fruits with light yellow skin	Fruit total soluble solids (TSS %) (^o Brix)	Fruit titratable acid (TA) (%)	Fruit flavor index (TSS/TA)
I- Salicylic acid (SA)										
(SA _{0.0} mM) (Ctrl.)	74.13±3.8a	18.87±1.3b	7.00±0.6c	7.93±0.3d	65.00±2.2a	21.00±1.2b	14.00±0.6d	15.87±0.3c	0.205±0.002b	79.33±0.06c
SA _{0.5} mM	62.03±3.2b	23.90±1.4a	14.07±0.8a	14.95±0.4b	52.60±2.1c	26.97±1.3a	20.43±0.5c	17.43±0.4ab	0.215±0.003a	83.02±0.07b
SA _{1.0} mM	60.70±3.4b	24.57±1.4a	14.73±0.8a	16.49±0.4a	50.70±2.1c	23.70±1.2b	25.60±0.7a	17.83±0.4a	0.214±0.002a	84.92±0.08a
SA _{1.5} mM	70.63±3.5a	18.77±1.3b	10.60±0.7b	10.67±0.3c	57.07±2.2b	20.93±1.2b	22.00±0.5b	16.83±0.3b	0.208±0.002b	82.89±0.07b
F. test	**	**	**	**	**	*	**	**	**	**
II- Biochar-Biofertilizer (B)										
No application (B ₀) (Ctrl.)	76.48±3.7a	17.18±1.2c	6.35±0.5c	8.06±0.3c	66.38±2.2a	17.95±1.0c	15.68±0.6c	16.18±0.3c	0.208±0.002a	77.92±0.06c
Biochar (B ₁)	67.53±3.5b	20.78±1.4b	11.70±0.6b	12.76±0.4b	58.25±2.1b	22.30±1.2b	19.45±0.6b	16.98±0.3b	0.209±0.002a	82.78±0.07b
Biochar + Biofertilizer (B ₂)	56.63±3.4c	26.63±1.3a	16.75±0.7a	16.70±0.4a	44.40±2.0c	29.20±1.3a	26.40±0.7a	17.83±0.4a	0.213±0.003a	86.92±0.07a
F. test	**	**	**	**	**	**	**	**	ns	**
Interaction (SA + B)										
SA _{0.0} mM + B ₀ (Ctrl.)	81.41±3.8a	15.01±1.2h	3.60±0.5h	5.63±0.3i	72.81±2.3a	16.50±1.1f	10.71±0.5i	15.08±0.3g	0.202±0.002f	75.5±0.06f
SA _{0.0} mM + B ₁	77.30±3.5ab	18.90±1.3cg	3.81±0.5h	7.95±0.4g	66.32±2.2b	19.42±1.2de	14.30±0.6h	15.79±0.3f	0.205±0.002ef	79.0±0.07e
SA _{0.0} mM + B ₂	63.68±3.5d	22.68±1.3c	13.62±0.7d	10.2±0.4f	55.87±2.1de	27.12±1.3c	17.02±0.7g	16.68±0.4d	0.209±0.002cd	83.5±0.06d
SA _{0.5} mM + B ₀	71.91±3.6bc	19.62±1.3def	8.51±0.5f	9.56±0.4f	63.70±2.2bc	18.29±1.2ef	18.01±0.7fg	16.80±0.4cde	0.212±0.002bcd	80.0±0.07e
SA _{0.5} mM + B ₁	61.82±3.4d	22.31±1.4cd	15.88±0.7c	16.12±0.4c	52.92±2.1ef	27.72±1.3bc	19.41±0.7ef	17.52±0.4bc	0.214±0.003abc	83.3±0.07d
SA _{0.5} mM + B ₂	52.41±3.3e	29.79±1.4b	17.79±0.8b	19.16±0.5b	41.21±2.0g	34.91±1.4a	23.90±0.7bc	18.05±0.4b	0.218±0.003a	85.68±0.07c
SA _{1.0} mM + B ₀	76.50±3.5ab	17.32±1.3fgh	6.20±0.5g	10.26±0.3f	65.87±2.2bc	19.68±1.0de	14.38±0.6h	16.71±0.3d	0.210±0.002cd	79.5±0.06c
SA _{1.0} mM + B ₁	61.72±3.6d	22.51±1.3c	15.81±0.6c	15.60±0.4c	55.45±2.2de	21.70±1.1d	22.91±0.7c	17.71±0.4b	0.215±0.003a	84.32±0.07cd
SA _{1.0} mM + B ₂	43.91±3.5e	33.90±1.5a	22.22±0.9a	23.61±0.5a	30.80±2.1h	29.68±1.2b	39.50±0.7a	19.12±0.4a	0.217±0.003ab	91.0±0.08a
SA _{1.5} mM + B ₀	76.11±3.3ab	16.78±1.3gh	7.11±0.5g	6.79±0.4h	63.11±2.3c	17.31±1.2f	19.62±0.7e	16.12±0.3ef	0.212±0.002bcd	76.7±0.06f
SA _{1.5} mM + B ₁	69.28±3.4c	19.41±1.4ef	11.28±0.6e	11.37±0.3e	58.42±2.2d	20.40±1.3d	21.21±0.6d	16.90±0.3cd	0.203±0.002f	84.5±0.07cd
SA _{1.5} mM + B ₂	66.51±3.5cd	20.11±1.3cde	13.40±0.5d	13.85±0.4d	49.70±2.1f	25.11±1.3c	25.19±0.6b	17.48±0.4bc	0.208±0.002de	87.5±0.07b
F. test	**	**	**	**	**	**	**	**	*	*

