Effect of Mycorrhizal Inoculation, Polymer, and Zeolite on Some Quantitative and Qualitative Traits of Eggplant (*Solanum melongena*) Under Two Irrigation Intervals.

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ABSTRACT

Water limitation is a major constraint affecting vegetable crop productivity worldwide. There are several agricultural techniques to mitigate the adverse effects of water deficit and increase crop yields in water-limited environments. This study was conducted to evaluate the effects of mycorrhizae, superabsorbent polymers, and zeolite on eggplant yield and quality under two irrigation intervals. Treatments consisted of AMF at 0 and 30 g plant^{-1}, polymers at 12 and 24 g plant^{-1}, and zeolite at 0 and 180 g plant^{-1}, applied individually and in combinations. The experiment was arranged in a randomized complete block design with three replications. The experimental field was divided into two blocks based on irrigation intervals of 4 and 8 days. The results showed that the best values of quantity and quality traits were observed in the triple combination of AMF, polymers, and zeolite, followed by the interaction between AMF and zeolite under both irrigation intervals. These applications significantly improved almost all measured quantity and quality traits compared with the control. Furthermore, resulted in the highest fruit number, fruit size, and total yield, and improved some quality traits under both irrigation intervals. This underscores the importance of combining these treatments to improve eggplant productivity. Also, revealed that there were no significant differences between the two irrigation intervals (4 days and 8 days). These integrated treatments mitigated the adverse effects of the extended 8-day irrigation interval and maintained yields comparable to those achieved under the shorter irrigation interval.

Keywords: *Solanum melongena,* Productivity, water stress, polymer, nutritional value

INTRODUCTION

Eggplant (*Solanum melongena* L.) is an herbaceous, warm-weather vegetable crop in the nightshade family (Solanaceae), with an erect branching stem, large lobed leaves, violet to white flowers, and a berry-type fruit that varies widely in shape and color [27,62]. Global eggplant production was approximately 61 million tons in 2023, with

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China and India together accounting for the majority of output, making it one of the world’s most widely cultivated vegetables [21]. In Iraq, eggplant is widely grown under open-field and protected cultivation systems; however, national production remains relatively low compared with global production. According to FAOSTAT data, Iraq produced approximately 87 thousand tonnes of eggplant in 2024, representing less than 0.2% of the world's total production [21]. This relatively small contribution highlights the need for improved management practices to enhance productivity and resource-use efficiency under Iraqi conditions. Nutritionally, eggplant fruits are low in calories but contain dietary fiber, minerals (such as potassium, magnesium, calcium), vitamins, and beneficial bioactive compounds like anthocyanins and phenolics, which confer antioxidant properties and potential health benefits [4,56]. However, eggplant cultivation faces numerous challenges amid climate change and increasing water scarcity. The crop's relatively high-water requirements, coupled with its sensitivity to drought stress, pose significant obstacles to sustainable production, particularly in arid and semi-arid regions where water resources are becoming increasingly limited [43].

There are different approaches to increasing eggplant yield in water-limited areas and mitigating the effects of water deficit. Among these strategies, using mycorrhizae is a suitable choice to increase plant tolerance to water stress and supply adequate nutrients from the soil. Mycorrhizal fungi represent one of nature's most sophisticated biological partnerships, forming symbiotic relationships with approximately 90% of terrestrial plant species [58]. In agricultural systems, AMF have gained considerable attention as biological soil amendments that can enhance plant nutrition, water uptake, and stress tolerance [13]. In vegetable crops, AMF are commonly applied at rates ranging from 10–50 g inoculum per plant at transplanting or the seedling stage, depending on spore density and formulation. [58,69]. The mechanisms by which AMF improve plant performance under water-limited conditions are multifaceted. The extensive hyphal network facilitates enhanced water and nutrient uptake, particularly phosphorus, which is often limiting in agricultural soils [59]. Additionally, mycorrhizal associations have been shown to improve plant drought tolerance through various physiological and biochemical mechanisms, including enhanced osmotic adjustment, improved antioxidant enzyme activity, and increased production of stress-protective compounds [50].

In addition, superabsorbent polymers (SAPs) represent a revolutionary approach to soil water management in agriculture, offering the potential to significantly improve water retention and reduce irrigation frequency [67]. These synthetic or semi-synthetic materials can absorb and retain water quantities ranging from 100 to 1000 times their own weight, slowly releasing this water to plant roots as soil moisture levels decline [19]. The application of SAPs in agricultural systems has shown promising results in improving plant water status, reducing irrigation requirements, and enhancing crop productivity under water-limited conditions. In agricultural applications, SAPs are typically incorporated into soil at rates of 0.1–0.3% (w/w) or 10–30 g per plant in the root zone. Their application improves soil water-

