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Deficit Irrigation Stabilizes Fruit Yield and Alters Leaf Macro and Micronutrient Concentration in Tomato Cultivation in Greenhouses: A Case Study in Turkey

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Abstract: Water is crucial for agriculture and needs to be used effectively due to climate change and drought in the Mediterranean region. For this reason, to adapt to water deficit scenarios, deficit irrigation applications are increasing in importance. The aim of this research was to determine the effect of varying levels of irrigation on growth parameters and concentration of nutrients in tomato plants grown under greenhouse conditions. The irrigation schedule used in this study was designed to include 100% (control), 90%, 80% and 70% of evaporation from the class-A pan. Water deficit was found to cause a stress effect in tomato plants, which was reflected in changes in the physiological function plants, such as flowering and early ripening. In addition, the SPAD values were examined, for which the lowest value of the green color intensity of the leaves was 47.3 (I3) and the highest was 48.7 (I4). However, the results of statistical analyses show that the difference was not significant. We also observed that the height values of tomato plants were the highest in the period of seedling and fruit ripening under full irrigation. Furthermore, analysis of the macronutrient content of tomato leaves showed that the obtained values were below the threshold values recommended for manganese. Based on these and similar studies, we believe that the application of water stress is most effective during the phases in which the plants are least affected. We believe that determining the periods during which tomato or any other crop is be affected by the least water stress will be more accurate for both plant development and economic production.

Keywords: growth parameters; leaf area index; *Solanum lycopersicum* L.; SPAD; water stress

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1. Introduction

Owing to its taste and health benefits, tomato (*Solanum lycopersicum* L.) one of the most important vegetables for human nutrition. This species is considered one of the most widely produced agricultural products in the world in terms of weight [1–3]. In Turkey, tomatoes are grown both in greenhouses and in open fields, especially in the Mediterranean region [2,4]. The world leader in tomato production is China, with an annual production of 62.8 million tons. India ranks second, with a production of 19 million tons; Turkey is third, with a production of 13 million tons; and the United States is fourth, with a production of 10.9 million tons. Turkey has several favorable factors for growing tomatoes, especially under greenhouse conditions, including (1) diverse climatic conditions with the possibility of cultivation at any time of the year; (2) geothermal resources, which make cultivation in winter more economical; and (3) proximity to European and Asian markets [5].

Tomatoes, which have a high rate of production in Turkey and worldwide, are important in terms of nutrition [6]. Tomato composition may vary depending on factors such as tomato type (beefsteak, large type, cherry, etc.), cultivar, cultivation method, growing environment (field vs. greenhouse), region and time of harvest [7,8]. This species is also an important source of antioxidants in human nutrition, such as lycopene, phenols and vitamin C [9,10].

When growing tomatoes, it is very important to ensure optimum moisture levels in the soil so that the plants are not stressed by water deficit, which causes yield losses. Especially on hot summer days, the rate of evapotranspiration is very high, and plants can be damaged before stress becomes apparent. In this case, irreversible losses in the amount and quality of the yield may occur. Under irrigation management, physiological measurements determining the water stress of plants are better indicators than measurements of soil moisture [11,12]. In arid and semi-arid regions where water resources are limited, the need for adequate irrigation for efficient water use has led scientists to develop new irrigation programming technologies. Previous studies confirm that plant-based methods have significant irrigation programming potential and have shown that measurements such as leaf water potential, leaf temperature, sap flow and stem diameter can be used for precise irrigation scheduling [12,13].

The use of deficit irrigation in tomato cultivation seems to be beneficial not only from the point of view of water use efficiency but also in terms of improving the quality of tomato fruit [14]. Furthermore, water deficit reduces the accumulation of ions in the leaves [15]. In a water deficit study reported by Rodriges et al., the content of some micro- and macronutrients decreased [16]. However, they found that fruits had increased color intensity, reduced water content and increased concentrations of sucrose, glucose and fructose when grown under conditions of water deficit.

Nuruddin et al. [17] applied water deficit during different growth stages of tomato plants under greenhouse conditions, both in summer and winter. In the summer period, the yield of fruit harvested from plants not exposed to stress related to water deficiency was only 1.78 kg plant^{-1}, whereas the yield of fruit harvested from plants cultivated under deficit irrigation conditions during flowering and fruit setting was 1.45 kg plant^{-1}. During the winter period, the yield of plants not subjected to stress was 1.34 kg plant^{-1}, and the yield of plants cultivated under the conditions of deficit irrigation during flowering and fruit setting was 1.40 kg plant^{-1}. The development of deficit irrigation practices as a tomato production management tool can be very effective in conditions of water scarcity and can reduce wastewater pollution. This is important because tomato is a popular vegetable grown all over the world. Water deficits and insufficient water supply are the main factors limiting crop production worldwide. Water-saving practices can reduce production costs, conserve water and reduce leaching of nutrients and pesticides into groundwater [17]. Kırda et al. [18] concluded that fruit yield and quality should be investigated before adopting deficit irrigation practices as a management tool.

We believe that the research on deficit irrigation of tomatoes will continue intensively, owing to the increasing demand for water. It is necessary not only to consider the relationship between deficit irrigation and crop production efficiency but also to study the nutrient intake of the plant. Micro- and macro elements are necessary for the proper metabolism of plants and cannot be replaced by other elements [19,20].

The tomato was chosen as the subject of this research owing to the very common production of this vegetable, both in Turkey and worldwide. The main objectives of this study were (a) the observation of changes in tomato development parameters in the face of water deficit during cultivation and (b) the correlation of yield with deficit irrigation and determination of the nutritional status of plants.

