The Future of Agriculture

FSA

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Modeling and Biochar Soil Amendments to Optimize Water-Use Efficiency and Yield in Arid Valencia Orange Orchards

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https://doi.org/10.37229/fsa.fja.2026.08.17

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Future Science Association

Available online free at
www.futurejournals.org

Print ISSN: 2687-8151

Online ISSN: 2687-8216

Received: 10 July 2026
Accepted: 1 August 2026
Published: 17 August 2026

Abstract: This study explores the sustainable optimization of Valencia orange production in Egypt's arid regions by analyzing the dual effects of deficit irrigation and biochar soil conditioning. Multi-season field experiments demonstrated that Partial Root-zone Drying (PRD) combined with 1200 kg ha^{-1} of biochar significantly enhances the vegetative growth, physiological traits, and final yield components of Valencia orange trees in degraded sandy soils. Severe water restriction (50% Full Irrigation [FI]) constrained canopy development and chlorophyll formation. In contrast, the PRD strategy produced superior growth responses, achieving an increased canopy volume of 4.1–4.3%, an expanded leaf area of 27.0–28.3 cm², and total chlorophyll levels up to 3.0 mg g^{-1} F.W. The application of biochar showed a significant, dose-dependent improvement in soil water-holding capacity and nutrient retention. Under the optimal interaction treatment (PRD combined with 1200 kg ha^{-1} biochar), the trees achieved peak agronomic performance. This synergistic combination maximized canopy volume increase to 5.5–5.8%, expanded leaf area to 37.9–40.1 cm², and elevated chlorophyll content to 3.7–4.0 mg g^{-1} F.W. Furthermore, this treatment upgraded fruit development and quality indices; fruit weight reached 231.4–240.6 g, total yield peaked at 48.5–50 ton ha^{-1}, TSS reached 13.7–14.2%, and Vitamin C maximized at 48.8–51.3 mg 100 mL^{-1} juice, confirming that biochar effectively mitigates drought stress. Complementing these findings, the treatments were simulated using the SALTMED model software to evaluate its predictive fidelity under local Egyptian conditions. The software demonstrated exceptional accuracy, establishing a robust correlation between field-collected data and model-generated values. This alignment was statistically validated by an outstanding coefficient of determination (R^2 ranging from 96% to 98%). Consequently, the study strongly recommends utilizing SALTMED for managing fruit crops in Egypt to save time, labor, and costs, while providing reliable predictive data to optimize export and import operations for vital commodities like citrus.

Key words: Valencia orange، Partial Root-zone Drying (PRD), Biochar amendment، Sandy soil productivity، SALTMED model simulation.

1. Introduction

Egypt's fixed freshwater resources and fast expanding population have created a serious water security dilemma **(Abd Ellah, 2020; El-Gafy, 2022)**. Nearly all of the nation's renewable water comes from the Nile River, which supplies more than 95% of it **(Ahmed and Soliman, 2024)**. Egypt's traditional water supply is still limited to about 60 BCM, despite the country's actual yearly water demand having increased to almost 114 BCM **(Nasef, 2024)**. Peer-reviewed research shows that this enormous deficit has reduced the nation's annual per capita water share to barely 500 cubic meters, less than half of the global threshold for acute water poverty **(Khedr *et al*., 2026)**.

For Egypt's survival, food security, and regional stability, it is essential to comprehend the significance of this scarce water supply. According to scholarly research, extreme water scarcity compels farmers to use drainage water for irrigation, raising soil salinity and endangering important agricultural areas like the Nile Delta **(Gado and El-Agha, 2025; Hassan *et al*., 2026).** Egypt's downstream water flow is further complicated by upstream geopolitical issues, such as the unilateral filling of the Grand Ethiopian Renaissance Dam (GERD) **(Ahmed and Soliman, 2024)**. According to research, proactive conservation methods are essential in response to these stringent boundaries **(Khedr *et al*., 2026)**. To avoid complete water depletion, they include building solar-powered coastal desalination facilities, switching to localized drip irrigation, and recycling wastewater on a massive scale **(Radwan *et al*., 2026; Mahmoud andAlazba, 2024; Sharaf El-Din *et al*., 2023)**.

The combined consequences of limited arable land, climate change, and water shortages are placing growing pressure on Egypt's agricultural economy. Egypt, a mostly dry nation, relies nearly exclusively on the Nile River for its freshwater supply, with over 80% of the water used for agriculture. However, competition for water is becoming more intense due to climate variability, upstream water consumption, and growing population needs, necessitating the adoption of more sustainable and efficient farming practices. In this regard, fruit production is an essential part of Egypt's agricultural economy, making a substantial contribution to export earnings, rural livelihoods, and food security **(Abd El Maksoud, 2022).**

Fruit crops such as citrus are widely cultivated across newly reclaimed lands and desert fringes, where environmental conditions are inherently harsh. Sandy or sandy loam soils with limited water-holding capacity, high infiltration rates, and poor nutrient retention are typical of these areas. In addition, high temperatures, intense solar radiation, and strong evaporative demand further exacerbate water loss, resulting in reduced crop water productivity. Another significant limitation is salinity, especially in irrigated areas where poor water management and poor drainage cause salt buildup in the root zone, which negatively impacts plant growth and productivity **(Farag, 2015).** These difficulties are predicted to get worse due to climate change. The Mediterranean and Middle East regions are among the most sensitive to the effects of climate change, with predicted temperature increases, an increase in the frequency of heatwaves, and a decrease in precipitation, according to projections from the Intergovernmental Panel on Climate Change. In addition to shortening growing seasons and increasing the frequency of abiotic challenges like salinity and drought, these changes are expected to modify crop water requirements. These hazards constitute a serious threat to sustainability and production for perennial fruit crops, which need long-term investment and consistent environmental conditions **(Medda *et al*., 2022).**

Adopting sustainable agriculture practices has become essential rather than optional in response to these issues. Precision irrigation technologies and controlled deficit irrigation are viable ways to increase water use efficiency while preserving or even raising crop quality and output **(Ali *et al*., 2025).**

Regulated deficit irrigation (RDI), which demonstrates that controlled water stress may significantly improve fruit quality while maintaining reasonable crop yields and boosting water consumption efficiency, is a crucial water management strategy in sustainable citrus production. In dry and semi-arid areas with very restricted water supplies, complete irrigation during all phenological stages often leads to excessive vegetative growth at the expense of fruit quality. On the other hand, citrus farmers can successfully manage vegetative and reproductive growth by using mild deficit irrigation during certain, less sensitive growth stages, maximizing total production economics. The notable improvement in the interior chemical and physical characteristics of citrus fruits is one of the main benefits of using a well-timed deficit irrigation approach. An osmoregulatory response is triggered inside the fruit cells when a mild water deficit is administered during the early fruit or maturation stages. This physiological stress causes an active build-up of total soluble solids, soluble reducing sugars, and titratable acidity rather than just dehydration. As a result, the fruit has a higher maturity index, becomes considerably sweeter, and has a fuller flavor, all of which make it very appealing for fresh markets. Additionally, recent studies have shown that minor water restrictions can raise the quantities of health-promoting substances including vitamin C, total flavonoids, phenols, and overall antioxidant activity, as well as slightly increase fruit hardness. In addition to increasing the harvest's organoleptic market value, this structural and chemical improvement greatly increases the fruit's storability and resistance to deterioration during post-harvest cold storage. economics **(Abou Ali *et al.*, 2024).**

The deliberate reduction of water application does not always result in a significant decline in economic returns from the standpoint of yield and water productivity. A carefully controlled mild-to-moderate deficit successfully protects the great majority of the complete yield, but severe or poorly timed drought stress definitely limits fruit expansion and lowers ultimate harvest value. Regulated deficit watering actually lowers orchard operating expenses by minimizing the amount of time and equipment needed for summer trimming by preventing excessive and needless vegetative flushes. When compared to traditional full irrigation methods, the reduction in water application directly increases crop water productivity and net economic water productivity, sometimes by up to 75% and 118%, respectively. Under increasing climate challenges, citrus production is guarantyd to stay extremely sustainable and commercially viable because to this water-saving capability. The benefits of a mild water deficit on canopy light reflection and fruit internal quality are further enhanced when combined with cutting-edge agronomic techniques like plastic film mulching, providing an ideal framework for contemporary citrus orchard management. economy **(Arbizu-Milagro *et al*., 2023)**