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holding capacity, reduces irrigation frequency, and enhances plant survival under drought stress conditions [68]. The mechanism of action of SAPs involves the absorption of irrigation water and soil moisture into their three-dimensional polymer matrix during periods of water availability. As soil moisture decreases and plant roots create a water potential gradient, the stored water is gradually released, maintaining optimal soil moisture levels for extended periods [33]. Moreover, natural zeolites represent a class of crystalline aluminosilicate minerals with unique structural and chemical properties that make them valuable amendments for agricultural soils [45]. These naturally occurring minerals possess high cation exchange capacity, excellent water retention properties, and the ability to slowly release nutrients, making them particularly suitable for improving soil physical and chemical properties in agricultural systems [38]. The structural characteristics of zeolites, including their microporous framework and high surface area, enable them to function as both water and nutrient reservoirs in soil systems. Research has demonstrated that zeolite applications can improve soil water holding capacity, reduce nutrient leaching, and provide a controlled release of essential nutrients such as potassium, calcium, and ammonium [44]. Zeolite is commonly applied at field rates of 2–10 $t\ ha^{-1}$, which is approximately equivalent to about 200–1000 g per plant depending on plant spacing and soil conditions. Its porous structure improves soil aeration, enhances retention of essential nutrients such as ammonium (NH_4^+) and potassium (K^+), and increases soil moisture availability to plants. [38]. Despite the increasing use of soil amendments to improve crop performance under water-limited conditions, there is still limited integrated understanding of how arbuscular mycorrhizal fungi (AMF), superabsorbent polymers (SAPs), and zeolite—individually and in combination—affect eggplant growth, yield, and quality under different irrigation regimes. Most previous studies have evaluated these amendments separately, with little information on their combined or comparative effectiveness under deficit irrigation conditions. In addition, their potential to sustain productivity while reducing irrigation frequency remains insufficiently quantified for eggplant under field conditions. Therefore, this study addresses these knowledge gaps by investigating the individual and combined effects of AMF, SAPs, and zeolite on eggplant growth, yield, and quality under two irrigation intervals. It also evaluates their capacity to maintain or improve crop performance while reducing irrigation frequency, thereby contributing to water conservation without compromising productivity.

MATERIALS AND METHODS

Experimental Site and Soil Analysis

This experiment was conducted during the growing summer season of 2024 in Mergapan, 30 kilometers west of Sulaymanyah, which is located in the north of Iraq, with a GPS reading of latitude: 35.776425 N, longitude:45.279154 E, altitude 853 masl. The study was carried out in an open field to investigate the effects of

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Mycorrhizae, Polymer, and Zeolite on the quantity and quality traits of Eggplant. The climatic condition of the area is classified as a semi-arid region, hot-dry in summer and cold-moist in winter, during the growing season. The properties of the experimental soil were analyzed and detailed in Table 1.

Table 1. Meteorological data of the study area during the growing season.

Months	**May**	**June**	**July**	**August**	**September**	**October**
Maxi.Tem	30.2 c	33.3	35.2	39.0	34.1	30.7
Min.tem	11.0	12.6	14.0	15.2	13.4	12.0
Precipitation (mm)	84.7	0.0	0.0	0.0	6.0	13.5

Table 2. Some physical and chemical properties of experimental soil.

soil components	**Quantity**	**Unit**
Sand	318.0	$g\ kg^{-1}$
Silt	384.0	
Clay	298.0	
Textural Class	Clay loam	
pH	7.03	
EC	0.26	$dS\ m^{-1}$
Carbonate minerals	183.4	$g\ kg^{-1}$
Organic matter	11.6	
Available Nitrogen	39.16	$mg\ kg^{-1}$
Available phosphate	9.40	
Available potassium	86.47	
Bulk density	1.15	$g\ cm^{-3}$
ECE	36.0	$cmol_c\ kg^{-1}$
Soluble cations and anions		
Calcium (Ca^{++})	2.12	
Magnesium (Mg^{++})	2.40	

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Potassium (K^{+})	0.79	meq L^{-1}
Carbonate ($CO3^{=}$)	Nil	
Chloride (Cl^{-})	2.03	
Sulfate ($SO4^{=}$)	1.98	
Sodium (Na^{++})	1.86	

Soil Preparation.

After soil plowing, smoothing, and leveling, the area was divided into two blocks based on irrigation intervals of 4 and 8 days, and each block was subdivided into three terraces, each serving as a replicate. A drip irrigation system was then installed, and the terraces were covered with black polyethylene mulch. Each replicate was further subdivided into twelve experimental units, with a spacing of 120 cm maintained between units.

Plant material

This crop is widely grown by farmers in Kurdistan and is consumed daily as a vegetable. The eggplant seeds of cultivar 'Dexy-F1' were first sown in seedling trays using a growing medium consisting of a mixture of peat moss and perlite. After the emergence of four to five true leaves, the seedlings were transplanted into the experimental field on 17/5. Moreover, each experimental unit consisted of 10 plants arranged in two lines, with an in-line spacing of 40 cm.

Plant management and Fertilizer application

Throughout the experimental period, plants were maintained under standard agronomic practices. Each plant in the experimental unit received half of the recommended NPK fertilizer dose, while the control plants received the full recommended dose. A drip irrigation system was installed to maintain precise control over irrigation scheduling. Irrigation was applied according to the designated irrigation intervals, and other cultural practices were conducted uniformly for all treatments.