2. Materials and Methods

2.1. Experimental Site

The study was conducted in a tunnel-type plastic greenhouse with an arched roof on the campus of Alaaddin Keykubat University (Latitude 36°31′21″ N, Longitude 32°05′07″ E). The experiment lasted from late September until mid-January 2022 (2021–2022 autumn–winter season).

In the Alanya region, summers are hot, dry and cloudless, and winters are long, cold, rainy and partly cloudy. During the year, the temperature usually ranges from 9 °C to 32 °C, rarely falling below 5 °C or rising above 36 °C. The average annual temperature in Alanya is 16.0 °C. The climate of this region is warm and temperate. The average annual precipitation is 955 mm. Alanya receives approximately 3584.82 h of sunshine per year. On average, there are 117.75 h of sunshine per month. Some of the meteorological data for the Alanya region are presented in Table 1 [21]. The region of Alanya is considered a "temperate rain climate (C)" according to Köppen [22,23].

Table 1. Meteorological characteristics of the Alanya region.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Average Temperature (°C)	8.1	8.8	11.4	14.6	18.9	23.3	26.5	26.7	23.5	19.1	13.9	9.9
Minimum Temperature (°C)	4.4	4.6	6.4	9.2	13.2	17.6	20.9	21.7	18.2	14.2	9.6	6.1
Maximum Temperature (°C)	11.9	13.0	15.8	18.9	23.1	27.6	30.8	30.9	28.0	23.7	18.5	13.9
Precipitation (mm)	178	134	96	66	47	19	11	13	26	58	119	188
Relative Humidity (%)	70	69	68	70	68	62	60	62	61	61	64	69
Precipitation Days (d)	9	7	7	7	6	4	2	3	3	4	5	9
Sunshine Duration (h)	6.9	7.9	9.2	10.4	11.7	12.4	12.3	11.3	10.6	9.6	8.4	7.2

The greenhouse was 18 m long and 6 m wide, and the planting area was 108 m^2. Plants were cultivated in the greenhouse in sandy loam soil. Other properties of the greenhouse soil are: soil pH, 7.8; electrical conductivity, 0.28 ds m^{-1}; organic matter content, 0.8%; lime content, 5%; and cation exchange capacity, 66 me 100 g^{-1}.

2.2. Crop Management

Tomato seedlings (*Solanum lycopersicum* cv. Demiröz) were transplanted on 24 September 2021. Before planting, the soil in the greenhouse was processed and adapted for the planting of seedlings. In each plot, tomato seedlings were planted in rows with a spacing of 0.50 m, and the spacing of plants in the rows was 0.50 m. During the growing season, the plants were fertigated with the drip irrigation method. Based on our previous experiences, we applied 200, 100 and 150 kg ha^{-1} N, P and K, respectively. Ammonium nitrate, monoammonium phosphate and potassium sulphate were used as fertilizer sources. In addition, taking into account the need for microelements (Fe, Cl, Mn, Cu, Ni, etc.) in tomato fertilization, foliar fertilizers were used. Solid fertilizers were applied to the plots before planting.

During the flowering period, the plants were preventively sprayed for green worm (*Helicoverpa armigera*) with an insecticide (5.7% emamectin benzoate; 25 g/100 L water). In addition, every 7–10 days, the plants were sprayed with a fungicide (259 g/L metallic copper equivalent copper hydroxide + 49 g/L metalaxyl; 400 mL/100 L water).

2.3. Experimental Design

The conditions inside the greenhouse were adapted to the climatic requirements of the tomato. The process of growing tomatoes in the greenhouse covered the dates from planting the seedling (24 September 2021) to the end of the harvest (17 January 2022). The experiment consisted of 12 plots and three replications. The plots were arranged in a completely random design. In each plot, 25 grafted tomato seedlings were planted in 5 rows. The area of each plot was 6.25 m^2 (2.5 m length × 2.5 m width).

Drip irrigation applications were located on one side of each row of plants. A class-A pan was used to calculate the water consumption of the plants. During the irrigation treatments, 100%, 90%, 80% and 70% of the total amount of evaporation measured from the class-A pan evaporation was applied. Accordingly, the irrigation treatments were performed as follows: (1) I100 irrigation, using the total amount of evaporated water from the class-A pan (100%) (full irrigation, I1, control); (2) I90 irrigation, for which 90% of the total evaporated water from the class-A Pan was used (I2 with a 10% water deficit); (3) I80 irrigation, for which 80% of the total evaporated water from the class-A pan was used (I3 with a 20% water deficit); and (4) I70 irrigation, for which 70% of the total evaporated water from the class-A pan was used (I4 with a 30% water deficit).

2.4. Crop Water Consumption

The water consumption of the crop is calculated using a class-A pan inside the greenhouse. Using the amount of irrigation water, open water surface evaporation and plant-pan coefficients, Gençoglan et al. [24] determined water consumption in accordance with the described method. The amount of water to be used in the plant water balance equation was calculated using Equations (1) and (2).

$$\mathrm{I} = \mathrm{Epan} \times \mathrm{Kcp} \times \mathrm{A} \times \mathrm{P}, \tag{1}$$

$$\mathrm{V} = \mathrm{A} \times \mathrm{I}, \tag{2}$$

where:

I = amount of irrigation water (mm);
Epan = amount of A-pan evaporation (mm);
Kcp = plant-pan coefficient (I70 = 0.70, I80 = 0.80, I90 = 0.90 and I100 = 1.00);
A = plot area (m^2);
P = percentage of wetted area (%); and
V = volume of water L^{-1} [24].