A very effective sustainable way to significantly boost citrus crop productivity and fruit quality is to increase the quantity of biochar put to orchard soils. Biochar, a highly stable carbon-rich material produced by pyrolyzing biomass, enhances the physical, chemical, and biological architecture of soil in sandy or degraded citrus-growing regions. When sprayed at progressively larger rates, biochar reliably increases soil porosity, bulk density, and aggregate stability, creating an environment that is more favorable for citrus root growth. This increased structural porosity immediately improves the soil's capacity to hold water, allowing trees to maintain optimal water status and more successfully withstand short-term dry stress. Additionally, due of its incredibly high surface area and dense cation exchange capacity, increasing the pace of biochar amendment leads to an outstanding retention of important macronutrients and micronutrients within the root zone. Biochar guaranties a steady and balanced supply of nitrogen, phosphorus, and potassium by decreasing nutrient leaching. This prevents common nutrient imbalances and significantly speeds up vegetative canopy growth, which directly increases the trees' overall reproductive potential **(Al-Saif *et al*., 2026; Wang *et al*., 2024).**

Applying biochar has been a ground-breaking method for improving citrus orchard output and fruit quality worldwide **(Abbas *et al*., 2025; Hassan *et al*., 2026)**. Citrus trees are often grown in sandy or severely deteriorated soils that have little moisture retention and poor fertilizer holding capacity. Biochar functions as a permanent sponge in the root zone because it is a very porous, carbon-rich substance made by pyrolyzing organic waste **(Santos *et al*., 2025).** According to recent research, adding biochar greatly increases the soil's water-holding limitations and Cation Exchange Capacity (CEC) **(Liu, and Zhang, 2025).** According to **Abbas *et al*. (2025) and Xu and Schulz (2024),** this fundamental shift enables the soil to hold onto important nutrients, preventing essential minerals like nitrogen and potassium from washing away into deep groundwater.

Biochar has a significant positive impact on citrus tree physiology, root architecture, and final crop marketability in addition to improving the soil fabric **(Hassan *et al*., 2026; Raza *et al*., 2024)**. Peer-reviewed research confirms that specific biochar amendments promote root elongation and increase total root surface area, enabling trees to absorb water and micronutrients much more effectively **(Tu *et al*., 2026).** greater fruit yields per tree, greater average fruit weight, and a raised sugar-to-acid ratio (Brix index) at harvest time are all directly correlated with this improved nutrient flow **(Hassan *et al*., 2026; Zheng *et al*., 2025)**. Additionally, crops show significantly increased concentrations of vitamin C and antioxidants, increasing the fruit's value for commercial markets **(Hassan *et al*., 2026; Raza *et al*., 2024).** Biochar also strengthens tree immunity against damaging vascular diseases like citrus greening **(Tu *et al*., 2026)**. Finally, by permanently locking atmospheric carbon into orchard soils, biochar gives growers a highly sustainable way to mitigate climate stress and maximize farm profitability **(Liu and Zhang, 2025; Santos *et al*., 2025)**.

Increased leaf chemical composition and improved photosynthetic efficiency are evident examples of the beneficial physiological reactions brought about by increasing biochar application rates. Higher biochar doses gradually enhance leaf nitrogen, phosphorus, and potassium concentrations together with a significant increase in overall chlorophyll content, according to recent field research. This nutritional boost significantly lowers premature fruit drop and supplies the metabolic energy required to handle higher fruit loads. As a result, as biochar rates rise, citrus output rises gradually and significantly. In comparison to unamended control soils, multi-season field trials concentrating on well-known citrus cultivars, such as Valencia oranges, have shown remarkable production increases of 67% to 73% at maximum biochar treatment thresholds. This increase in yield is strongly associated with a significant increase in tree size and canopy volume, demonstrating that biochar acts as a transformative soil conditioner that directly supports commercial-scale productivity **(Schumann and Spann, 2025)**. High biochar application rates significantly improve the structural and organoleptic quality characteristics of citrus fruits in addition to causing enormous yield improvements. The improved soil qualities have a positive effect on the fruit's physical and chemical indices, such as average weight, diameter, peel thickness, and edibility percentage. More significantly, by improving the ratio of soluble solids to titratable acidity and raising the absolute accumulation of soluble solids, the use of biochar significantly improves the interior fruit chemistry. The harvested citrus fruits will have a higher maturity index, a deeper flavor profile, and improved market sweetness thanks to this chemical treatment. In addition to encouraging saprophytic fungi that quicken nutrient cycling, the enhanced soil environment simultaneously increases the richness, evenness, and functional diversity of advantageous soil bacterial populations. According to **Liu *et al*. (2024)**, these coordinated microbial alterations increase the tree's resistance and maximize nutrient uptake, resulting in fruits that are not only larger and more abundant but also rich with vital vitamins and health-promoting antioxidants, guaranteeing top-tier economic value.

Researchers can forecast crop yields, soil salinity, and water usage efficiency under various climate scenarios using simulation models, which are essential tools in contemporary agricultural water management **(Ragab *et al*., 2024; Silva *et al*., 2026).** Among these tools, the SALTMED model is particularly noteworthy as a highly adaptable, physically-based simulation platform intended to assess the effects of crop types, irrigation systems, water management, and soil characteristics on crop yields and soil salinity accumulation **(Ragab *et al*., 2024; Al-Omran *et al*., 2025).** SALTMED, which was designed to manage a variety of water types, such as brackish, saline, and treated wastewater, is essential for anticipating solute transport in the root zone and improving deficit irrigation **(Karimi and Neshat, 2026; Zou Voss *et al*., 2025).**

SALTMED's remarkable accuracy in mimicking soil moisture profiles, dry matter generation, and final crop productivity across a variety of conditions has been highlighted by recent scientific studies **(Aly and Al-Selini, 2026; Raza *et al*., 2025).** The model gives farmers and policymakers data-driven strategies to improve water productivity and minimize soil degradation by entering localized meteorological data, crop coefficients, and soil hydraulic characteristics **(Hassanli *et al*., 2025; Yanes *et al*., 2024).** SALTMED helps create precise irrigation plans that protect food security and save valuable freshwater resources in nations with extreme water scarcity **(El-Mowelhi *et al*., 2024).** It is essential for climate change adaptation and sustainable agriculture due to its capacity to replicate complicated field conditions and multi-crop systems **(Ragab *et al*., 2024; Silva *et al*., 2026).**

According to the real results of several studies, the SALTMED model offered a high simulation of crop yield, dry matter, and soil moisture **(Afzal *et al*., 2016; El-Shafie *et al*., 2017; Abdelraouf and Ragab 2018)**. **Abdelraouf and Ragab (2017)** claim that employing simulation models is the quickest and least expensive way to access and forecast important information that may be obtained from the model simulation results as a quick and inexpensive substitute for doing several field trials.

The main objective of the study is to improve the production and quality of Valencia oranges in Egypt under water scarcity conditions, and to address current and future climate change scenarios through sustainable irrigation management by increasing the use of biochar as a sustainable material, in addition to evaluating the performance of the SALTMED model in simulating the production process under Egyptian conditions.

2. Materials and Methods

Experimental Sites and Environmental Conditions

The studies were carried out in the Nubaria region of Egypt over the course of two consecutive growing seasons. The area is characterized by arid climatic conditions, low annual rainfall, high evaporative demand, and sandy soil texture with low water-holding capacity. As seen in Figures (1,2), orchards of Valencia orange trees cultivated under drip irrigation systems were chosen for the experiment.