Experimental factors

The fungal inoculant *Glomus mosseae* was used. The inoculant contained mycorrhizal spores, with 47 spores per gram of dry soil, along with remnants of infected roots. Mycorrhizal inoculum was applied at rates of (0 and 30 g plant^{-1}) by placing it into the planting hole and mixing it lightly with the surrounding soil before transplanting. Also, a commercially available superabsorbent polymer (SAP) (potassium polyacrylate-based) was used at application rates of (0, 12, and 24 g plant^{-1}). Moreover, the type of zeolite used was Clinoptilolite, which was applied at rates of (0, and 180 g plant $^{-1}$ a class of microporous, aluminosilicate minerals with a unique crystalline structure that allows them to absorb and exchange ions. Clinoptilolite is composed of a 3-dimensional framework of silicon-oxygen (Si-O) and aluminum-oxygen (Al-O) tetrahedra. The chemical formula for

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Clinoptilolite is typically written as: (Na, K, Ca)$_6$($Al_6Si_{30}O_{72}$) $20H_2O$.

Treatment application

Mycorrhizae, superabsorbent polymers, and zeolite were applied directly to the soil at planting to ensure close contact with the plant root zone. Mycorrhizal inoculum was applied by placing it into the planting hole and lightly mixing it into the surrounding soil before transplanting. Superabsorbent polymer was incorporated into the soil and thoroughly mixed into the root zone (15 cm depth). Zeolite was applied by uniformly mixed with the soil in the planting hole. All treatments were applied once at planting to ensure uniform distribution and effective interaction with plant roots.

Measurements

Yield characters

During the fruiting stage, the following parameters were assessed: number of fruits per plant, fruit length (cm), fruit size (cm^3), and yield per hectare. To count the number of fruits per plant, mature fruits from each plot were harvested during the growing season. To derive the average number of fruits per plant, the total fruit number is divided by the number of plants in each plot [12]. Fruit length was measured with the use of a standard ruler immediately after harvesting the mature eggplant fruits. The measurement was typically taken from the base of the fruit, where it attached to the plant, to the fruit tip; three plants were randomly selected [7]. Fruit size (volume) was measured using the water displacement technique. In this method, each fruit was immersed in a graduated cylinder containing a known volume of water, and the increase in water level was recorded. The difference between the initial and final volumes represents the fruit volume. [28]. The total yield (Mg ha^{-1}) was calculated according to the following equation:

$$\text{Yield (Mg ha}^{-1}\text{)} = \frac{\text{Yield per plot (kg)}}{\text{Plot area (m}^2\text{)}} \times 10{,}000$$

Fruit quality characters

Some fruit quality traits, such as total soluble solids (TSS), total phenolic content (TPC), total Anthocyanin content (TAC), and number of seeds in fruits, were determined to evaluate the eggplant fruit quality under different treatments in this experiment. The Total soluble solids (TSS) were measured by using a digital Refractometer. A drop of eggplant juice was placed on the prism, and the brix value was read. [8]. Total anthocyanin concentration was calculated from the absorbance difference and expressed as mg cyanidin-3-glucoside equivalents per 100 g dry weight. This method is widely used for the analysis of anthocyanins in plant tissues [26]. Total phenolic content in eggplant fruit on a dry matter basis was determined using the Folin–Ciocalteu colorimetric method. The total phenolic was then calculated from a gallic acid standard curve and exhibited as mg gallic acid equivalent (GAE) per 100 g Dry weight [57]. The number of seeds in eggplant fruits was determined using the flotation method. In this method, the fruit was cut open, and the pulp containing seeds was placed in a container of water. The mixture was gently stirred so that the seeds would separate from the pulp tissues. The seeds that settled at the bottom were

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collected, dried, and then counted to estimate the total number of seeds per fruit [25].

Determination of N, P, K, Fe, and Zn concentrations in leaf tissues

Plant samples were taken, cleaned of dust, dried to constant weight, and then ground carefully in a mortar. (0.2) g was taken for digestion. The digestion process was carried out using perchloric acid and sulphuric acid in a 5:3 ratio [18]. After the digestion process, these nutrients were estimated: Nitrogen percentage (%): Nitrogen percentage in the leaves was determined through the Kjeldahl Method with acid digestion, followed by distillation and titration according to the procedures described by [51]. Phosphorus percentage (%): The phosphorus percentage was measured by the molybdenum blue colorimetric method using a spectrophotometer at 880 nm, as described by [39]. Potassium percentage (%): The potassium (K) percentage was determined by flame photometry [5]. Fe concentration (mg Kg^{-1} dry matter) and Zn: The concentration of iron (Fe) and zinc (Zn) was determined using an Atomic Absorption Spectrophotometer according to the method mentioned [16].

RESULTS

Quantity characters

Table 3 indicates that AMF, SAP, and zeolite, individually or in combinations, positively affected some quantitative characters such as the number of fruits, fruit length, fruit size, and fruit yield under both irrigation intervals. Within the four-day irrigation interval, most treatments markedly improved the quantity parameters relative to the control. The lowest number of fruit (10.2), the shortest fruit length (10.6 cm), the smallest fruit (180 cm^3), and plant yield (1.259 kg plant $^{-1}$) were achieved in T1. This indicated thar that without amendments to the soil, optimal yield was impossible, even with an adequate water supply. Each of the individual treatments, AMF, SAP, and zeolite, gave better yield performance. T2 and T5 were the most effective of the individual treatments, exhibiting the greatest fruit number and fruit length (12.2 and 12.7 cm) and (12 and 13.6 cm respectively). The combinations of the treatments performed better. The combinations of AMF + SAPs + zeolite produced significantly higher fruit numbers, larger fruit size, and increased yield per plant. The best overall performance was recorded in T12, which gave the highest number of fruit (13), the longest fruit (14.1 cm), the largest fruit size (273.3 cm^3), and, along with the highest yield of (2.114 kg $plant^{-1}$). Compared with the control treatment, T12 increased fruit number by 27.5%, fruit length by 33.0%, fruit size by 51.8%, and yield by 67.9%, demonstrating the synergistic effect of the combined soil amendments on eggplant productivity.