The amount of water for irrigation calculated in the above equation is used in Equation (3) to calculate the water consumption of plants (evapotranspiration) [25]. Water meters placed on each plot were used to supply the appropriate amount of water for irrigation. Fertilizers, which were determined depending on the content of nutrients in the soil and the needs of plants, were applied in equal amounts to all tested individuals.

$$\mathrm{ET} = \mathrm{I} + \mathrm{R} + \mathrm{Cr} + \mathrm{Dp} + \mathrm{Rf} + \Delta \mathrm{s}, \tag{3}$$

where:

ET = water consumption (mm);
I = amount of irrigation water (mm);
Cr = capillary rise (mm);
Dp = penetration losses (mm);
R = runoff (mm);
Rf = runoff losses (mm); and
Δs = soil moisture content at the time of planting/harvesting ($\Delta s = W_{in/out}$ mm).

The capillary rise used in Equation (3) was ignored because there was no drainage problem in the experimental area. The values of deep infiltration and surface runoff were assumed to be zero because the drip irrigation method was used, and the practice of irrigation by bringing the missing moisture to the field capacity was taken into account.

After calculating the reference water consumption by tomatoes, using the values of the plant coefficient Kc for tomato, the potential values of water consumption by plants during the growing season were calculated (Table 2). We found that with an increased amount of water used for irrigation, the values of seasonal water consumption by plants also increased. The I1 irrigation treatment corresponds to the level of full irrigation, at which the standard amount of water needed to irrigate tomatoes was used, with the highest seasonal water consumption by plants amounting to 399 mm. Seasonal water consumption by plants under deficit irrigation treatments I2, I3 and I4 was 359, 319 and 279, respectively. In a study on tomatoes conducted in a plastic greenhouse in Turkey, Kirda et al. [26] determined the value of seasonal water consumption by plants at the level of 375 mm with full irrigation and 245–247 mm with deficit irrigation.

Table 2. Seasonal water consumption (mm) for tomatoes cultivated under different irrigation treatments (I1, I2, I3 and I4).

I1	I2	I3	I4
399	359	319	279

2.5. Soil Analysis

Soil organic matter (OM) was determined on the basis of studies by Walkley and Black [27]. In addition, the pH and EC of the soil (soil:water; 1:2.5, w w^{-1}) were determined using an electrical conductivity meter (EC) and a pH meter [28]. The calcimetric method was used to determine the content of $CaCO_3$ in the soil [29]. Soil cation exchange capacity (CEC) was determined by the BCl_2 method as described by Hendershot et al. [30]. pH (6.20 KCl), organic material (0.8%), total N (2250.00 kg ha^{-1}), total P (5542.5 kg ha^{-1}) and total K (4999 kg ha^{-1}) were determined based on the soil analysis carried out before planting.

2.6. Plant Analysis Procedures

Plant height (cm) determined using a measuring tape and the number of leaves per plant (pcs.) were used as vegetative characteristics. The height of the tomatoes was measured during four stages of plant development: seedling (6 October 2021), flowering (26 October 2021), fruit growth (26 November 2021) and ripening (22 November 2021).

Total yield (kg ha^{-1}), number of fruits (pcs. per 18.75^{-2}) and fruit weight (g) were assessed as generative features of tomatoes.

To determine the nutritional status of the plants, 8–10 leaves from different plants were collected, representing each parallel of the 5th or 6th leaf from the top on all sides of the plants [31]. After washing the samples with distilled water, they were placed in an air-flow oven at 70 ± 5 °C until a stable weight was obtained. Dried samples were ground and wet-digested in a microwave oven (CEM Mars X-press, CEM Corporation, Matthews, NC, USA) at 180 °C, then filtered into to 50 mL with deionized water to measure N, P, K, Ca, Mg, Cu, Mn, Fe and Zn. The concentrations of K, Ca, Mg, Cu, Mn, Fe and Zn were determined using an atomic absorption spectrophotometer. Phosphorus analysis was performed using a spectrophotometer [32]. For nitrogen analysis, the samples were wet digested with concentrated H_2SO_4 in 250 mL macro-Kjeldahl tubes at 350–400 °C. After digestion, the samples were distilled with NaOH (40%), and NH_4-N was fixed in H_3BO_3 (2%) and then titrated with 0.1 normal H_2SO_4 [33].

2.7. SPAD (Soil Plant Analysis Development)

A Minolta SPAD 502 was used to determine the intensity of the green color of the leaves. As part of the measurement, 3 readings were taken from the leaves collected for mineral analysis, and the values were averaged. SPAD measurements were taken 2 months after the start of the experiment.

2.8. Leaf Area Index (LAI)

Leaf area index (LAI) values were also calculated in the study. A portable leaf area meter (ADC BioScientific, Model: AM300, Hoddesdon, UK) was used to measure leaf area (LA). The leaf area index was calculated using Equation (4).

$$\mathrm{LAI} = \mathrm{LA}/\mathrm{PA}, \tag{4}$$

where:

LAI = leaf area index (m^2 m^{-2});
LA = leaf area (mm^2); and
PA = unit area of each plant (mm^2) [34].

2.9. Statistical Evaluation

ANOVA (analysis of variance) was used to determine differences between the mean values obtained in this study. ANOVA is used to determine whether there is a difference between 3 or more groups based on a particular variable. The data were statistically evaluated using the MSTAT package program. In one-way ANOVA, the means are compared assuming that k populations are normally distributed with $\mu_1, \mu_2, \ldots \mu_k$ means and common variance σ^2. Because the condition of one-way analysis of variance is suggested for the normal distribution of the group data, the conformity of the data with the normal distribution was previously tested with tests of normality. The Shapiro–Wilk normality test was preferred in this study. After testing whether there was a significant difference between the groups using a one-way ANOVA, the difference between the groups was examined with the post hoc technique using Tukey's test.