Figure (1). The site where the experiments were conducted is in the Nubaria area of Beheira Governorate, Egypt

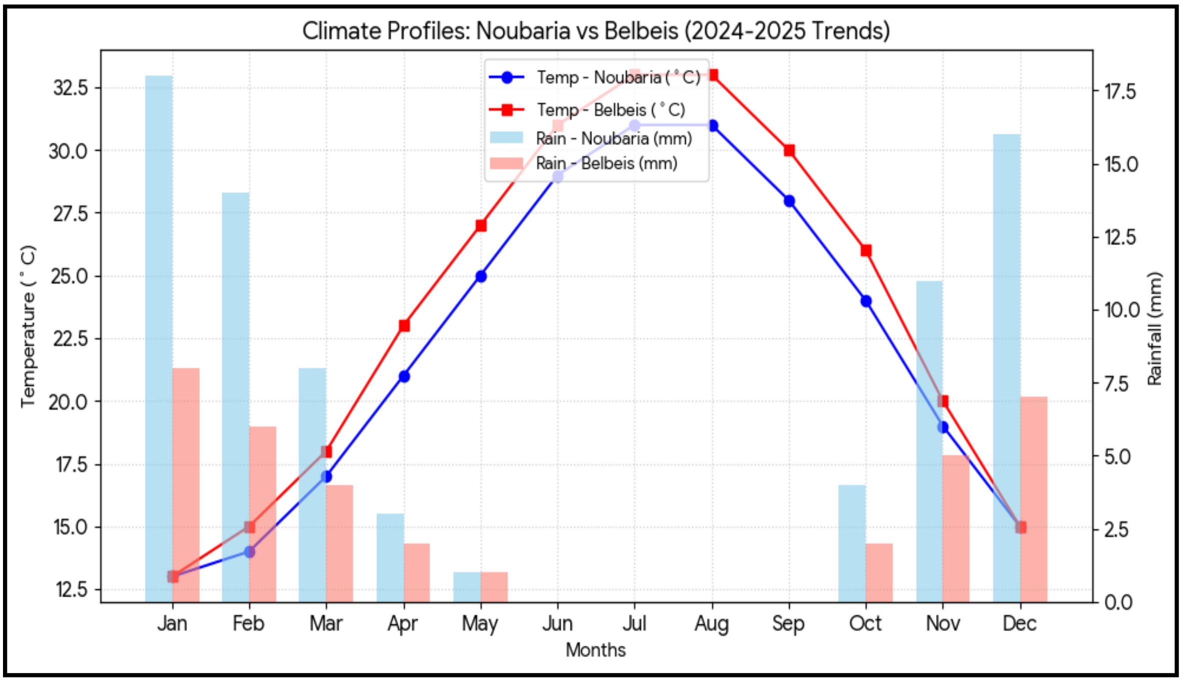


Figure (2). Some climatic factors of the project's experimental sites in Nubaria and Bilbeis, Egypt, during the two years of the study

Characteristics of agricultural soil and irrigation water quality

With 85.4% sand, 9.5% silt, and 5.1% clay, the soil is sandy. It has a pH of 7.7, an electric conductivity (EC) salinity of 1.67 dS m^{-1}, and 0.41% organic matter in the top 30 cm. The values of accessible soil N, P, and K were 17.2, 4.3, and 25 mg kg^{-1} soil, respectively, whereas the amounts of extractable Fe, Mn, and Zn were 2.99, 1.75, and 0.67 mg kg^{-1} soil. The chemical characteristics of irrigation water are shown in Table (1). The irrigation water, which had an average electrical conductivity of 0.43 dS m^{-1} and a pH of 7.18, came from an open creek in the experimental region.

Table (1). The lists of irrigation water's chemical properties

SAR (%)	Anions (meq L^{-1})				Cations (meq L^{-1})				EC (dS m^{-1})	pH
	SO_4^{--}	Cl^-	HCO_3^-	CO_3^{--}	K^+	Na^+	Mg^{++}	Ca^{++}		
2.67	1.44	1.73	1.15	0.73	0.34	2.62	0.63	1.46	0.45	7.15

Crop evapotranspiration and the timing of irrigation

The Food and Agriculture Organization of the United Nations, or FAO, served as the basis for the crop evapotranspiration computation. The Modified Penman-Monteith equation, FAO 56 **(Allen *et al.*, 1998),** is the basis for the reference evapotranspiration (ETo), which was computed using daily meteorological parameters recorded at the experimental location (Figure 3). The FAO calculator (http://www.fao.org/land-water/databases-and-software/eto-calculator/en/) was used to determine the ETo. Crop evapotranspiration was estimated using the CLIMWAT 2.0 and CROPWAT 8.0 algorithms based on Equation 1.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where T stands for the mean daily air temperature at 2 m height (°C), U2 for wind speed at 2 m height (ms^{-1}), es Andean for saturated vapor pressure deficit (kPa), G for soil heat flux density (MJ m^{-2} day^{-1}), Rn for net radiation at the crop surface (MJ m-2 day^{-1}), and ETo for reference evapotranspiration (mm day^{-1}). The methodology and procedures described in FAO Irrigation and Drainage Paper No. 56 **(Allen *et al*., 1998)** are still used to calculate the crop's evapotranspiration, which already represents the daily plant water consumption thru the collection of water evaporation from soil and water transpiration from plant leaf stomata and evaporation:

$$\mathrm{ET_C} = ET_O \times Kc \qquad (2)$$

where Kc represents the crop coefficient, and ETo represents the daily reference evapotranspiration (mm day^{-1}). The gross irrigation requirements for green beans was performed by the following equation (3) of **Brouwer and Heibloem (1986):**

$$IR_g = \left(\frac{ET_O \times K_c \times K_r}{E_i}\right) \qquad (3)$$

where IRg stands for gross irrigation requirement (mm day^{-1}), Ei for irrigation efficiency (%), ETo for reference evapotranspiration, Kc for crop coefficient, and Kr for ground cover reduction factor. The values of Kr are determined using the Keller equation (Eq. 4) as follows:

$$K_r = GC + 0.15(1 - GC) \qquad (4)$$

where GC, or ground cover percentage, is calculated by dividing each plant's shaded area by the total plant area.

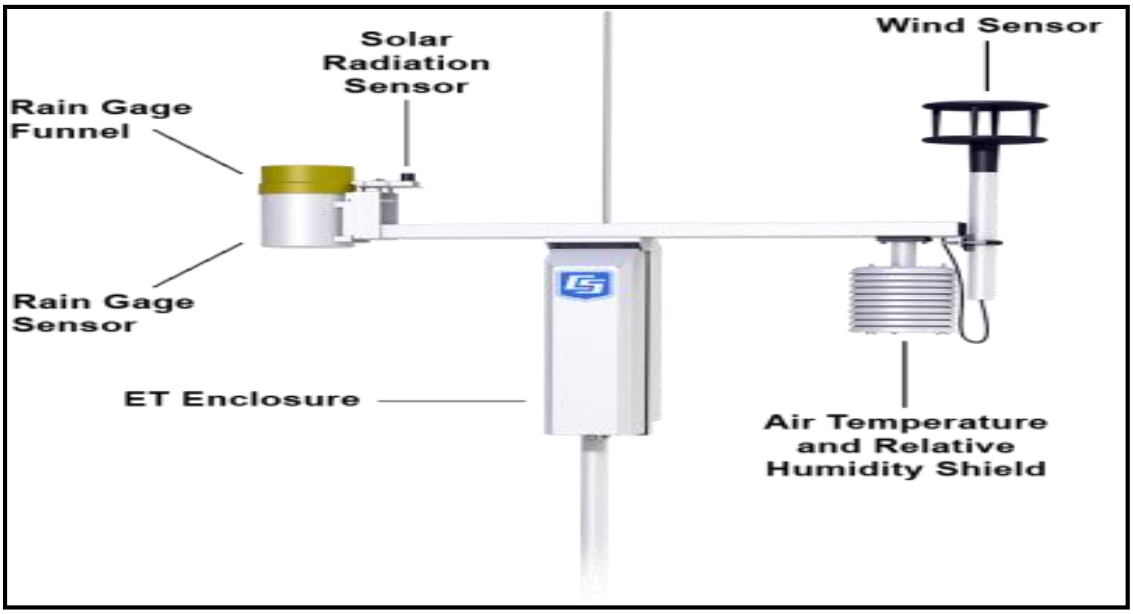


Figure (3). Components and sensors of the weather station used in estimating reference evapotranspiration according to the FAO method and the modified Penman-Monteith equation

Based on the above water requirements calculation formula, the water requirements for irrigating Valencia orange during the two growing years were calculated as follows: 9000 m^3/ha/year for 2024 and 8980 m^3/ha/year for 2025. The irrigation water volumes were distributed in detail for each experimental treatment as shown in the Table (2).

Table (2). Total irrigation water consumed to irrigate one hectare Valencia orange in two growing seasons for each experimental treatment

Deficit Irrigation	Biochar rate, kg ha^{-1}	Total irrigation water consumed to irrigate one hectare, m^3/ha/year	
		First season	Second season
100% FI	0	9000	8980
	600		
	800		
	1200		
75% FI	0	6750	6735
	600		
	800		
	1200		
50% FI	0	4500	4490
	600		
	800		
	1200		
PRD	0	4500	4490
	600		
	800		
	1200		

PRD stands for partial root zone drying, whereas FI stands for full irrigation

Botanical description of orange trees

The Valencia Orange trees in the orchard are 15 years old, which is the pinnacle of full technical and commercial maturity and guaranties the highest possible economic yield as well as established structural stability. A professional and methodical planting grid of 4 × 6 meters (4 meters between trees within the same row and 6 meters between rows) is used in the design of the plantation.