Under an 8-day irrigation interval, the yield metrics were somewhat lower than those under 4 days of irrigation but not significantly different. The control treatment again yielded the lowest number of fruits

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(7.8), fruit length (9.0 cm), fruit size (135 cm3), and yield (0.998 kg $plant^{-1}$). Despite low water availability, plants treated with AMF, SAPs, and zeolite significantly increased fruit production relative to the control. When AMF alone increased fruit number, fruit length, fruit size, and yield, showing that there was an improvement in the root absorbance as well as drought tolerance. The combination treatments produced the best results. For instance, T8 had the greatest fruit Size (240.0 cm^3), and the highest yields (2.023 kg $plant^{-1}$), while the triple combination in T12 recorded the greatest fruit length (13.3 cm), the largest fruit size (253.3 cm^3), and a high overall yield (2.090 kg $plant^{-1}$). Relative to the control treatment, T12 increased fruit number by 66.7%, fruit length by 47.8%, fruit size by 87.6%, and yield by 109.4%.

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Table 3. Effect of Mycorrhizae, polymer, zeolite, and their interaction on some quantitative characters under the two irrigation intervals.

4 days of irrigation				
Treatments	**Number of fruits**	**Fruit length (cm)**	**Fruit size (cm3)**	**Yield/plant (Kg)**
T1(Control)	10.2 ab	10.6 d	180.0 e	1.259 d
T2 (AMF)	12.2 a	12.7 ab	243.3 b	2.032 ab
T3 (SAP 12 g)	10.9 ab	10.7 d	223.3 bcd	1.406 cd
T4 (SAP 24 g)	11.5 a	11.1 bcd	220.0 bcd	1.475 cd
T5 (Zeo 180 g)	12.0 a	13.6 a	230.0 bc	1.904 abc
T6 (AMF +SAP 12 g)	11.8 a	11.4 bcd	206.6 cde	1.629 bcd
T7 (AMF +SAP 24 g)	10.8 b	10.8 cd	196.6 de	1.679 abcd
T8 (AMF + Zeo 180 g)	12.1 a	13.3 a	250.0 ab	2.191 a
T9 (SAP 12g + Zeo 180 g)	10.9 ab	10.73 d	223.3 bcd	1.406 cd
T10 (SAP 24 g+ Zeo 180 g)	10.3 ab	11.5 bcd	200.0 de	1.706 abcd
T11 (AMF + SAP 12g +Zeo 180 g)	11.7 a	12.5 abc	233.3 bc	2.098 ab
T12 (AMF + SAP 24 g+Zeo 80 g)	13.0 a	14.1 a	273.3 a	2.114 ab
8 days of irrigation				
Treatments	**Number of fruits**	**Fruit length (cm)**	**Fruit size (cm3)**	**Yield/pant (Kg)**
T1(Control)	7.8 b	9.0d	135.0 f	0.998 e
T2 (AMF)	11.5 a	12.4 ab	216.6 bcd	1.747 bc
T3 (SAP 12 g)	12.3 a	10.9 bc	200.0 de	1.334 d
T4 (SAP 24 g)	11.4 a	11.4 bc	183.3 e	1.600 cd
T5 (Zeo 180 g)	11.8 a	11.7 bc	230.0 abc	2.276 a
T6 (AMF +SAP 12 g)	10.9 a	12.4 ab	196.6 de	1.587 cd
T7 (AMF +SAP 24 g)	10.4 a	10.9 bc	193.3 de	1.555 cd
T8 (AMF + Zeo 180 g)	10.6 a	11.6 bc	240.0ab	2.023 ab
T9 (SAP 12g + Zeo 180 g)	11.5 a	10.6 c	186.6 e	1.482 cd
T10 (SAP 24 g+ Zeo 180 g)	10.9 a	10.6 c	206.6 cde	1.749 bc
T11 (AMF + SAP 12g +Zeo 180 g)	12.1 a	12.4 ab	216.6 bcd	1.818 bc
T12 (AMF + SAP 24 g+Zeo 80 g)	12.2 a	13.3 a	253.3 a	2.090 ab

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Values with different letters indicate significant differences at P< 0.05 according to the Duncan multiple range test.

Table 4 demonstrates that changing the irrigation interval from 4 days to 8 days had no significant effect on all measured yield traits of the plant. Although plants irrigated every 4 days produced slightly higher fruit counts, fruit length, fruit size, and yield per plant, these differences were very small and not statistically significant. The unpaired t-test results confirm this, as all p-values (0.871, 0.286, 0.181, and 0.682) are greater than 0.05, indicating non-significant (NS) differences between the two irrigation treatments. In general, extending the irrigation interval to 8 days did not significantly reduce fruit production or yield, suggesting that plants tolerated the longer irrigation interval under the conditions of this experiment.