3. Results and Discussion

In this study, we investigated tomatoes grown in a greenhouse under water deficiency conditions. During the experiment, the effect of four levels of irrigation on growth parameters and nutrient concentrations was assessed. The first irrigation treatment (I1) was full irrigation, the second irrigation treatment (I2) comprised a deficit of irrigation water of 10% in relation to I1, the third irrigation treatment (I3) comprised a deficit of irrigation water of 20% in relation to I1 and the fourth irrigation treatment (I4) comprised a deficit of irrigation water of 30% in relation to I1.

Table 3 presents changes in the height of tomatoes in different stages of development depending on the level of water deficit. The tallest tomato seedlings were obtained under the full irrigation (I1) treatment. The data show a normal distribution according to the Shapiro–Wilk test of normality ($p > 0.05$). Whether there was a significant difference between them was examined using ANOVA. The results are shown in Table S1.

Table 3. Tomato pant height during the seedling, flowering, fruit growth and ripening growth stages under different irrigation conditions (I1, I2, I3 and I4). Data in columns with the same letters are not significantly different at $p > 0.05$; SD = standard deviation; ns = not significant at $p > 0.05$.

Irrigation Treatment	Plant Development Stage and Date of Height Measurement (cm)							
	Seedling 6 October 2021		Flowering 26 October 2021		Fruit Growth 26 November 2021		Fruit Ripening 22 November 2021	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
I1	24.0 ^{a}	1.95	52.8 ns	8.69	108.4 ns	19.19	135.8 ^{a}	23.29
I2	23.0 ^{ab}	1.67	46.6 ns	7.06	109.8 ns	11.43	128.0 ^{ab}	12.17
I3	20.2 ^{b}	3.89	59.0 ns	8.02	97.4 ns	19.46	125.8 ^{b}	23.91
I4	20.9 ^{b}	3.68	41.6 ns	11.36	103.2 ns	21.33	128.4 ^{ab}	25.28

According to the ANOVA results, there was a statistically significant difference between the groups (F = 19.07; $p \leq 0.05$). Tukey's test was conducted to group the differences according to origin, showing that differences occurred between full irrigation (I1) and limited irrigation (I3 and I4) ($p \leq 0.05$). In the case of deficit irrigation, the height of tomatoes was lower than in the case of full irrigation. Generally, researchers do not recommend a water deficit during the seedling stage. Water restrictions applied during this stage have a negative impact on plant growth. The height of tomatoes measured both during the flowering stage and in fruit growth and ripening stages was similar for all irrigation treatments. Differences in tomato height between the tested irrigation treatments measured both during flowering and fruit growth were not statistically significant ($p > 0.05$). Taking into account the average height of tomatoes during the fruit ripening stage, we found that plants cultivated under full irrigation conditions (I1) were significantly ($p > 0.05$) taller than plants cultivated under deficit irrigation conditions (I3). The tomato is sensitive to water deficiency. In this regard, the use of deficit irrigation in tomato cultivation has a negative effect on plant height. According to Nangare et al. [35], tomato plant height was higher under full irrigation than under deficit irrigation. In addition, the researchers reported that not all stages of tomato development are equally susceptible to soil moisture deficiency, and deficit irrigation may be more beneficial during non-critical stages. We found that tomato plants are most sensitive to water deficiency during flowering and fruit setting [17,36,37].

We also assessed the effect of deficit irrigation treatments on the intensity of tomato leaf coloration (SPAD). These measurements were conducted about 2 months after the start of the experiment, and the results are presented in Figure 1. We observed that the lowest value of green leaf color intensity was measured for I3 plants and amounted to 47.3, whereas the highest value was 48.7 for I4 plants. We found that the SPAD values assessed in plants cultivated under I2 and I4 deficit irrigation conditions were higher than in the case of full irrigation (I1). However, these differences were not significant according to ANOVA results ($p > 0.05$) after performing the Shapiro–Wilk normality test of ($p > 0.05$). Thus, a post hoc test was not performed, as there were no differences between the groups according to the ANOVA result (Table S2).

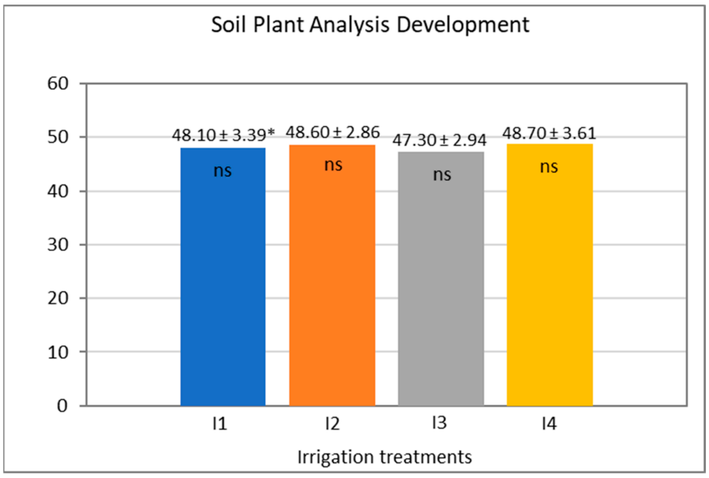

Figure 1. Intensity of green color of leaves (SPAD) of tomato cultivated under different irrigation conditions; * mean ± standard deviation; ns = not significant at $p > 0.05$ according to Tukey's test.

Abdelhay et al. [38] found that water restriction affects SPAD values. Their measured SPAD value in fully irrigated tomatoes was significantly lower than that in plants treated with 80% full irrigation [38], which is similar to our research results. The main reason for this situation is probably the early start of ripening and fruit setting resulting from the conditions of water deficit.