† Values represent means ± standard error (*n* = 6)

Means within the same column followed by the same letter are not significantly different at the 0.05 level, based on Duncan's Multiple Range Test

F-test significance levels: *P* < 0.05 (*), *P* < 0.01 (**), and *ns* = not significant

Table 5 Principal component loadings of selected traits in Fig trees (*Ficus carica* L. 'Sabz') based on PCA (2021–2024 average)

Variable	PC1	PC2	PC3	PC4
Volumetric soil moisture content (%) 0–60 cm	0.136	-0.398	0.077	-0.264
Volumetric soil moisture content (%) 60–120 cm	0.140	-0.375	0.106	-0.312
Volumetric soil moisture content (%) 120–180 cm	0.147	-0.328	0.233	-0.2
Shoot length (cm)	0.177	0.185	-0.007	0.05
Shoot diameter (mm)	0.176	0.144	-0.02	0.083
No. of leaves per shoot	0.171	0.16	-0.104	-0.192
No. of sunburned leaves per shoot	-0.161	-0.096	0.053	0.355
Leaf temperature (°C)	-0.177	-0.069	-0.139	0.034
Leaf chlorophyll content index	0.174	0.168	-0.048	-0.228
Leaf areas (cm ²)	0.173	0.115	0.036	-0.13
Stomatal conductance (mol.m ⁻² . s ⁻¹)	0.181	0.042	-0.02	-0.158
Leaf transpiration (mmol.m ⁻² . s ⁻¹)	0.178	0.098	0.077	-0.009
Light-saturated net CO ₂ assimilation (μmol.m ⁻² . s ⁻¹)	0.182	0.075	0.016	-0.106
Leaf water potential (MPa)	0.170	0.142	-0.115	-0.278
No. of fruits with diameters < 17 mm (grade B)	-0.180	-0.061	-0.001	-0.093
No. of fruits with diameters 17–22 mm (grade A)	0.176	0.069	-0.07	0.145
No. of fruits with diameters > 22 mm (grade AA)	0.176	0.05	0.067	0.039
No. of fruits with dark brown skin	0.164	-0.132	-0.324	0.106
No. of fruits with light brown skin	0.178	-0.111	0.055	0.149
No. of fruits with light yellow skin	0.155	-0.157	-0.359	0.233
Fruit total soluble solids (TSS %) (°Brix)	0.177	0.066	0.177	0.204
Fruit titratable acid (TA) (%)	0.152	-0.112	-0.44	0.025
Fruit flavor index (TSS/TA)	0.169	-0.231	0.02	0.201
Yield	0.177	0.129	0.102	-0.087
Eigenvalues	28.958	2.324	1.260	0.796
Explained variance (%)	0.827	0.066	0.036	0.023
Accumulated variance (%)	0.827	0.894	0.930	0.953
Selection criterion (SC)	0.093	0.328	0.445	0.560

Note: Variables exceeding the selection criterion [SC] in each PC are in bold

Fig. 2 Principal Component Analysis (PCA) score plot showing the distribution of treatment effects on vegetative growth, physiological traits, and fruit characteristics of *Ficus carica* L. 'Sabz' averaged over 2021–2024. PC1 and PC2 explain 82.7% and 6.6% of the total variance, respectively. Treatments include salicylic acid (SA) at four concentrations (0.0, 0.5, 1.0, and 1.5 mM) combined with biochar (B1) and biochar+biofertilizer (B2). The control (SA0.0 mM+B0) is located in the bottom-left quadrant