Water intervals	Number of fruits	Fruit length (cm)	Fruit size (cm3)	Yield/pant (Kg)
4 days of irrigation	11.22	11.99	221.11	1.74
8 days of irrigation	11.13	11.46	204.86	1.68
Unpaired T.test	(P=0.871) ^{NS}	(P=0.286) ^{NS}	(P=0.181) ^{NS}	(P=0.682) ^{NS}

Table 4. The comparison between two irrigation intervals (4 and 8 days) in terms of the mean values of some fruit quantity characters.

Differences among means were considered statistically significant at the 0.05 probability level ($p < 0.05$) according to the t-test.

Qualitative characters of eggplant fruit

In Table 5, the quality measurements, including total soluble solids, anthocyanin content, total phenolic content, and the number of seeds per fruit, were explained. Based on the collected data (Table 5), TSS values under the 4-day irrigation interval ranged from 4.0 in T6 and T7 to 5.0 in T11 and T12, representing a 25.0% increase over the lowest values. The lowest anthocyanin contents were observed in T1 (296.93 mg 100 g^{-1} DW) and T4 (302.59 mg 100 g^{-1} DW), whereas the highest value (427.86 mg 100 g^{-1} DW) was recorded in T12, corresponding to a 44.1% increase compared with T1. Similarly, the lowest total phenolic content was found in T1 (44.06 mg 100 g^{-1} DW), while T12 produced the highest value (103.36 mg 100 g^{-1} DW), representing a 134.6% increase over the control. These results indicate that the combined application of AMF, SAPs, and zeolite markedly enhanced fruit quality and antioxidant-related compounds under the 4-day irrigation interval.

Under the prolonged 8-day irrigation interval, TSS values remained relatively

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stable among treatments, ranging from 3.8 in T1 to 4.9 in T12, an increase of 28.9%. Anthocyanin content was lowest in T1 (332.98 mg 100 g^{-1} DW) and highest in T12 (593.12 mg 100 g^{-1} DW), reflecting a 78.1% increase relative to the control. Likewise, total phenolic content increased from 54.65 mg 100 g^{-1} DW in T1 to 122.58 mg 100 g^{-1} DW in T12, corresponding to a 124.3% increase. These findings demonstrate that the combined treatments substantially improved antioxidant properties and fruit quality even under reduced irrigation conditions, suggesting their effectiveness in alleviating drought-induced stress.

Table 5. Effect of Mycorrhizae, polymer, zeolite, and their interaction on some quality characters under the two irrigation intervals.

4 days of irrigation				
Treatments	**TSS**	**Anthocyanin (mg/100 g DW)**	**Total phenols (mg GAE/100 g DW**	**No of seeds**
T1(Control)	4.1de	296.93 g	44.06 g	450.6 d
T2 (AMF)	4.5 abcde	313.48 efg	76.07 e	535.0 abcd
T3 (SAP 12 g)	4.3 bcde	306.22 efg	45.20 g	464.0 cd
T4 (SAP 24 g)	4.1 de	302.59 fg	47.12 fg	450.6 d
T5 (Zeo 180 g)	4.8 abcd	316.92 ef	51.76 f	524.3 abcd
T6 (AMF +SAP 12 g)	4.0 e	324.11 de	75.70 e	510.0 a
T7 (AMF +SAP 24 g)	4.0 de	336.33 cd	74.66 e	556.6 abc
T8 (AMF + Zeo 180 g)	4.9 abc	346.51 c	88.23 c	459.0 cd
T9 (SAP 12g + Zeo 180 g)	4.2 cde	340.36 cd	78.32 de	505.0 bcd
T10 (SAP 24 g+ Zeo 180 g)	4.2 bcde	341.42 cd	83.06 cd	493.0 bcd
T11 (AMF + SAP 12g +Zeo 180 g)	5.0 a	403.01 b	95.60 b	486.3 bcd
T12 (AMF + SAP 24 g+Zeo 80 g)	5.0 ab	427.86 a	103.36 a	483.0 bcd
8 days of irrigation				
Treatments	**TSS**	**Anthocyanin (mg / 100 gm DW)**	**Total phenols (mg GAE/100 g DW**	**No of seeds**
T1(Control)	3.8 d	332.98 e	54.65 f	682.0 a
T2 (AMF)	4.8 ab	396.38 d	84.39 de	602.3 abc
T3 (SAP 12 g)	4.2 abcd	342.76 e	56.07 f	545.3bcd
T4 (SAP 24 g)	3.9 cd	342.98 e	58.85 f	525.6 cd

T5 (Zeo 180 g)	4.6 ab	377.95 d	56.56 f	483.0 d
T6 (AMF +SAP 12 g)	4.3 abcd	439.50 c	81.43 de	597.6 abc
T7 (AMF +SAP 24 g)	4.2 bcd	434.82 c	80.87 e	641.3 ab
T8 (AMF + Zeo 180 g)	4.5 abc	503.32 b	93.94 c	579.0 bcd
T9 (SAP 12g + Zeo 180 g)	4.4 abcd	475.60 b	91.58 c	556.0 bcd
T10 (SAP 24 g+ Zeo 180 g)	4.8 ab	430.92 c	88.09 cd	598.6 abc
T11 (AMF + SAP 12g +Zeo 180 g)	4.5 abc	583.35 a	106.59 b	543.3 cd
T12 (AMF + SAP 24 g+Zeo 80 g)	4.9 a	593.12 a	122.58 a	537.3 cd

Values with different letters indicate significant differences at P< 0.05 according to the Duncan multiple range test.