Source of biochar production

By using the dry organic pruning waste from the 15-year-old Valencia orange trees to produce high-quality biochar, the on-site sustainability framework is improved. Repurposed scrap metal barrels are used as artisanal pyrolyzers to carry out this circular economy technique inside the orchard in an economical, conventional, and environmentally friendly manner. This localized recycling method efficiently captures carbon, lowers the costs associated with managing farm waste, and produces a useful soil amendment that enhances the sandy Nubariya soil's ability to retain moisture and nutrients as shown in Figure (4).

Figure (4). Biochar and how to add it to the summer orange experimental treatments in Nubaria

Design of experiments

The experiment was carried out at the Nubaria Research Station to assess how applying biochar affected the fruit quality and productivity of Valencia orange trees under conditions of deficit irrigation. Four irrigation techniques were used in the experiment: PRD and sub-main plot with biochar rates, moderate deficit irrigation (75% FI), severe deficit irrigation (50% FI), and full irrigation (100% FI). Biochar was produced from agricultural organic residues using indirect thermal decomposition under limited oxygen conditions as shown in Figure (4). Four application rates of biochar (0; 400; 800; 1200 kg ha^{-1}) were incorporated into the soil around the root zone before the beginning of the irrigation season.

Measurements and Analytical Procedures

Measurements included canopy-volume increase, leaf area, chlorophyll content, fruit diameter, fruit weight, pulp weight, total yield, TSS, acidity percentage, and vitamin C content. Fruit-quality analyses were carried out using standard laboratory procedures during both seasons.

1. Canopy-Volume Increase: Take a measurement of the tree's overall height (H) from the ground to the top of the canopy. To get the average diameter, measure the canopy diameter in two perpendicular directions: East-West (D1) and North-South (D2) (Eq. 5) (Westwood, 1993). Mathematical Formula: The modified prolate spheroid formula, which is typical for fruit trees, is used to compute canopy volume (CV) (Eq. 6) **(Vashisth *et al*., 2026)**:

$$CV = \frac{4}{3} \times \pi \times \left(\frac{D}{2}\right)^2 \times \frac{H}{2} \text{ ....(5)}$$

$$\text{Canopy} - \text{Volume Increase} = CV_{\text{Final}} - CV_{\text{Initial}} \text{ ....(6)}$$

2. Leaf Area: use an electronic leaf area meter (LI-3100C, for example**) (Radford, 1967)**.

3. Chlorophyll Content: obtaining relative SPAD values using a portable SPAD-502 Chlorophyll Meter (Arnon, 1949).

4. Fruit Diameter: At the fruit's broadest equatorial zone, measure it. a digital vernier caliper that has been calibrated (ISHS).

5. Fruit Weight and Pulp Weight: Fruit Weight: Use a high-precision digital laboratory balance to weigh individual fruits that have been randomly selected. Pulp Weight: Weigh the edible fleshy portion (pulp) after peeling the fruit and removing the seeds or core (Srivastava and Sanjeev, 2002).

6. Total Yield: During the harvest season, gather and weigh every mature fruit from each experimental tree (Snedecor and Cochran, 1989).

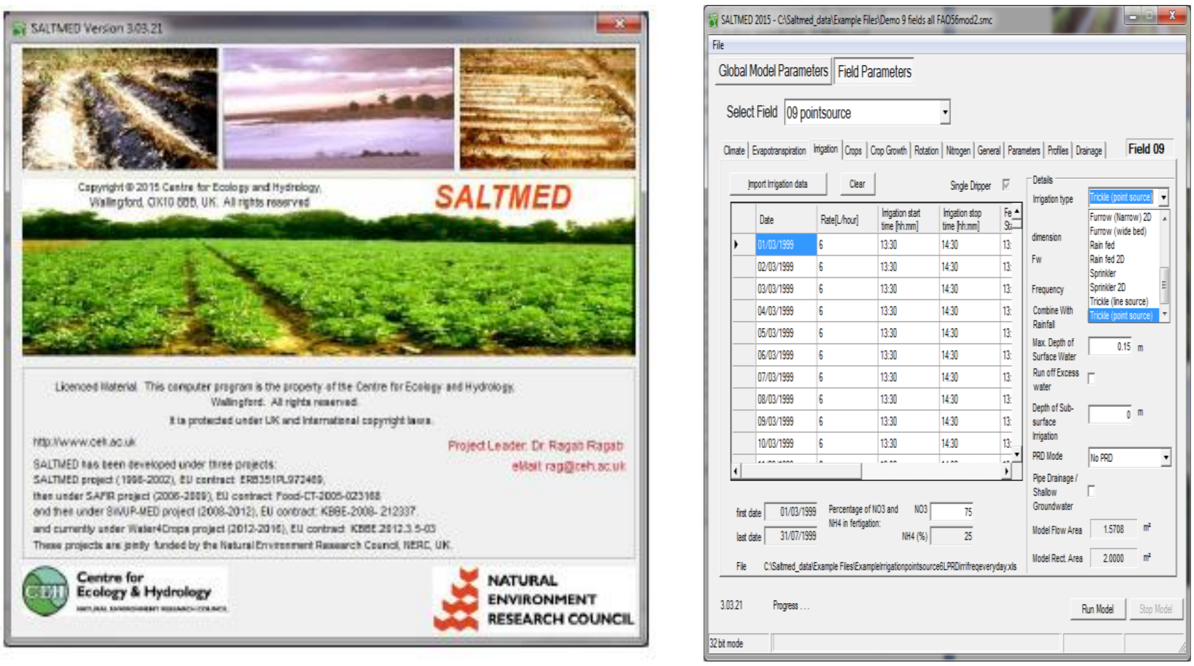
7. Total Soluble Solids (TSS): Take a few drops of pure juice out of the pulp of the fruit. Put them on a digital handheld refractometer's prism (AOAC International, 2019).

8. Acidity Percentage (Titratable Acidity): Using phenolphthalein as a visual indicator, titrate a known volume of filtered fruit juice (for example, 10 ml) against a standardized sodium hydroxide solution (NaOH, 0.1 N) until a faint pink tint remains for 15 seconds.

9. Vitamin C Content (Ascorbic Acid): Fruit juice should be titrated against a standard 2,6-dichlorophenolindophenol (DCPIP) dye solution. When a noticeable rose-pink hue remains in the acid solution for at least 15 seconds, the endpoint is reached (AOAC International, 2019).

Simulation Modeling and Sustainability Evaluation

Simulation-based approaches using SALTMED model were used throughout the project to evaluate irrigation performance and sustainable management practices under water-limited conditions. The experiments were designed to simulate current and future conditions through deficit irrigation scenarios and sustainable soil management practices as shown in Figure (5).



Source: https://link.springer.com/chapter/10.1007/698_2016_74
Figure (5). SALTMED model

The root mean square error (RMSE), coefficient of determination (R^2), and coefficient of residual mass (CRM) were the quality of fit expressions employed in the model validation. The RMSE values show how much the simulations overestimate or underestimate the measurements. They are computed using Eq. (7).

$$RMSE = \sqrt{\frac{\sum(y_o - y_s)^2}{N}} \quad (7)$$

If N is the total number of observations, y_s is the observed value, and y_o is the predicted value. The ratio of the average measurement value to the dispersion of simulated values is shown by the R2 statistics (Eq. 8).

$$R^2 = \left\{\frac{1}{N}\frac{\sum(y_o - \bar{y_o})(y_s - \bar{y_s})}{\sigma y_o - \sigma y_s}\right\} \quad (8)$$

where σy_o is the observed data standard deviation, σy_s is the simulated data standard deviation, and (y_o)¯is the average observed value and (y_s)¯is the average simulated value. Equation (9) defines the coefficient of residual mass (CRM):

$$CRM = \frac{(\sum y_o - \sum y_s)}{\sum y_o} \quad (9)$$

The CRM quantifies the model's propensity to overestimate or underestimate the measurements. Positive CRM values show a propensity to overestimate, whereas negative CRM values show that the model underestimates the data. The values of RMSE, CRM, and R2 should be 0.0 and 1.0, respectively, for an ideal match between the simulated and observed data.

Analysis of Statistics

An analysis of variance (ANOVA) appropriate for a split-plot design with a randomized complete block design structure was applied to all of the measures in this study. The blocks were replicates, the subplots were biochar rates, and the main plot was deficit irrigation schemes. The error term was the mean square of the product between the biochar materials and deficit irrigation schemes in order to evaluate the interaction between the two elements. The least significant difference (LSD) of Duncan's test was used in the ANOVA to find statistically significant differences between average groups. At less than 0.05, the probabilities were significant. All analyzes were conducted using the MSTAT software, which is written in the C programming language and operates on DOS-compatible computers **(Freed and Peacor, 1989)**.