The effect of different irrigation levels on the concentrations of N, P, K, Ca and Mg in tomato leaves is shown in Figure 2. The Shapiro–Wilk normality test ($p > 0.05$) and ANOVA were used to evaluate the differences between irrigation treatments (I1, I2, I3 and I4). We observed that the use of varying levels of plant irrigation had a significant (F: 0.865: $p \leq 0.05$) effect on leaf nitrogen concentration. The highest concentration of N (3.16%) was observed in the leaves of plants growing under the I2 irrigation treatment, and the lowest (2.58%) was observed in plants growing under the I4 irrigation treatment. We found that the concentration of N in the leaves of plants growing all levels of irrigation was below the threshold level for tomatoes indicated by Jones et al. [32] and Bergman [39]. All nutrients perform specific functions in plant physiology. In the case of nutrient deficiency, the plants show corresponding symptoms. For example, tomato shows poor vegetative growth under nitrogen-deficient conditions. Regression of flowering and fruiting occurs in association with phosphorus deficiency. In the case of potassium deficiency, fruits show quality problems, such as changes in color and taste. Magnesium deficiency in plants slows down photosynthesis and reduces yield [39].

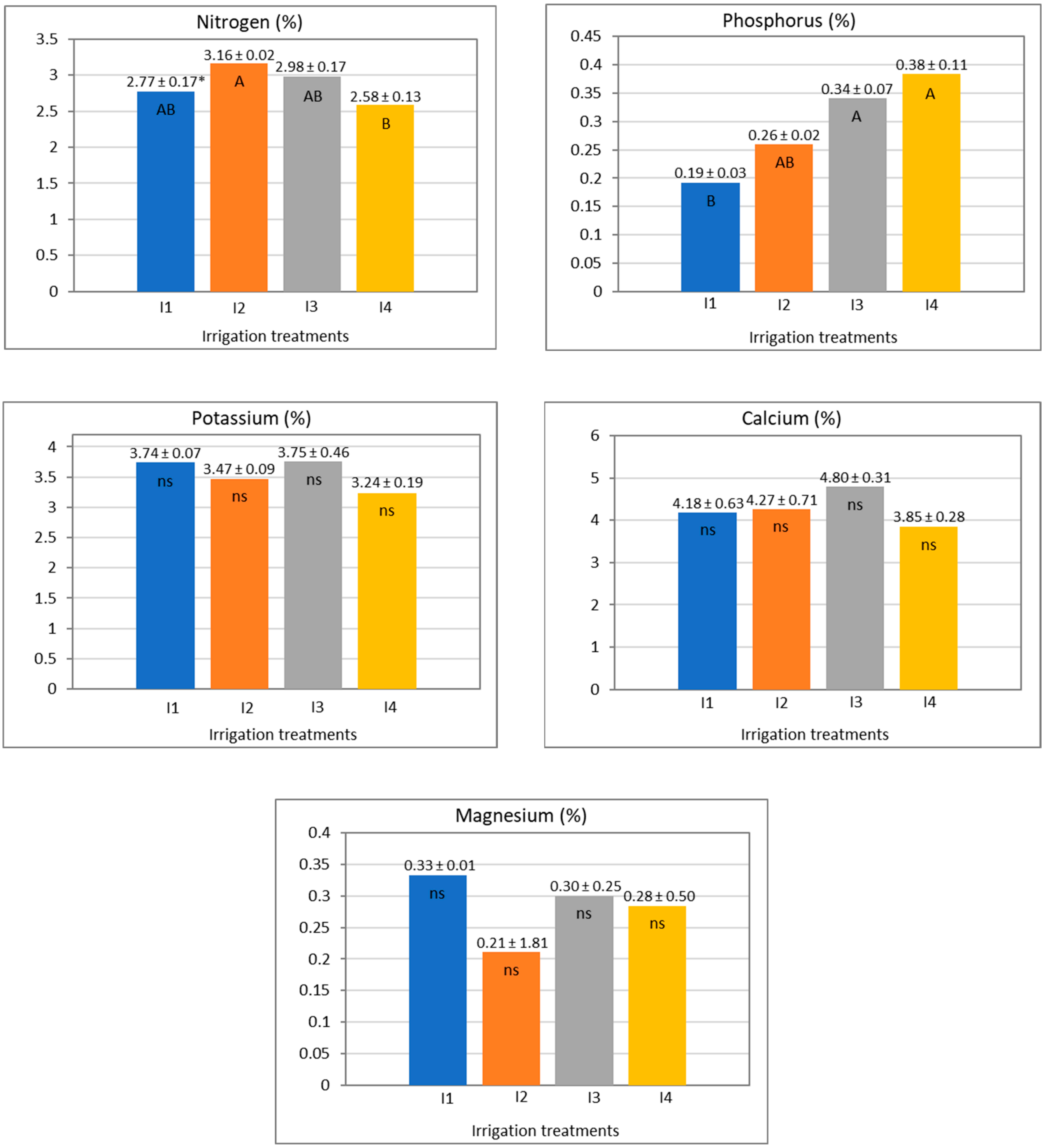

Figure 2. Concentrations of N, P, K, Ca and Mg in tomato leaves cultivated under different irrigation treatments; * mean ± standard deviation; ns = data in bars with the same letters are not significantly different at $p > 0.5$ according to Tukey's test.

The concentration of phosphorus for all irrigation treatments was below the recommended values (0.5–1.2%) [32,39]. We found that the effect of irrigation conditions on P concentration in leaves was statistically significant ($p \leq 0.05$). The concentration of P decreased with an increase in the amount of water used for irrigation (Figure 2), and the lowest P (0.19%) was measured in plants grown under the I1 condition, whereas the highest P (0.38%) was associated with condition I4. This situation can be explained by the concentration of P resulting from delayed plant growth and reduction in leaf area due to water deficit [40,41]. With a deficiency of P, the yield of tomatoes decreases, and the fruit is smaller than normal. P deficiency has also been reported to deteriorate the quality of tomatoes, and frosts may damage the plant [42].