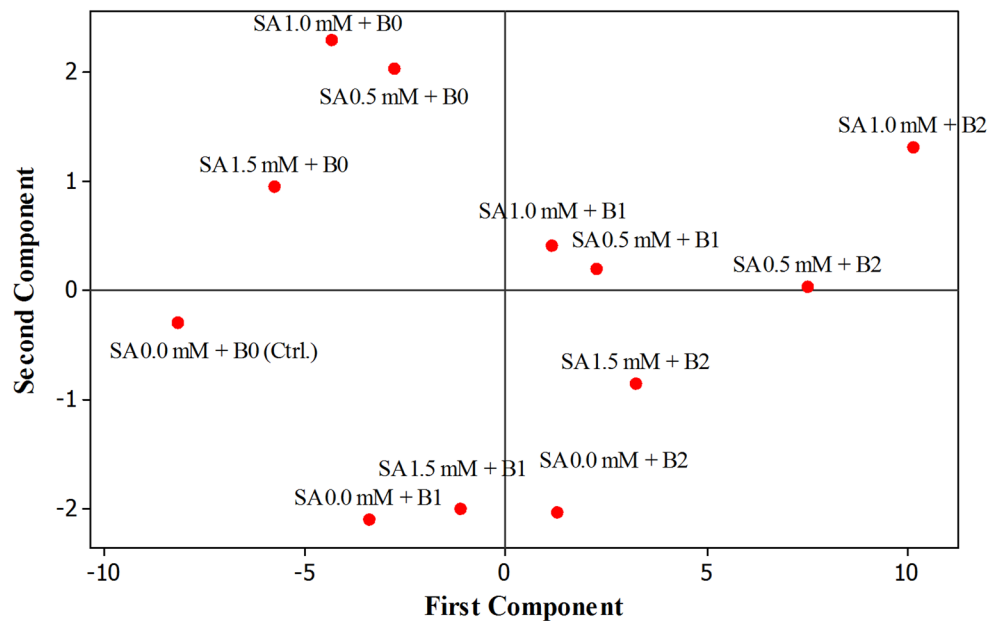


Table 6 Benefit-Cost analysis (BCA) of selected treatments applied to *Ficus carica* L. 'Sabz' trees under rainfed conditions during 2021–2024

Analysis	SA _{0.0mM} ⁺ B ₀ (Ctrl.)	SA _{1.5 mM} + B ₂	SA _{1.0 mM} + B ₁	SA _{0.5 mM} + B ₁	SA _{0.5 mM} + B ₂	SA _{1.0 mM} + B ₂
The present cost (\$ USD)	0.00	12.41	6.80	5.72	10.25	11.34
The future costs=The present cost+ Increased costs due to reduced yield compare to the yield in normal condition* (\$ USD)	48.43	40.28	30.30	27.90	24.80	14.78
The future benefits (Increase in profit due to increment in yield) (\$ USD)	14.08	34.63	39.00	40.30	47.90	59.03
Present value factor=1/(1+r) ⁿ	0.36	0.08	0.04	0.03	0.01	0.00
Present value of future benefits=Future benefits × Present value factor (\$ USD)	5.07	2.89	1.43	1.13	0.65	0.09
Present value of future costs=Future costs × Present value factor (\$ USD)	17.45	3.37	1.11	0.78	0.34	0.02
Net Present Value=Present value of future benefits–Present value of future costs (\$ USD)	-12.38	-0.47	0.32	0.35	0.31	0.07
Benefit-Cost Ratio=Present Value of Future Benefits / Present Value of Future Costs	0.29	0.86	1.29	1.44	1.93	3.99

Salicylic acid (SA), No application (B0) (Ctrl.), Biochar (B1) and Biochar+Biofertilizer (B2)

* About 25 kg. tree⁻¹ and the average price of \$2.5 USD per kg of dry fig fruit

Future benefits were calculated based on yield increments (up to 25 kg tree⁻¹) at an average market price of \$2.5 USD per kg of dry fig fruit

Present Value Factor (PVF)=1 / (1+r)ⁿ, where r=interest rate (rate of return) and n=4 years

NPV=Present Value of Future Benefits– Present Value of Future Costs

BCR=Present Value of Future Benefits / Present Value of Future Costs

capacity, which improve soil buffering and reduce leaching losses (Adekiya et al. 2023; Kapoor et al. 2022).