3. Results

Field study

As shown in Table (3), the findings showed that both biochar application and deficit irrigation techniques had a substantial impact on the physiological characteristics, vegetative growth, and fruit development of Valencia orange trees during the two seasons. When compared to full irrigation (100% FI), 75% FI, and severe deficit irrigation (50% FI), PRD often yielded better growth responses. The 50% FI treatment resulted in a clear reduction in all studied parameters, indicating that severe water limitation negatively affected canopy development, leaf expansion, chlorophyll formation, and fruit size.

Across irrigation strategies, PRD showed the highest overall performance, particularly in the second season. Canopy volume increase under PRD reached 4.1–4.3%, leaf area ranged from 27.0 to 28.3 cm^2, total chlorophyll reached up to 3.0 mg g^{-1} F.W, and fruit diameter increased to 6.2–6.6 cm. Full irrigation and 75% FI produced similar intermediate values, while 50% FI consistently recorded the lowest growth and physiological performance, with canopy increase declining to about 2.0–2.1%, leaf area below 14 cm^2, chlorophyll around 1.5–1.7 mg g^{-1} F.W, and fruit diameter not exceeding 3.3–3.5 cm.

Biochar application showed a strong positive effect on all measured parameters, with a clear dose-dependent response. Increasing biochar rate from 0 to 1200 kg ha^{-1} resulted in steady improvements in canopy growth, leaf area, chlorophyll content, and fruit diameter. At the highest application rate (1200 kg ha⁻¹), canopy volume increase reached 4.6–4.8%, leaf area increased to 31.8–33.5 cm², chlorophyll reached 3.2–3.4 mg g^{-1} F.W, and fruit diameter reached 7.1–7.6 cm. In contrast, the absence of biochar (0 kg ha^{-1}) produced the lowest values across all traits, confirming the beneficial role of soil amendment in improving water and nutrient retention under arid conditions.

A significant synergistic effect was also demonstrated by the interaction between irrigation technique and biochar rate. The combination of PRD with the highest biochar rate (1200 kg ha^{-1}) produced the best overall results, with canopy volume increase reaching 5.5–5.8%, leaf area reaching 37.9–40.1 cm², chlorophyll content reaching 3.7–4.0 mg g^{-1} F.W, and fruit diameter reaching 8.5–9.2 cm across the two seasons. Similar but slightly lower values were recorded under full irrigation and 75% FI combined with high biochar application, confirming the consistent positive impact of biochar under different irrigation regimes.

In contrast, the lowest performance was observed under 50% FI without biochar, where all growth and fruit parameters were significantly reduced. However, even under severe water deficit, increasing biochar rates partially alleviated stress effects and improved plant performance compared with untreated soil conditions.

Table (3). Effect of deficit irrigation strategies and biochar rates onpercentage increase in canopy volume, leaf area, total chlorophyll and fruit diameter of Valencia orange

Deficit Irrigation	Biochar rate, kg ha^{-1}	Percentage increase in Canopy Volume, %		Leaf Area, cm^2		Total Chlorophyll, mg/g F.W		Fruit diameter, cm	
		First season	Second season	First season	Second season	First season	Second season	First season	Second season
100% FI		3.9a	4.1a	27.1a	28.3a	2.7a	2.9ab	6.1a	6.5b
75% FI		3.9a	4a	26.7a	27.9a	2.6a	2.8b	6a	6.4b
50% FI		2b	2.1b	13.5b	14b	1.5b	1.7c	3.3b	3.5c
PRD		4.1a	4.3a	27a	28.3a	2.8a	3a	6.2a	6.6a
LSD at 5%		**0.29**	**031**	**0.48**	**0.58**	**0.2**	**0.21**	**0.17**	**0.13**
	0	2.5d	2.6d	15.7d	16.3d	1.7d	1.8d	3.7d	3.9d
	600	3.1c	3.2c	21.2c	22.1c	2.3c	2.4c	4.9c	5.2c
	800	3.7b	3.9b	25.7b	26.7b	2.5b	2.7b	5.9b	6.2b
	1200	4.6a	4.8a	31.8a	33.5a	3.2a	3.4a	7.1a	7.6a
LSD at 5%		**0.15**	**0.15**	**0.48**	**0.65**	**0.14**	**0.13**	**0.15**	**0.16**
100% FI	0	2.5fg	2.7f	17.6e	18.2d	1.7efg	1.8fg	4.1e	4.3e
	600	3.5c	3.6d	24.3d	25.2c	2.6c	2.8c	5.4d	5.8d
	800	4.2b	4.4c	30c	31.2b	3b	3.1b	6.7c	7c
	1200	5.3a	5.5b	36.7b	38.8a	3.6a	3.8a	8.2b	8.7b
75% FI	0	2.7ef	2.8f	17e	17.6d	1.7efg	1.8fg	4e	4.2ef
	600	3.3cd	3.4de	23.5d	24.7c	2.3d	2.5d	5.4d	5.6d
	800	4.1b	4.3c	29.1c	30.2b	2.8bc	3bc	6.7c	7c
	1200	5.4a	5.6ab	37.3ab	39.2a	3.6a	3.8a	8.1b	8.7b
50% FI	0	1.6i	1.6i	10.7h	11.1g	1.3h	1.5i	2.7h	2.8i
	600	2h	2.1h	13.5g	14f	1.5gh	1.6ghi	3.3g	3.5h
	800	2.3gh	2.4gh	14.3g	14.8ef	1.3h	1.6ghi	3.5fg	3.6gh
	1200	2.2gh	2.4gh	15.5f	16.1e	1.8ef	2ef	3.7f	3.9fg
PRD	0	3de	3.2e	17.6e	18.3d	2e	2.1e	4e	4.3e
	600	3.4c	3.6d	23.4d	24.4c	2.7bc	2.8c	5.4d	5.8d
	800	4.3b	4.5c	29.2c	30.4b	2.7bc	3.1b	6.7c	7.2c
	1200	5.5a	5.8a	37.9a	40.1a	3.7a	4a	8.5a	9.2a
LSD at 5%		**0.3**	**0.3**	**0.95**	**1.3**	**0.27**	**0.26**	**0.29**	**0.32**

PRD stands for partial root zone drying, whereas FI stands for full irrigation.

The results clearly indicated that both deficit irrigation strategies and biochar application significantly influenced fruit physical attributes and yield of Valencia orange trees over the two growing seasons as presented in Table (4). In general, PRD consistently outperformed full irrigation (100% FI), 75% FI, and severe water deficit (50% FI), particularly in enhancing fruit weight, pulp weight, and total yield. The 50% FI treatment showed a pronounced decline in all yield components, confirming the negative impact of severe water stress on fruit development and productivity.

Among irrigation strategies, PRD produced the highest overall values for all yield-related parameters. Fruit weight under PRD reached 167.8–173.4 g, pulp weight increased to 127.6–136.7 g, and yield reached 34.7–35.6 ton ha^{-1} across the two seasons. These values were slightly higher than those recorded under full irrigation and 75% FI, which showed comparable but marginally lower performance. In contrast, 50% FI resulted in a substantial reduction in productivity, where fruit weight dropped to 87.8–91.5 g, pulp weight to 68.7–72.9 g, and yield to only 18.3–18.8 ton ha^{-1}.