Depending on the irrigation treatment, leaf potassium levels ranged from 3.24% to 3.75% (Figure 2), although these differences were not significant (F: 1.105: $p > 0.05$). All potassium values for all irrigation treatments were below the recommended value [32,39]. Potassium has many functions in plant metabolism. It plays an important role in the growth and yield of plants. Moreover, it increases the resistance of plants to diseases, cold and pests [42,43].

The highest calcium concentration(4.80%) was recorded in plants cultivated under I3 deficit irrigation, and the lowest value (3.85%) was recorded in I4 plants (Figure 2). The recommended concentration of Ca ranges from 1.5% to 2.40% [32,39]. We found that Ca concentrations for all irrigation treatments were above the recommended value. However, differences between irrigation levels were statistically insignificant ($p > 0.05$).

The required level of magnesium in plants ranges from 0.32% to 0.80% [32,39]. The Mg level assessed in this experiment was below the recommended level in all irrigation treatments, except I1 (Figure 2). The highest concentration of Mg occurred under the full irrigation condition (I1) and amounted to 0.33%, and the lowest Mg concentration occurred under the I2 condition (0.21%). Differences in Mg concentration in individual irrigation levels were not statistically significant ($p > 0.05$). We found that water deficiency had a negative effect on Mg levels. Mg plays an important role in plant physiology. It is also the central element of chlorophyll molecules [42,43].

Regarding the macronutrient values obtained in the present experiment, the concentration of nutrients in tomato leaves appears to be below the threshold values defined by Jones et al. [32] and Bergman [39]. Macronutrients are elements that plants need more than microelements. In the absence of these elements or when their availability is delayed, plant growth slows down, their resistance to diseases decreases, the quality of fruits may be impaired and their storage period is shortened [44,45]. The result of the ANOVA test to investigate differences between the irrigation treatments for N, P, K, Ca and Mg are presented in Table S3.

Tukey's test results show that there were significant differences between irrigation treatments I1 and I2, I2 and I4, and I3 and I4 ($p \leq 0.05$). Differences are shown in Figure 2, indicated by letters such as A, B, AB and BC according to post hoc results. The same letters indicate similarities, whereas different letters indicate differences. The results of the post hoc test for the concentration of microelements are shown in Figure 2.

Another parameter studied in the experiment is the change in the level of micronutrients in tomatoes. The concentration of micronutrients such as Cu, Mn, Fe and Zn was tested (Figure 3). The highest cooper value (9.8 ppm) was recorded for I1 plants, and the lowest value (6.5 ppm) was recorded for I4 plants. The recommended level of this element in tomatoes ranges from 5 ppm to 6 ppm [32]. In this case, it was determined that all irrigation treatments achieved the recommended Cu levels. The Shapiro–Wilk test was applied to the data ($p > 0.05$), and according to ANOVA results, the Cu concentration obtained under full irrigation (I1) was statistically significantly (F: 18.01: $p \leq 0.05$) higher compared to treatments I2 and I4. Therefore, water deficit negatively affects the uptake of Cu by tomatoes.