The comparison between two irrigation intervals (4 and 8 days) in terms of the mean values of some fruit quality characters is presented in Table 6. The table shows that extending the irrigation interval from 4 to 8 days had different effects on fruit quality traits, with some parameters significantly affected and others not. Total soluble solids (TSS) and total phenols were not significantly influenced by irrigation interval, as their p-values (0.887 and 0.285) are greater than 0.05. In contrast, anthocyanin content and seed number were significantly affected, as indicated by p-values of 0.002 and 0.008, respectively. Anthocyanin decreased under 8-day irrigation, while the number of seeds increased significantly, suggesting that longer irrigation intervals influenced pigment accumulation and seed development.

Table 6. The comparison between two irrigation intervals (4 and 8 days) in terms of the mean values of some fruit quality characters.

Water intervals	**TSS**	**Anthocyanin (mg / 100 g DW)**	**Total phenols (mg GAE/100 g DW**	**No of seeds**
4 days of irrigation	4.44	337.99	71.92	512.0
8 days of irrigation	4.42	437.14	81.2.9	574.3
Unpaired T.test	(P=0.887) ^{NS}	(P=0.002) *	(P=0.285) ^{NS}	(P=0.008) *

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Differences in means were considered statistically significant at the 0.05 probability level ($p < 0.05$) using the t-test.

Leaf elements determination

The results obtained in Table 7 showed that nutrient concentrations in plant tissues (N, P, K, Fe, and Zn) were significantly affected by the different treatments under both irrigation intervals (4 and 8 days). Under the 4-day irrigation interval, the combined treatment T12 recorded the highest values of N (3.04%), P (0.46%), K (3.27%), Fe (252.16 mg/kg DW), and Zn (47.59 mg/kg DW), indicating superior nutrient uptake compared with the control treatment, which had the lowest values (N 1.74%, P 0.20%, K 1.65%, Fe 106.54 , Zn 19.26 mg/kg DW).

Under the 8-day irrigation interval, the combined treatments still performed better than single applications or the control. The highest values were again observed in T12, which recorded N (2.67%), P (0.43%), K (3.07%), Fe (217.71 mg/kg DW), and Zn (44.90 mg/kg DW). In contrast, the control treatment had the lowest nutrient levels (N 1.51%, P 0.19%, K 1.49%, Fe 94.21, Zn 17.07 mg/kg DW). The results demonstrate that the integration of AMF, SAPs, and zeolite significantly improves plant nutrient uptake under both normal and water-stress conditions compared with individual applications.

Table 7. Effect of Mycorrhizae, polymer, zeolite, and their interaction on some leaf elements content.

4 days of irrigation					
Treatments	**N%**	**P%**	**K%**	**Fe (mg/kg DW)**	**Zn (mg/kg DW)**
T1(Control)	1.74 g	0.20 e	1.65 d	106.54 h	19.26 h
T2 (AMF)	2.10 f	0.30 cd	1.85 d	129.02 efg	33.69 ef
T3 (SAP 12 g)	1.61 g	0.21 e	1.58 d	114.37 gh	21.11 h
T4 (SAP 24 g)	1.55 g	0.20 e	1.77 d	117.23 fgh	26.29 g
T5 (Zeo 180 g)	2.17 f	0.26 d	2.20 c	130.53 ef	31.34 f
T6 (AMF +SAP 12 g)	2.19 ef	0.35 b	2.24 c	135.51 de	39.45 cd
T7 (AMF +SAP 24 g)	2.38 de	0.37 b	2.35 c	151.08 d	42.72 bc
T8 (AMF + Zeo 180 g)	2.64 bc	0.44 a	2.90 b	195.12 b	45.05 ab
T9 (SAP 12g + Zeo 180 g)	2.17 f	0.31 c	2.48 c	148.79 d	33.78 ef

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T10 (SAP 24 g+ Zeo 180 g)	2.47 cd	0.31 c	2.34 c	166.88 c	36.39 de
T11 (AMF + SAP 12g +Zeo 180 g)	2.75 b	0.44 a	2.91 b	242.17 a	43.19 bc
T12 (AMF + SAP 24 g+Zeo 80 g)	3.04 a	0.46 a	3.27 a	252.16 a	47.59 a
8 days of irrigation					
Treatments	N%	P%	K%	Fe (mg/kg DW)	Zn (mg/kg DW)
T1(Control)	1.51 e	0.19 g	1.49 gh	94.21 de	17.07 f
T2 (AMF)	2.53 a	0.34 c	2.42 c	178.27 b	40.52 b
T3 (SAP 12 g)	1.40 e	0.19 g	1.45 h	94.96 de	19.19 f
T4 (SAP 24 g)	1.36 e	0.19 g	1.55 gh	101.63 cde	18.21 f
T5 (Zeo 180 g)	2.01 d	0.25 f	1.83 f	114.35 cde	26.62 e
T6 (AMF +SAP 12 g)	2.12 cd	0.32 cd	1.89 ef	124.24 cd	31.59 cd
T7 (AMF +SAP 24 g)	2.20 bc	0.34 c	2.14 d	122.18 cd	33.77 c
T8 (AMF + Zeo 180 g)	2.53 a	0.34 c	2.42 c	178.27 b	40.52 b
T9 (SAP 12g + Zeo 180 g)	1.98 d	0.30 de	2.13 d	117.23 cde	30.08 d
T10 (SAP 24 g+ Zeo 180 g)	2.31 b	0.29 e	2.03 de	134.42 c	32.59 cd
T11 (AMF + SAP 12g +Zeo 180 g)	2.65 a	0.39 b	2.75 b	218.92 a	40.65 b
T12 (AMF + SAP 24 g+Zeo 80 g)	2.67 a	0.43 a	3.07 a	217.71 a	44.90 a

Values with different letters indicate significant differences at P< 0.05 according to the Duncan multiple range test.