Table (4). Effect of deficit irrigation strategies and biochar rates on fruit weight, pulp weight and yield of fruits of Valencia orange

Deficit Irrigation	Biochar rate, kg ha^{-1}	Fruit weight, gm		Pulp weight, gm		Yield of oranges fruits, ton ha^{-1}	
		First season	Second season	First season	Second season	First season	Second season
100% FI		163.2b	168.2b	125.3ab	130.8b	34.6ab	35.4a
75% FI		161.6b	166.9b	124.3b	130.9b	34.2b	34.9b
50% FI		87.8c	91.5c	68.7c	72.9c	18.3c	18.8c
PRD		167.8a	173.4a	127.6a	136.7a	34.7a	35.6a
LSD at 5%		**3.59**	**3.94**	**2.8**	**2.87**	**0.44**	**0.45**
	0	102.3d	105.9d	77.4d	82.4d	20.9d	21.3d
	600	129.1c	133.4c	100.6c	106.9c	27.4c	27.9c
	800	156.1b	161.1b	119.6b	126.3b	32.8b	33.6b
	1200	193a	199.7a	148.4a	155.8a	40.6a	41.9a
LSD at 5%		**2.43**	**2.27**	**2.84**	**2.31**	**0.48**	**0.63**
100% FI	0	109.9f	114.1g	84.9e	88.6g	23.4e	23.8e
	600	145.5d	150.4d	111.3d	116.3e	30.9d	31.5d
	800	177.5c	182.8c	136.1c	141.5d	37.6c	38.8c
	1200	220b	225.5b	168.8b	176.6b	46.5b	47.7b
75% FI	0	110f	113.5g	84.4e	88.3g	23e	23.1ef
	600	141.9d	146.8de	111d	118.5e	30.1d	30.7d
	800	174.4c	181c	133.5c	138.8d	37.1c	38c
	1200	219.9b	226.4b	168.3b	178.1b	46.5b	47.8b
50% FI	0	69.4j	72.8k	54.8h	59.2k	14i	14.2h
	600	87.8i	91.2j	68.9g	71.9j	18.5h	18.8g
	800	93.2h	95.9i	72.7fg	77.7i	19.5g	19.8g
	1200	100.7g	106h	78.3f	83h	21f	22.3f
PRD	0	119.7e	123.3f	85.4e	93.5f	23.1e	24.2e
	600	141d	145.2e	111.1d	120.9e	30d	30.6d
	800	179.2c	184.6c	136c	147.1c	37c	37.7c
	1200	231.4a	240.6a	178a	185.4a	48.5a	50a
LSD at 5%		**4.85**	**4.55**	**5.68**	**4.62**	**0.97**	**1.26**

FI: Full Irrigation, PRD: Partial Root zone Drying

Biochar application had a strong and consistent positive effect on all yield components, with a clear dose-response relationship. Increasing biochar rate from 0 to 1200 kg ha^{-1} significantly enhanced fruit development and productivity. At the highest application rate (1200 kg ha^{-1}), fruit weight increased dramatically to 193–199.7 g, pulp weight reached 148.4–155.8 g, and yield rose to 40.6–41.9 ton ha^{-1}, representing the highest values recorded in the study. Conversely, the absence of biochar (0 kg ha^{-1}) resulted in the lowest performance, with fruit weight, pulp weight, and yield all markedly reduced across treatments.

The interaction between irrigation strategy and biochar rate further emphasized the synergistic effect of combining efficient water management with soil amendment. The best performance was achieved under PRD combined with the highest biochar rate (1200 kg ha^{-1}), where fruit weight reached 231.4–240.6 g, pulp weight increased to 178–185.4 g, and yield peaked at 48.5–50 ton ha^{-1} across the two seasons. Similarly, high values were also observed under full irrigation and 75% FI when combined with high biochar application, though slightly lower than PRD.

In contrast, the lowest fruit yield and quality attributes were recorded under 50% FI without biochar, where all parameters declined sharply. However, even under severe water deficit, increasing biochar application partially alleviated stress effects and improved fruit performance compared with untreated conditions, highlighting its role in enhancing soil water retention and nutrient availability.

The findings showed that both deficit irrigation techniques and biochar application had a substantial impact on the fruit chemical quality of Valencia oranges, as measured by TSS, acidity, and vitamin C content, during the course of the two seasons shown in Table (5). When compared to full irrigation (100% FI), 75% FI, and severe water deficiency (50% FI), PRD often yielded fruit of higher quality. All quality parameters significantly decreased after the 50% FI treatment, demonstrating the detrimental effects of extreme water stress on fruit biochemical development.

Across irrigation strategies, PRD achieved the highest overall fruit quality. TSS values under PRD reached 10.0–10.4% in the main treatment comparison and increased further to 13.7–14.2% when combined with higher biochar rates in the interaction analysis. Acidity followed a similar trend, reaching 2.7–3.1% in the main effect and up to 3.8–4.3% under optimal biochar application. Vitamin C content was also maximized under PRD, reaching 34.9–36.9 mg 100 mL^{-1} juice, and increasing substantially to 48.8–51.3 mg 100 mL^{-1} juice under the highest biochar treatment. In contrast, 50% FI consistently recorded the lowest values, where TSS dropped to 3.9–5.8%, acidity to 1.3–2.0%, and vitamin C to 14.1–20.5 mg 100 mL^{-1} juice.

Biochar application showed a strong and consistent positive influence on all measured fruit quality traits, with a clear dose-dependent response. Increasing biochar rate from 0 to 1200 kg ha^{-1} progressively improved TSS, acidity, and vitamin C content under all irrigation regimes. At the highest application rate (1200 kg ha^{-1}), TSS reached 11.6–12.3% in the main comparison and up to 13.7–14.2% under interaction conditions, while vitamin C increased from 20.8–22.0 mg 100 mL^{-1} juice at zero application to as high as 48.8–51.3 mg 100 mL^{-1} juice.

The interaction between irrigation strategy and biochar rate further highlighted the synergistic effect of combining PRD with high biochar application. The best overall fruit quality was achieved under PRD with 1200 kg ha^{-1} biochar, where TSS reached 13.7–14.2%, acidity reached 3.8–4.3%, and vitamin C content reached 48.8–51.3 mg 100 mL^{-1} juice across the two seasons. Comparable but slightly lower values were observed under full irrigation and 75% FI when combined with high biochar rates.

In contrast, the lowest fruit quality values were recorded under 50% FI without biochar, where all parameters were severely reduced. However, even under water stress conditions, increasing biochar application partially improved fruit biochemical characteristics, suggesting its role in enhancing soil moisture retention and nutrient availability.

Table (5). Effect of deficit irrigation strategies and biochar rates onTSS, acidity and vitamin C of Valencia orange

Deficit Irrigation	Biochar rate, kg ha^{-1}	TSS, %		Acidity, %		Vitamin C, mg/100 mL Juice	
		First season	Second season	First season	Second season	First season	Second season
100% FI		9.7a	10.1ab	2.8a	3a	34b	35.8b
75% FI		9.6a	9.8b	2.8a	3a	33.9b	36.2b
50% FI		5.4b	5.8c	1.7b	2b	18.3c	20.5c
PRD		10a	10.4a	2.7a	3.1a	34.9a	36.9a
LSD at 5%		**0.42**	**0.41**	**0.18**	**0.16**	**0.67**	**0.67**
	0	6.1d	6.4d	1.7d	2d	20.8d	22d
	600	7.8c	7.8c	2.2c	2.4c	27.7c	29.6c
	800	9.4b	9.6b	2.7b	2.9b	32.2b	35b
	1200	11.6a	12.3a	3.4a	3.7a	40.4a	42.9a
LSD at 5%		**0.24**	**0.33**	**0.14**	**0.12**	**0.68**	**0.92**
100% FI	0	6.7ef	7.1f	1.9ef	2fg	23.1e	24.2ef
	600	8.7d	8.8d	2.4d	2.5d	30.5d	32d
	800	10.6c	10.8c	3.2b	3.4b	36.8c	39c
	1200	12.9b	13.4b	3.7a	4.1a	45.7b	47.9b
75% FI	0	6.5f	6.6f	1.8ef	2.1fg	22.5e	24.1ef
	600	8.6d	8.2de	2.5d	2.6d	30.8d	32.3d
	800	10.6c	10.9c	3bc	3.2c	36.3c	39.7c
	1200	12.9b	13.5b	3.9a	4.2a	46b	48.5b
50% FI	0	3.9h	4h	1.3g	1.7h	14.1h	14.6h
	600	5.3g	5.4g	1.6f	1.8gh	18.4g	21g
	800	5.6g	5.8g	1.9ef	2.1fg	19.5g	22.7fd
	1200	6.9ef	7.9e	2e	2.2ef	21f	23.8ef
PRD	0	7.1e	7.9e	1.8ef	2.4de	23.5e	25e
	600	8.5d	8.7d	2.3d	2.6d	31d	33.1d
	800	10.6c	11c	2.9c	3.1c	36.3c	38.4c
	1200	13.7a	14.2a	3.8a	4.3a	48.8a	51.3a
LSD at 5%		**0.48**	**0.65**	**0.28**	**0.24**	**1.35**	**1.84**

PRD stands for partial root zone drying, whereas FI stands for full irrigation.

