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ARTICLE

Effects of Greenhouse Microclimates on Nutrient Concentration and Growth in Maize under Deficit Irrigation Condition

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ABSTRACT: The aim of the study examines the effects of contrasting greenhouse microclimates on nutrient uptake, dry matter yield (DMY), and water use efficiency (WUE) in maize (*Zea mays* L.) during the early vegetative stage, under limited irrigation conditions. The study addresses the question of how microclimatic factors, particularly airflow and the humidity of the greenhouse, affect plant growth and nutrient dynamics under deficit irrigation conditions. The experiment was established at the Research and Application Greenhouses of the Department of Soil Science and Plant Nutrition, Çukurova University, Adana, Türkiye. Two greenhouse environments were compared: first with a whitewashed glass surface and active ventilation, and second with a transparent glass surface without ventilation. Three irrigation levels were applied based on available water capacity: 50%, 75%, and 100%, with three replications. Maize P2105 was used in the experiment, and plants were harvested following 40 days of deficit irrigation management. Research findings show that a microclimate greenhouse plays a critical role in maize growth and WUE under limited irrigation. In the ventilated and lime-whitewashed greenhouse, total dry matter yield reached 18.08 g pot^{-1}, and water use efficiency peaked at 4.76 g mm^{-1} under 75% irrigation, approximately three times higher than values observed in the non-ventilated greenhouse. Additionally, nitrogen and phosphorus uptake was significantly enhanced, reaching 277.87 mg pot^{-1} and 20.85 mg pot^{-1}, respectively. The optimized microclimate also significantly promoted the accumulation of other macro and micronutrients; the highest potassium (1239.56 mg pot^{-1}) and magnesium (235.61 mg pot^{-1}) uptakes were recorded under ventilated conditions, while shoot Mn concentration significantly increased to 37.71 mg kg^{-1} compared to the unventilated control. These results suggest that optimized airflow and humidity conditions substantially improve physiological efficiency and nutrient acquisition under water-limited environments. Microclimate engineering is therefore recommended as a sustainable strategy to mitigate drought stress in greenhouse-based crop production.

KEYWORDS: Microclimate; water use efficiency; maize; nutrient dynamics and deficit irrigation

1 Introduction

Climate change a serious threat to the agricultural sector. One promising strategy to combat climate change is greenhouse farming. Because meteorological factors are highly interdependent and subject to fast change, short-term microclimate prediction is difficult [1]. Greenhouses and other controlled environments provide good solutions by letting people manage the small climate conditions inside. This helps use water more efficiently and improves how plants take in nutrients [2]. In a greenhouse, you can carefully control temperature, humidity, and air movement, which can greatly improve how well crops use water (WUE) and absorb nutrients. It also increases yield by providing suitable microclimate conditions. Considering that global warming causes drought and depletion of freshwater resources, microclimate technology (such as greenhouses) can prevent plants from being affected by the external environment (high temperatures, etc.) in plant production and can also increase plant water use efficiency [3].

Ventilation systems in greenhouses facilitate the exchange of warm air inside the greenhouse with the cool air outside, thereby providing a suitable environment (temperature) for plant production [4]. Additionally, ventilation affects not only the cooling of the greenhouse but also its humidity content [5]. Therefore, the internal environment of the greenhouse (such as ventilation, temperature, and humidity) comes to the fore as a determining factor in the plant's resistance to water stress under limited irrigation conditions. Ventilation systems affect the humidity and evapotranspiration rates in the greenhouse through their cooling effect. This also affects the plant's nutrition and growth [6]. Maize was selected as a test crop because it is one of the most widely cultivated cereals worldwide, is highly sensitive to water availability, and thus serves as a reliable indicator of plant responses under limited irrigation conditions. Its relatively high water requirements compared to other cereals make it a suitable plant for evaluating microclimate interventions. Furthermore, maize has significant economic importance, and its nutrient uptake efficiency under stress conditions provides valuable insights for sustainable water management. However, studies on the effect of microclimatic environments on maize nutrition and development, especially under insufficient irrigation regimes, are extremely limited. Airflow and humidity in greenhouse conditions can increase water use efficiency (WUE) and nutrient uptake in maize, thereby mitigating the adverse effects of drought stress under limited irrigation conditions by comparing two different greenhouse microclimate environments.

The daily increase in the world population, unstable climate conditions, and the gradual depletion of water resources create serious problems in terms of agricultural production and sustainability [7]. Today, food security is related not only to increased yields but also to the resilience of production systems and their environmental impacts. Consequently, drought and irregular rainfall (such as sudden downpours or low rainfall) are among the main causes that directly affect plant growth and lead to yield declines. To mitigate these adverse environmental conditions, innovative strategies that enhance water use efficiency in agriculture must be developed. Therefore, water-centered microclimate management systems, such as ventilated and water-saving greenhouses, play a critical role in reducing drought stress, increasing water use efficiency, and increasing the plant's resistance to drought (by exposing it to drought little by little and frequently) by optimizing the humidity, temperature, and evapotranspiration of the environment. Research in this area is extremely limited.