The unpaired t-test for the means of both irrigation intervals in Table 8 reveals that these differences were not statistically significant, as all p-values (0.361, 0.373, 0.233, 0.229, and 0.251) are greater than 0.05. This means that the observed decreases in nutrient content with longer irrigation intervals are not statistically Different. Nutrient uptake in leaves remained relatively stable under the experimental conditions.

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Table 8. The comparison between two irrigation intervals (4 and 8 days) in terms of the mean values of some leaf elements content

Water intervals	N %	P %	K %	Fe (mg/kg DW)	Zn (mg/kg DW)
4 days of irrigation	2.23	0.32	2.29	157.45	34.99
8 days of irrigation	2.06	0.29	2.03	133.47	30.58
Unpaired T.test	P=(0.361) NS	(P=0.373) NS	(P=0.233) NS	(P=0.229) NS	(P=0.251) NS

Differences among means were considered statistically significant at the 0.05 probability level ($p < 0.05$) according to the t-test.

DISCUSSION

Yield characters

Biofertilizers and soil amendments play an important role in improving vegetable growth and yield by enhancing soil fertility, increasing nutrient availability, and stimulating beneficial microbial activity in the rhizosphere, which ultimately improves plant growth and productivity [37, 66]. The results indicated that the application of AMF, individually or in combination with SAP and zeolite, significantly influenced several yield traits, including fruit number, fruit length, fruit size, and yield/plant, under both irrigation intervals (4 and 8 days). As shown in Table 3, the best results were achieved for T2, T8, and T12. The improvement in yield may be attributed to the beneficial effects of arbuscular mycorrhizal fungi (AMF), which increase root surface area and enhance the uptake of nutrients such as phosphorus, nitrogen, zinc, and copper, thereby promoting vegetative growth and biomass accumulation that support higher fruit production [9]. Moreover, the extensive AMF hyphal network enhances water and mineral uptake beyond the root depletion zone and transfers these to the host plant in exchange for carbohydrates [11]. Similar findings were reported by Rilling et al. (2004), who observed increased phosphorus uptake and fruit weight in tomato. The interaction of AMF with superabsorbent polymers (SAPs) further enhanced yield traits, likely because SAPs improve soil moisture retention, root growth, nutrient availability, and water-use efficiency, leading to greater biomass and yield stability under deficit irrigation [1,20]. In addition, zeolite application, particularly when combined with AMF, significantly improved eggplant yield components, including fruit length, fruit number, and total yield. Similar positive effects of zeolite amendments on crop productivity have been reported for several crops, including carrot,

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eggplant, potato, wheat, and apple, mainly due to improved soil water retention and nutrient availability [14, 38, 42].

Under the 8-day irrigation interval, the effects of AMF, SAPs, and zeolite were evident in mitigating water stress and maintaining yield traits, as indicated by the non-significant differences between the two irrigation intervals (Table 4). This response may be attributed to AMF production of glomalin, a glycoprotein that improves soil aggregation, structure, and water retention, thereby reducing drought damage [47,60]. AMF also regulate hormonal and redox signaling under water deficit, enhancing plant water status and protecting photosynthetic machinery [24]. Likewise, SAPs significantly increased eggplant fruit length, fruit size, and yield under the 8-day irrigation interval due to their ability to absorb and gradually release water in the root zone, thus sustaining plant hydration under drought conditions [3]. Furthermore, zeolites are porous crystalline aluminosilicate minerals that reduce the adverse effects of prolonged irrigation intervals by improving soil water-holding capacity, cation exchange capacity, and nutrient retention, thereby enhancing plant performance under limited water supply. Zeolite has also been reported to improve water-use efficiency, reduce oxidative stress, and stimulate antioxidant enzyme activity in drought-stressed plants [29,30]