Evaluating the simulation model

The experiments were simulated using the SALTMED Model software as shown in figures (6.7.8.9) and Table (6). The software demonstrated high accuracy in simulating experimental factors and provided a high degree of predictive and simulation accuracy. The accuracy of the software's evaluation criteria was very high, reflecting the strong correlation between actual values and the simulation values generated by the software. The accuracy R^2 ranged from 96% to 98%. This led to the recommendation to use the SALTMED Model software with fruit crops under Egyptian conditions. This will result in saving time, effort, and money, and will assist decision-makers in import and export operations based on the values generated by the software for the supply or export of fruit crops (citrus and mangoes in particular) in Egypt.

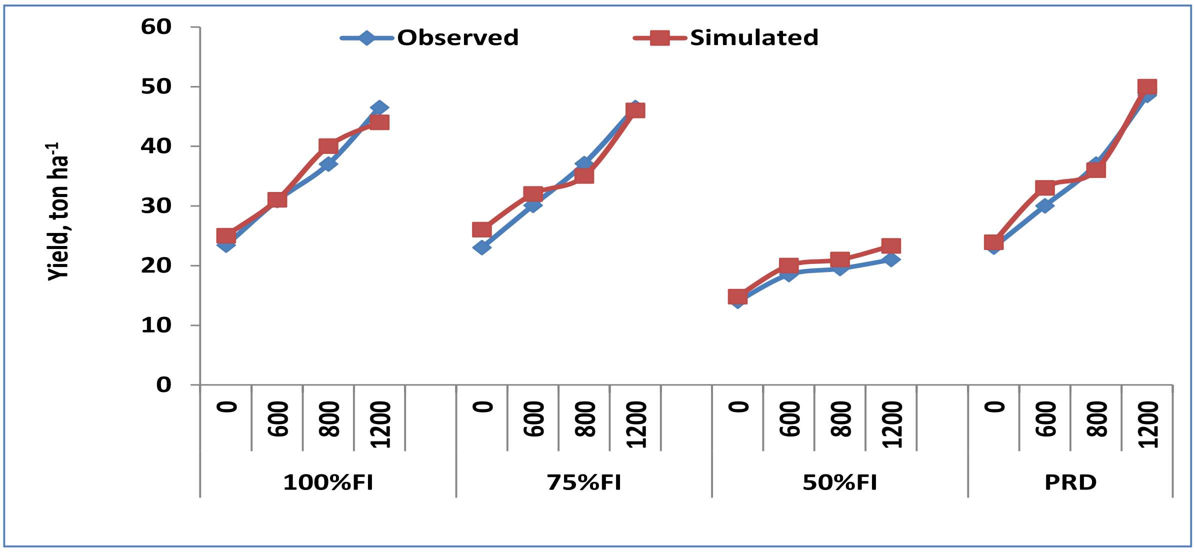


Figure (6). For the 2024 season, yield for every treatment was observed and simulated

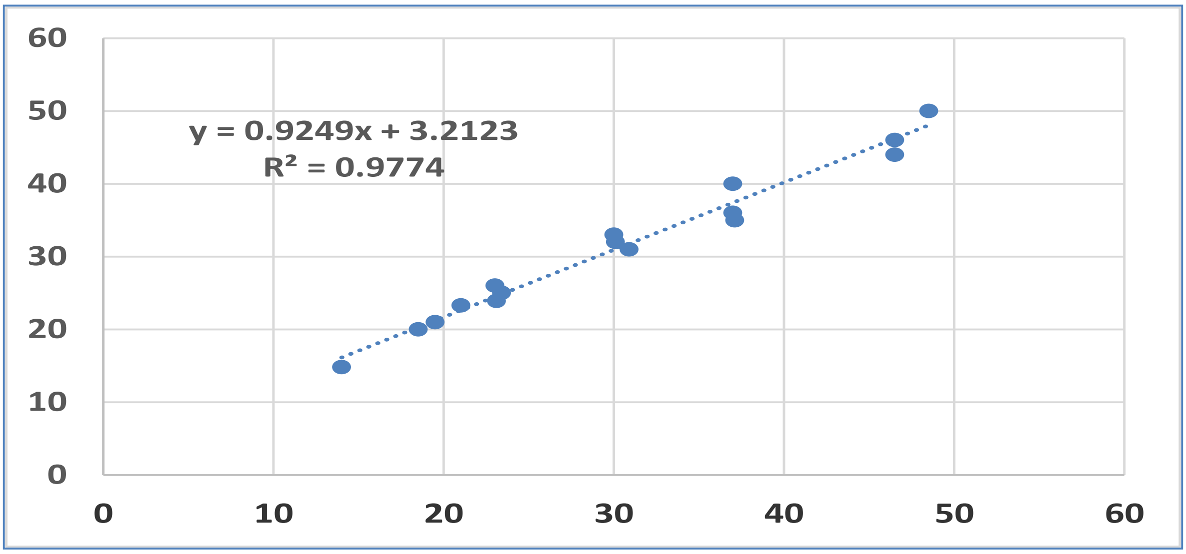


Figure (7). Total yield for all treatments compared to simulation for the 2024 season

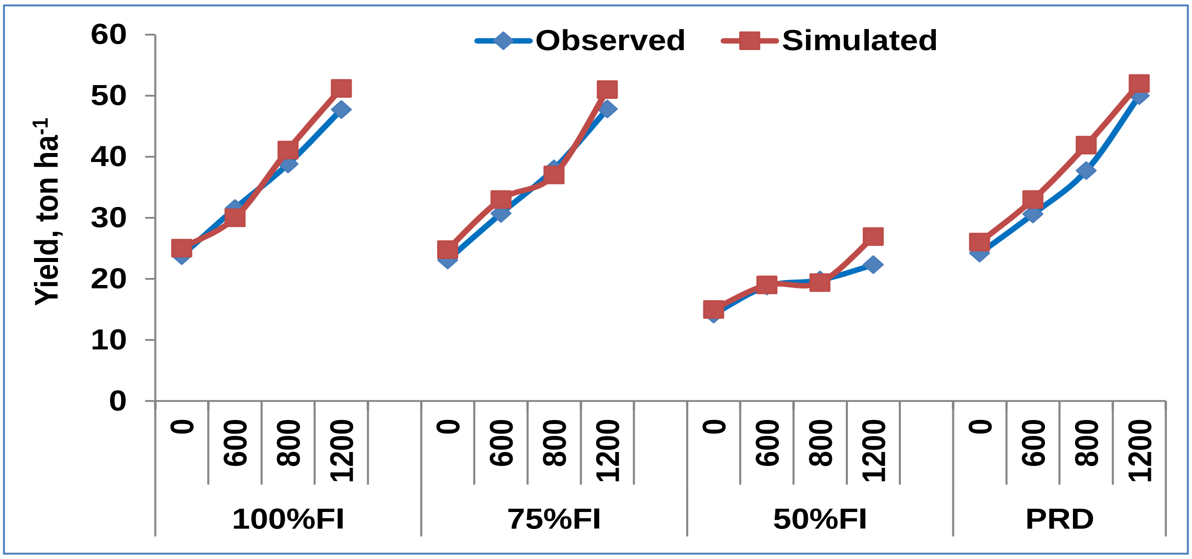


Figure (8). Yield for each treatment was observed and projected for the 2025 season

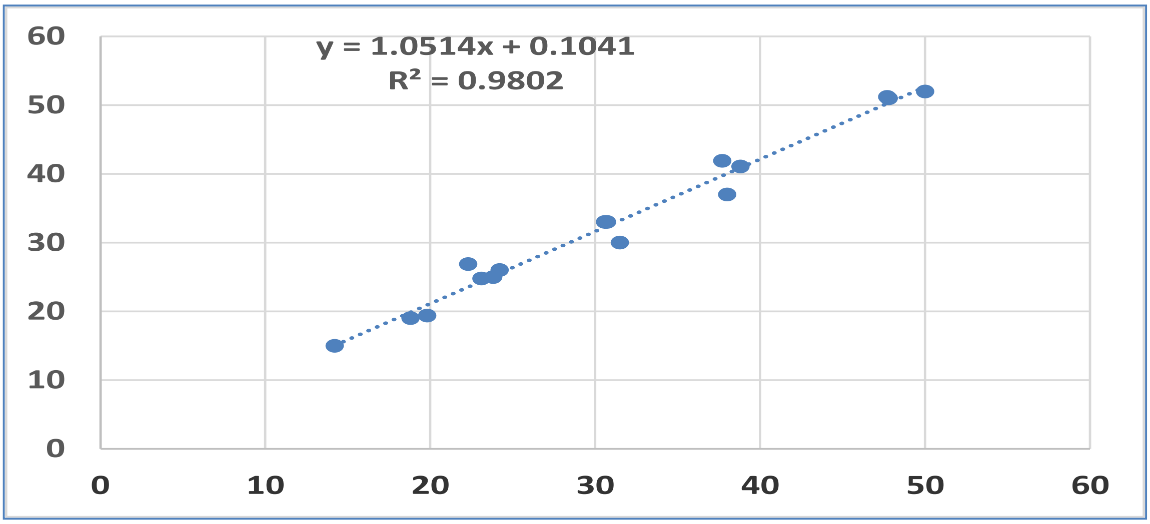


Figure (9). Total yield for all treatments compared to simulation for the 2025 season