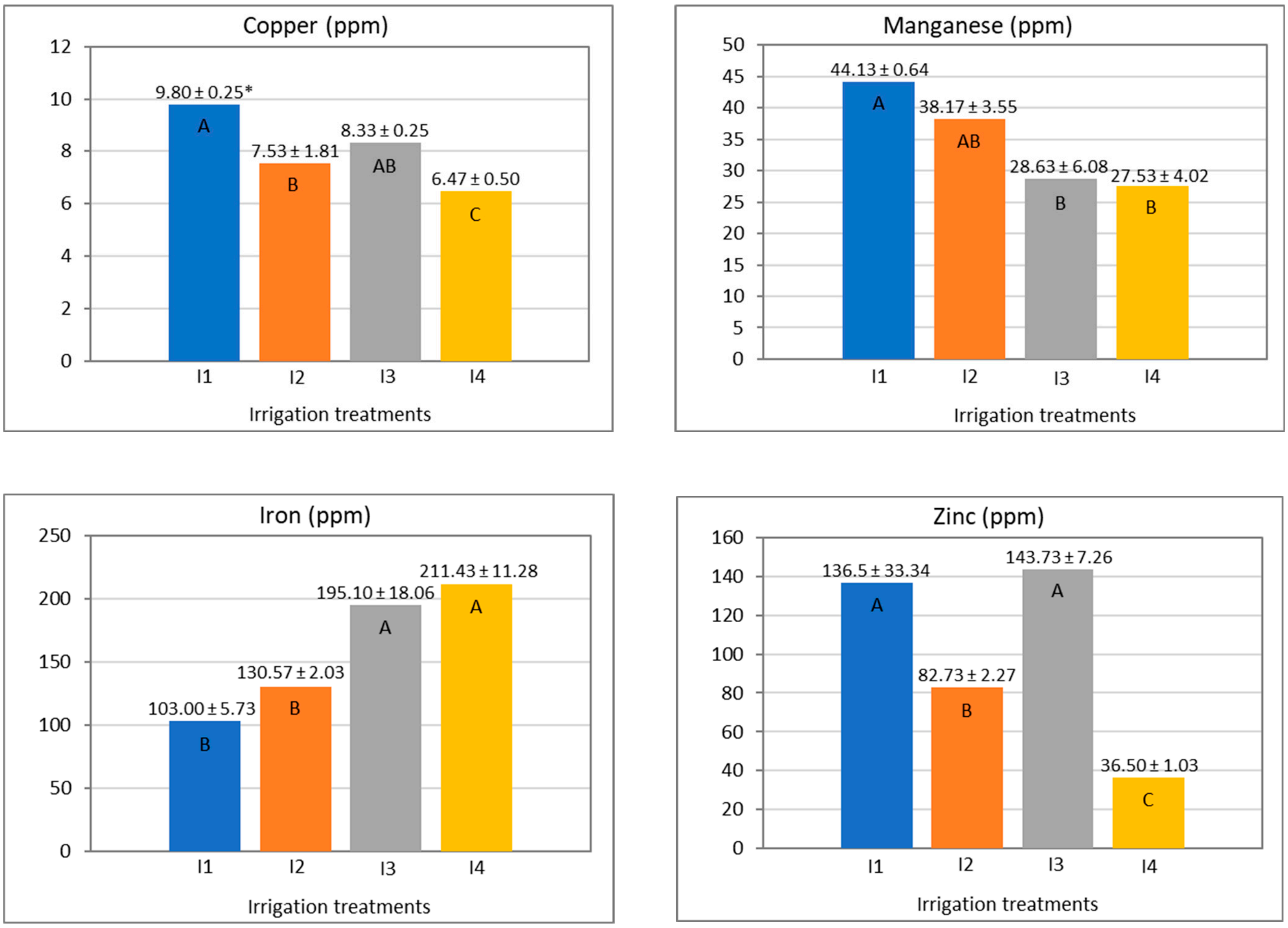

Figure 3. Concentrations of Cu, Mn, Fe and Zn in tomato leaves cultivated under different irrigation conditions; * mean ± standard deviation; data in bars with the same letters are not significantly different at $p > 0.05$ according to Tukey's Test.

Considering the effect of irrigation treatments on the concentration of manganese, we found that the value of this element determined in plants at all irrigation levels was below the recommended level (50–250 ppm) [32,39]. We found that the Mn value closest to the recommended value was obtained for I1 (44 ppm). As shown in Figure 3, increasing the water constraint increases the Mn deficiency. We found that the Mn level obtained for I1 was significantly ($p \leq 0.05$) higher than the values obtained for I3 and I4. In this study, we found that water deficit adversely affects the concentration of Mn. Manganese deficiency causes chlorosis in tomatoes. Additionally, Mn is essential in the process of photosynthesis [43,46].

The recommended concentration of another micronutrient, iron, is between 60 ppm and 300 ppm. We determined that Fe concentrations in tomato leaves measured for each irrigation treatment were within the recommended values [32,39]. The lowest Fe value was obtained under condition I1 (103 ppm), and the highest value (211.43 ppm) was obtained under condition I4 (Figure 3). The Shapiro–Wilk test was applied to the data to observe normality ($p > 0.05$) before ANOVA was used to assess differences between irrigation treatments. The Fe concentration measured in irrigation treatments I3 and I4 was statistically higher (F: 14.95: $p \leq 0.05$) than that measured in irrigation treatments I1 and I2 according to ANOVA results. Therefore, we believe that increasing water restriction led to an increase in Fe concentration in tomato leaves due to limited vegetative growth.

The analysis of zinc concentrations showed that under all irrigation treatments, the concentration of this microelement was higher than the recommended values (Figure 3).

The highest values were obtained for I3 (144 ppm) and I1 (136 ppm). We found that the concentration of Zn in the leaves of tomato grown under irrigation treatments I1 and I3 was significantly (F: 21.01: $p \leq 0.05$) higher than that in plants grown under irrigation treatments I2 and I4. The lowest concentration of Zn occurred in the case of I4. The differences are shown in Table S4 according to the ANOVA test of different irrigation treatments.

Although no visual symptoms of nutrient deficiency were observed, most of the micro- and microelements measured in the leaves were below the threshold levels indicated by Jones et al. [32] and Bergman [39], possibly as a result of genotypic diversity. As is well known, one of the most important factors with respect to the mineral nutrition of plants is genetic differences. Even plants grown under the same conditions can accumulate varied amounts of nutrients. These differences can be observed among different plant species, as well as among different genotypes of the same species. One plant may show deficiency symptoms under a given condition, whereas another does not [42,47,48].

The average leaf area per plant (LA) and the average leaf area index (LAI) assessed in the experiment increased depending on the level of irrigation (Table 4). A linear relationship with a high regression coefficient was obtained between LAI and the amount of water used for irrigation.

Table 4. Leaf area, leaf area index and average number of leaves per plant of tomato cultivated under different irrigation conditions (I1, I2, I3 and I4); SD = standard deviation; ns = not significant at $p > 0.05$.

Irrigation Treatment	Leaf Area (mm^2)		Leaf Area Index (m^2 m^{2-})		Number of Leaves per Plant (Pieces)	
	Mean	SD	Mean	SD	Mean	SD
I1	17202.5 ns	9372.12	0.014 ns	0.008	10.33 ns	1.62
I2	15349.9 ns	3040.86	0.012 ns	0.002	11.20 ns	1.60
I3	15021.5 ns	1544.85	0.012 ns	0.001	11.13 ns	1.31
I4	14119.5 ns	2007.24	0.011 ns	0.002	11.00 ns	1.32

A reduction in irrigation water by one unit reduced the LAI value by 0.0009 units. The highest value of LAI (0.014 m^2 m^{-2}) was obtained for the I1 irrigation treatment (full irrigation), and the lowest value (0.011 m^2 m^{-2}) was obtained for the I4 irrigation level (30% of full irrigation). With respect to the I4 irrigation treatment, LAI values increased by 127%, 109% and 109% for I1, I2 and I3, respectively. In the case of LA, similar linear relationships were observed in parallel with the leaf area index. Korkmaz [49] and Avuk [50] also reported that water deficit negatively influenced the leaf area index. The values we obtained in our study are consistent with the above reports. As in the case of LAI, the highest average leaf area per plant was obtained for irrigation level I1 (17,202 mm^2), and the lowest value (14,119 mm^2) was obtained for irrigation level I4. However, there were no statistically significant (F: 0.657: $p > 0.05$) differences between irrigation treatments for the LAI and LA parameters. There was no clear difference in the average values of number of leaves per plant depending on the irrigation treatments. However, in the case of cultivation under water deficit conditions (I2, I3 and I4), the number of leaves per plant was higher (11.13, 11.2 and 11.0 leaves, respectively) than in plants subjected to full irrigation (10 leaves). Nevertheless, there was no statistically significant ($p > 0.05$) difference between LA, LAI and the number of leaves for different irrigation treatments (Table S5).