Qualitative characters in fruits and leaves

Soil amendments and biological treatments can improve fruit quality in vegetable crops by enhancing nutrient availability, improving soil properties, and promoting better plant physiological activity, ultimately leading to better fruit development and quality [49]. Eggplant fruit quality characters, which included TSS, anthocyanin, total phenols, and number of seeds, were evaluated. The highest TSS, anthocyanin, and total phenol values in eggplant fruit were observed in the T12 treatment, as demonstrated in Table 5 under both irrigation intervals (4 and 8 days). This improvement may be related to the positive effect of the combined application of AMF, SAPs, and zeolite. AMF enhances fruit quality by improving nutrient uptake, particularly phosphorus and micronutrients, which increases sugars, free amino acids, carotenoids, and other beneficial compounds in fruits [55]. AMF colonization also promotes photosynthesis and translocation of assimilates from leaves to fruits, resulting in greater sugar accumulation and higher total soluble solids (TSS) values [59]. In addition, inoculated plants have shown increased phenolic and anthocyanin contents, indicating improved antioxidant capacity and fruit flavor [15]. Likewise, SAPs, when applied alone or in combination with AMF and zeolite, significantly improved eggplant fruit quality under both 4- and 8-day irrigation intervals, mainly through enhanced soil moisture availability and plant physiological performance [6,52]. Moreover, zeolite improved fruit quality by retaining nutrients in the root zone through its high cation exchange capacity, allowing gradual nutrient release and uptake, while also enhancing phenolic and anthocyanin accumulation through better soil aeration and root nutrition [44,54]. In a study conducted by [31]. reported that zeolite application significantly enhances fruit yield and quality parameters in tomato, due to improved nutrient supply and reduced environmental stress. Furthermore, foliar and soil applications of zeolite have been shown to enhance photosynthetic activity and improve fruit biochemical quality, including sugar accumulation and antioxidant content [63]. In addition, zeolite improves nutrient translocation and reduces nutrient leaching, thereby contributing to better fruit development and quality under both normal and stress conditions [44]

A comparison of the mean values for both irrigation treatments in Table 6 showed that extending the irrigation interval to 8 days resulted in a slight increase in phenolic content and significantly increased anthocyanin content. This may be due to water stress enhancing the accumulation of phenolic compounds and anthocyanins through increased oxidative stress and activation of secondary metabolic pathways. Under drought conditions, plants produce higher levels of reactive oxygen species (ROS), which stimulate the biosynthesis of antioxidant compounds such as phenolics and anthocyanins to protect cellular structures from oxidative damage [34,40]. While showed no significant effect on the TSS value. This may be attributed to the positive effects of AMF, SAPs, and zeolite in alleviating water-deficit stress. SAPs maintain stable soil moisture, thereby supporting metabolic activity required for phenolic compound synthesis [2]. AMF improve plant drought tolerance by enhancing root hydraulic conductivity, osmotic adjustment, and photosynthetic efficiency, which contribute to better fruit production under stress conditions [48]. Likewise, zeolite helps mitigate drought stress by improving soil water retention and nutrient availability, thereby maintaining fruit size and sustaining yield under limited irrigation [45].

Element content in leaves

Leaf nutrient content is strongly influenced by soil properties, irrigation, fertilization, and environmental conditions, making it an important indicator in agronomic research and crop management [36]. As shown in Table 7, treatments T2, T8, and T12 recorded the highest concentrations of N, P, K, Fe, and Zn, indicating that AMF, SAPs, and zeolite significantly improved leaf nutrient status. AMF, alone or in combination with SAPs and zeolite, enhanced nutrient accumulation by extending the root absorption zone through hyphal networks, increasing the uptake of mobile and immobile nutrients, activating transporter mechanisms, and improving nutrient translocation from roots to shoots. This effect is particularly important for phosphorus and micronutrients such as zinc and iron due to their low mobility in soil [17]. Likewise, SAPs improved nutrient concentrations under both 4- and 8-day irrigation intervals by increasing soil water-holding capacity and maintaining moisture in the root zone, which facilitates nutrient dissolution and uptake under water-limited conditions [7]. Moreover, zeolite enhanced leaf nutrient content through its high cation-exchange capacity, enabling adsorption and the gradual release of nutrients such as NH_4^+ and K^+, thereby reducing leaching

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losses and increasing nutrient availability [44]. Similar findings were reported by [35], who observed higher K and Mg concentrations in plant tissues grown in zeolite-amended media. Zeolite also helps regulate soil pH, retain nitrogen, and stimulate beneficial soil microorganisms, further improving plant nutrition and growth [22,23]. Under the 8-day irrigation interval, leaf nutrient status did not differ significantly from the 4-day irrigation treatment, as shown in Table 8. This may be due to the mitigating effects of AMF, SAPs, and zeolite on soil water limitation. AMF improve plant tolerance to environmental stress by enhancing photosynthetic activity, nutrient uptake, and overall growth through their extensive hyphal network and improved host physiological performance under stress conditions [61]. Similarly, hydrogels and zeolites serve as effective soil amendments, alleviating drought stress by improving soil moisture retention and plant water availability. SAPs (hydrogels) absorb large amounts of water and gradually release it into the rhizosphere, thereby stabilizing soil moisture and supporting plant water status under dry conditions [3,53].

CONCLUSION

The present study demonstrated that mycorrhizae, superabsorbent polymers, and zeolite significantly enhanced eggplant yield and quality under both 4-day and 8-day irrigation intervals. Individually, each factor improved quantity and quality compared with the control, while their combined application showed the greatest synergistic effect. Specifically, the integrated use of mycorrhizae (30 g plant^{-1}), polymer (24 g plant^{-1}), and zeolite consistently produced the highest number of fruits, fruit length, fruit size, and yield per plant. In addition, some quality parameters were also positively affected by these factors even under the extended 8-day irrigation interval. These results indicate that combining biological and physical soil amendments can effectively mitigate the adverse effects of water deficit and improve yield. Therefore, the integration of mycorrhizae, polymers, and zeolite represents a promising and sustainable strategy for enhancing eggplant productivity under limited irrigation conditions.

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