Table (6). Effect of deficit irrigation strategies and biochar rates on observed and simulated yield of Valencia orange

Deficit Irrigation	Biochar rate, kg ha^{-1}	Yield of oranges fruits, ton ha^{-1} 202 و4		Yield of oranges fruits, ton ha^{-1} 2025 و	
		O	S	O	S
100% FI	0	23.4	25	23.8	25
	600	30.9	31	31.5	30
	800	37.	40	38.8	41.1
	1200	46.5	44	47.7	51.2
75% FI	0	23	26	23.1	24.8
	600	30.1	32	30.7	33
	800	37.1	35	38	37
	1200	46.5	46	47.8	51
50% FI	0	14	14.8	14.2	15
	600	18.5	20	18.8	19
	800	19.5	21	19.8	19.4
	1200	21	23.3	22.3	26.9
PRD	0	23.1	23.9	24.2	26
	600	30	33	30.6	33
	800	37	36	37.7	41.9
	1200	48.5	50	50	52
LSD at 5%		**0.97**		**1.26**	

PRD stands for partial root zone drying, and FI stands for full irrigation; O: Observed yield; S: Simulated Yield

4. Discussion

This experiment showed that, in arid environments, combining the use of biochar with deficit irrigation management greatly increased the fruit quality and output of Valencia orange plants. The purpose of the study was to determine whether biochar, especially when paired with PRD, could sufficiently increase soil water retention and nutrient availability to maintain citrus production under reduced irrigation conditions. The results show that the combined strategy was very effective in enhancing tree performance, indicating that biochar can be a vital component of sustainable citrus production systems that are dealing with growing water constraint.

One of the most notable outcomes of the study was the superior performance of PRD compared with conventional irrigation treatments. Despite receiving regulated irrigation, trees under PRD consistently exhibited higher canopy development, leaf area, chlorophyll concentration, fruit size, and productivity than trees under full irrigation or severe water deficit. These findings indicate that controlled root-zone drying stimulated physiological adaptations that improved water-use efficiency without negatively affecting plant metabolism. The improvement in chlorophyll concentration under PRD suggests that photosynthetic activity remained active even under reduced irrigation supply, which may be associated with improved stomatal regulation and hormonal signaling between roots and shoots. **Slamini *et al*. (2022)** reported similar interpretations, explaining that PRD improves crop performance by lowering excessive transpiration while preserving adequate physiological activity for growth and fruit development.

The substantial decline in vegetative growth and fruit performance under 50% FI demonstrates that severe water stress exceeded the adaptive capacity of Valencia orange trees. Reductions in canopy expansion, leaf area, and chlorophyll content indicate impaired photosynthetic efficiency and restricted assimilate production under severe moisture limitation. This reduction was directly reflected in fruit diameter, fruit weight, and overall yield. However, the study also revealed that biochar application partially alleviated these negative effects, even under severe deficit irrigation. This observation confirms that soil amendment with biochar can reduce the impact of drought stress by improving soil physical and hydraulic properties.

Strong evidence that biochar improved the root-zone environment in a dose-dependent manner is shown by the progressive improvement seen with increasing biochar rates. Fruit development, biochemical quality, and vegetative growth all showed significant increases at the maximum application level (1200 kg ha^{-1}). It is well recognized that biochar improves nutrient retention and lowers water loss from the soil profile by increasing soil porosity, water-holding capacity, and cation exchange capacity. Throughout the growing season, these characteristics probably improved root activity and nutrient uptake efficiency. According to **Khan *et al*. (2024),** biochar functions as a long-term soil conditioner that can increase plant productivity and soil fertility, especially in coarse-textured, low-organic-matter soils that are typical in dry areas.

One of the study's most significant conclusions was the interplay between PRD and high biochar application. The combination of PRD with 1200 kg ha^{-1} biochar consistently produced the highest values for all growth, yield, and fruit quality parameters. This result indicates that biochar and PRD complemented each other physiologically and hydraulically. While PRD improved irrigation efficiency and regulated plant water relations, biochar enhanced soil moisture storage and nutrient availability around the active root zone. Consequently, trees were able to maintain vigorous growth and high productivity despite reduced irrigation inputs. This synergistic response highlights the importance of integrating soil amendment strategies with advanced irrigation management rather than relying on irrigation techniques alone.

The improvements in fruit yield and fruit physical characteristics under biochar application also provide important practical implications. Fruit weight, pulp weight, and total yield increased dramatically with increasing biochar rates, particularly under PRD conditions. These responses indicate that biochar improved carbohydrate accumulation and fruit filling processes during fruit development. The enhancement in pulp weight further suggests improved internal fruit development and water balance within fruit tissues. Similar findings were reported by **Abdelghany *et al*. (2023),** who discovered that applying biochar improved soil moisture conservation and nutrient efficiency, which in turn raised crop productivity.

Fruit biochemical quality also responded positively to the integrated treatments. The increase in TSS, acidity, and vitamin C under PRD combined with biochar suggests that moderate water regulation and improved nutrient availability stimulated fruit metabolic activity. Higher TSS values reflect increased sugar accumulation, while elevated vitamin C content indicates enhanced synthesis of antioxidant compounds. These quality improvements are particularly important for citrus marketability and nutritional value. The results imply that biochar not only improved yield quantity but also enhanced fruit quality attributes that determine commercial acceptance and consumer preference.

The efficacy of biochar as a sustainable amendment for citrus orchards under water-limited situations is evident from the comparison of treatments with and without biochar. Regardless of irrigation technique, soils devoid of biochar consistently showed inferior growth, yield, and fruit quality values, demonstrating that inadequate soil moisture retention and restricted nutrient availability hinder citrus productivity in arid locations. In contrast, biochar-amended soils maintained higher productivity even under reduced irrigation, highlighting its role in increasing soil resilience to drought stress.

From an environmental perspective, the study also supports the growing importance of biochar in sustainable agriculture. In addition to improving crop productivity, biochar contributes to carbon sequestration and recycling of organic waste materials, making it an environmentally beneficial technology. Therefore, the findings extend beyond irrigation management and provide evidence that biochar can contribute to climate-smart agricultural practices in citrus production systems.

Overall, the experiment's primary goal was well met by the results, which showed that using charcoal greatly increases Valencia orange productivity and fruit quality in situations with insufficient watering. The best method for optimizing water productivity and preserving good fruit quality in arid environments was the combination of PRD with high biochar application. The integration of biochar technology with contemporary irrigation techniques as a sustainable option for citrus growth in water-scarce regions is strongly supported by these findings, both practically and scientifically.

5. Conclusion

This comprehensive study demonstrates that integrating advanced deficit irrigation management with organic soil conditioning offers a highly sustainable and economically viable strategy for optimizing Valencia orange production in arid regions. In particular, the severe structural and nutritional limitations present in degraded sandy soils are successfully addressed by combining the Partial Root-zone Drying (PRD) irrigation approach with a high biochar application rate of 1200 kg ha^{-1}. This synergistic approach maximizes vegetative growth, plant nutritional status, and vital physiological traits, while driving remarkable improvements in total fruit yield (peaking at 48.5–50 ton ha^{-1}) and critical internal quality indices, including TSS and Vitamin C content. Consequently, biochar serves as an excellent agronomic tool to effectively mitigate severe drought stress without compromising fruit marketability. Furthermore, the outstanding predictive fidelity of the SALTMED model software, validated by a very high coefficient of determination (R^2 of 96–98%), proves its operational reliability in accurately simulating complex soil-water-crop dynamics under local Egyptian environmental conditions. Therefore, the adoption of the SALTMED model is strongly recommended for modern fruit crop management. This digital framework provides farmers and policymakers with reliable predictive data to drastically minimize operational labor, time, and financial expenditures, while strategically optimizing trade, export, and import logistics for vital national commodities like citrus and mangoes.

Acknowledgement

The authors acknowledged the financial support of the NationalResearch Centre (NRC), Egypt, through the internal research projectNo. [13050508].

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