SA application, particularly at 0.5 and 1.0 mM, improved shoot growth and foliar nutrient content independently and synergistically with biochar and biofertilizers. As a key phytohormone, SA modulates stress responses by regulating ion transporter activity (e.g., NRT1, ZIP), enhancing membrane stability, and priming antioxidant defenses under abiotic stress conditions (Li et al. 2022; Song et al. 2023). Our results show that SA promoted photosynthetic function by increasing chlorophyll content, leaf area, and stomatal conductance, while also reducing leaf temperature and mitigating oxidative stress symptoms. These outcomes are consistent with earlier reports of SA improving photosynthetic machinery and water-use efficiency under drought (El-Hady et al. 2021; González-Villagra et al. 2022; Rai et al. 2024).

The interaction between SA and the biochar-biofertilizer treatment produced clear synergistic effects. SA1.0 mM+B2 yielded the highest chlorophyll content, stomatal conductance, CO₂ assimilation rate, and leaf water potential, alongside the lowest leaf temperature and sunburn incidence. These results suggest that while biochar and biofertilizers improved belowground resource availability and root function, SA modulated aboveground physiological responses, creating a feedback loop that optimized stress tolerance and carbon assimilation (Ammar et al. 2022; Torun et al. 2024). The superior physiological performance directly translated into agronomic benefits: higher yields (23.61 kg/tree), larger fruit sizes, improved skin color, and a superior flavor index (91.0), demonstrating the link between improved water relations and fruit quality.

Multivariate analysis using PCA further confirmed these conclusions. The first principal component (PC1), which explained 82.7% of the total variance, was strongly influenced by traits such as chlorophyll content, net photosynthetic rate, leaf water potential, and premium-grade fruit yield (AA). The score plot positioned SA1.0 mM+B2, followed by SA0.5 mM+B2, at the optimal end of the PCA space, clearly separating these treatments from the control (SA0.0 mM+B0). These results reinforce the notion that the combination of biochemical (SA) and organic (biochar+microbial) inputs effectively modulates drought stress responses and fruit development in rain-fed fig trees.

Economic analysis validated the agronomic outcomes, showing that SA1.0 mM+B2 had the highest Benefit-Cost Ratio (BCR=3.99), far exceeding all other treatments. Despite higher initial costs, the substantial yield increase and superior fruit quality, factors critical for marketability, resulted in a highly favorable net return. Given biochar's longevity (5–10 years) and SA's low application rate, the combined treatment also supports four-year sustainability and input efficiency. Farmers in semi-arid zones could implement this strategy to buffer against climate-induced yield variability and increase profitability, in line with broader goals for sustainable, climate-resilient agriculture (Chaurasia et al. 2024).

In conclusion, this study demonstrates that a combined strategy of moderate-dose SA foliar application (1.0 mM) and biochar enriched with microbial and organic biofertilizers offers a highly effective, sustainable, and economically viable solution for enhancing drought resilience, soil health, and productivity in rain-fed fig orchards. The success of this approach lies in its integration of soil physical and

microbial benefits with plant hormonal regulation, forming a comprehensive response to water stress. Future research should explore the longevity of biochar's effects, optimize SA and biofertilizer application timing and rates, and assess applicability across diverse fruit crops and environmental conditions.

5 Conclusion

This four-year field study demonstrated that the integration of foliar-applied salicylic acid (SA) with soil-applied biochar and biofertilizers significantly enhances drought resilience, physiological performance, and yield in rain-fed fig (*Ficus carica* L. 'Sabz') orchards under semi-arid conditions. Among the tested treatments, the application of 1.0 mM SA combined with biochar enriched with mycorrhizal fungi, beneficial bacteria, fulvic acid, and amino acids consistently delivered the most pronounced improvements in leaf nutrient concentrations, chlorophyll content, gas exchange parameters, and water-use efficiency. This integrated approach not only increased fruit yield by over 300% relative to the control but also enhanced fruit quality and marketable grade, confirming the synergistic benefits of combining organic, microbial, and biochemical amendments.

The results highlight biochar's role in improving soil structure and moisture retention, while biofertilizers facilitated nutrient solubilization and uptake, and SA enhanced physiological responses to drought stress. Economic analysis further supports this integrated method, with the highest benefit-cost ratio (3.99) recorded for the SA1.0 mM+ biochar-biofertilizer treatment. These findings provide a scalable and economically viable strategy for improving rain-fed horticulture in water-limited environments. Future research should focus on optimizing the timing and frequency of SA and microbial applications, evaluating the long-term persistence of biochar effects, and expanding trials to other fruit crops and agroecological zones to validate broader applicability and refine sustainable, climate-resilient management practices.

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Declarations

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