According to the obtained results, it can be concluded that the number of leaves per plant may increase under water deficit conditions, although their development is limited. The study results show that the leaf area of tomatoes grown under water stress decreased. In plants, leaves are the most important organs, through which light energy is captured and used to produce metabolites necessary for plant growth. The level of vegetative activity of plants depends on the amount of light energy they capture with their leaves. Therefore, a reduction in the plant assimilation area as a result of treatments with water deficit adversely affects the development and yield [51–53]. In addition, LAI has been reported to control multiple processes, such as photosynthesis, canopy interception of solar radiation, evapotranspiration and pollutant storage [54–56]. Therefore, a decrease in LAI has a negative impact on photosynthesis, plant growth and yield.

Harvesting of ripe tomatoes under all irrigation treatments started on 15 December 2021 and was completed on 17 January 2022. During the harvest of tomato fruits, yield characteristics such as fruit weight, number of fruits and total yield were assessed (Table 5). However, no statistically significant differences occurred (F: 0.803: $p > 0.05$) with respect to the assessed traits of plants grown under different irrigation conditions according to ANOVA. Tomato fruits harvested from plants cultivated under I4 deficit irrigation had the highest weight, and fruits harvested from the I3 plot had the lowest weight. The largest amount of fruit and the highest yield were also harvested from plants cultivated the under condition with the most water deficit (I4). I1 plants grown under full irrigation conditions were characterized by the second highest yield, with the fewest tomatoes. Water restriction was found to stress tomatoes, leading to earlier flowering and fruit ripening (Table 5).

Table 5. Fruit number, fruit weight and total yield of tomato cultivated under different irrigation conditions (I1, I2, I3 and I4); ns = not significant at $p > 0.05$.

Irrigation Treatment	Average Fruit Number (Pieces per 18.75 m^{-2})	Average Fruit Weight (g $Fruit^{-1}$)	Total Yield (t ha^{-1})
I1	908	92.2	44.80 ns
I2	926	82.4	40.69 ns
I3	921	80.7	39.63 ns
I4	956	97.4	49.60 ns

Stress conditions increased the total number of flowers per plant, but no data were recorded for this parameter. As the number of flowers increased, so did the number of fruits, but few reached commercial quality. Although the yield under deficit irrigation was higher than that under control irrigation, the difference was not statistically significant (Table S6).

Some researchers have reported that water stress practices do not significantly reduce fruit yield and quality or save water. The tomato is not equally sensitive to the lack of water in the soil during each stage of cultivation. In particular, the most critical stage of development affecting yield is flowering and fruit setting [17,35,57–59]. Therefore, it is considered appropriate to focus research on this stage of tomato development. Nuruddin et al. [17] conducted a study during the flowering and fruiting phase of tomatoes in winter and found that the sizes and yield of fruit were higher under deficit irrigation than under control irrigation, although the difference was statistically insignificant. Moreover, it is believed that the number of fruits on plants cultivated under water stress conditions increases with early flowering.

In the present study, we determined growth parameters and nutrient concentrations in tomatoes grown at varying levels of irrigation. The values of water deficit used in the present research are important because they differ from implemented in other experiments. Our research on the concentration of macro- and micronutrients in tomato leaves is also innovative in relation to previously published studies. Given that the global human population will continue to increase in the future, in association with water deficit, similar research is becoming increasingly important. Previous studies on the impact of water deficit on tomatoes focused on the assessment of growth and yield parameters. It has been widely reported that the use of water deficit has a negative effect on the yield and development of tomatoes. In our research, we focused on other important issues, such as growth parameters and nutrients. Taking into account fruit yield and quality, as well as nutrient deficiencies, in our research on the impact of water deficit on tomatoes, the reported results significantly expand knowledge in this field.

4. Conclusions

We found that the use of water deficiency in tomato cultivation adversely affects some growth parameters, such as plant height, yield, leaf area index, SPAD and uptake of macro- and micronutrients. We found that water deficit had a negative effect on plant height. With respect to the values of the leaf area index, we found that the leaf surfaces were smaller and less developed in plants grown under conditions of water deficit compared to fully irrigated plants. With respect to the SPAD values, the lowest value of green leaf color intensity was 47.3 (I3), and the highest was 48.7 (I4). However, the difference was not statistically significant. The tallest tomato heights were achieved during the stages of seedling and fruit ripening with full irrigation (I1). In the case of I3, the lowest values were obtained during other development stages, apart from the flowering period. Analysis of macronutrients in tomato leaves showed that the obtained values were below the threshold values of the recommended values. The concentration of micronutrients in tomato leaves was also determined. Under all irrigation treatments, the manganese values were lower than the recommended values. We believe his is and similar studies will contribute to the success of water stress applications during the phases in which plants are least affected. Determining the periods during which tomato plants or any other crop are affected by the least water stress can contribute to both plant development and economic production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12122950/s1, Table S1: Height results for different irrigation treatments; Table S2: SPAD results for different irrigation treatments; Table S3: Macronutrients results for different irrigation treatments; Table S4: Micronutrients results for different irrigation treatments; Table S5: Results of leaf area, leaf area index and average number of leaves per plant (pcs.) for different irrigation treatments; Table S6: Yield results for irrigation treatments.

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