While the isolated effects of deficit irrigation on maize are widely known, there is a distinct gap in the literature regarding how these stress factors interact with contrasting greenhouse microclimates. Therefore, the novelty of this study lies in its holistic approach: simultaneously evaluating the coupled effects of structural microclimate modification (shading and ventilation) and limited irrigation on the nutrient (N, P, K, Mg, Ca, Fe, Zn, Cu and Mn) acquisition and water use efficiency of maize during its critical early vegetative stage.

Thus, humidification has many effects on photosynthesis and nutrient absorption; however, only a few studies have discussed these effects together [8]. The aim of the study is to understand the effect of the difference between ventilated, limed greenhouses and non-ventilated, non-limed greenhouses on maize growth, dry matter weight, and nutrient uptake, during the early vegetative stage. Hypotheses to be tested: (I) maize grown in ventilated and whitewashed greenhouses will produce significantly higher dry weight compared to those grown in non-ventilated, transparent greenhouses under limited irrigation conditions, (II) maize grown in ventilated greenhouses will exhibit higher water use efficiency (WUE) across all irrigation levels compared to those in non-ventilated environments and (III) the positive effects of ventilation and humidity on biomass and nutrient uptake will be more pronounced under 50% and 75% irrigation levels than under full irrigation (100%).

2 Materials and Methods

2.1 Soil Collection and Analysis

The study was established as a pot experiment in the Research and Application Greenhouses of the Department of Soil Science and Plant Nutrition at Çukurova University Faculty of Agriculture in Türkiye. The Menzilat soil series, classified as Typic Xerofluvents by USDA classification [9] was collected from a soil depth of 0–15 cm. The collected soil was air-dried, passed through a sieve (4 mm mesh), and physicochemical properties of the collected soil, which was air-dried and passed through a sieve (2 mm mesh), were analyzed. Before establish of experiment 50 mg P kg^{-1} from Triple Super Phosphate (TSP) and 100 mg N kg^{-1} from Urea were applied. Menzilat series soil properties are presented in Table 1. The Menzilat soil series is a soil series widely used in agricultural production in the region and is suitable for maize cultivation due to its physicochemical properties. The experiment was set up using a split-plot design with 18 pots, consisting of two media (greenhouses), three irrigation levels (50%, 75%, and 100%), and three replications (Table 2). The pots used in the experiment have a base diameter of 14 cm and a height of 22 cm, with a total volume of approximately 4 L. Each pot was filled with exactly 4.0 kg of air-dried soil.

Table 1: Some physicochemical characteristics of the Menzilat soil series used in the experiment.

pH	**EC**	**OM**	**P_2O_5**	**CEC**	**$CaCO_3$**	**BD**
(H_2O 1:2.5)	**(dS cm^{-1})**	**(%)**	**(Kg da^{-1})**	**(me 100 g^{-1})**	**(%)**	**(g cm^3)**
7.66 ± 0.10	1.04 ± 0.02	0.99 ± 0.10	8.00 ± 0.2	16.14 ± 1.24	36.21 ± 0.73	1.43 ± 0.01
Texture Ratio (%)			**Texture**	**FC**	**PW**	**K**
Sand	**Silt**	**Clay**	**Group**	**(%)**	**(%)**	**(mg kg^{-1})**
32.00 ± 0.1	33.4 ± 0.1	34.6 ± 0.1	CL	30 ± 0.1	20 ± 0.1	437 ± 5.66

OM: organic matter, CEC: cation exchange capacity, EC: electrical conductivity, BD: bulk density, FC: field capacity and PW: permanent wilting. Mean of three samples with ±standard error.

Table 2: Experiment design.

Green House GWV and WLR			**Green House GV and LR**		
Bloc I	**Bloc II**	**Bloc III**	**Bloc I**	**Bloc II**	**Bloc III**
I50	I50	I50	I50	I50	I50
I75	I75	I75	I75	I75	I75
I100	I100	I100	I100	I100	I100

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water.

Microclimatic variables, including temperature and relative humidity, were monitored daily throughout the 40-day experimental period. A digital data logger was centrally positioned at the plant canopy height in each greenhouse to continuously record the representative daily averages. Although higher-resolution hourly monitoring was not employed, the daily average values provided a clear and consistent representation of the environmental contrast between the two greenhouse treatments. One of the media (greenhouses) is covered with lime to increase light reflection, with airflow from a fan, and has a temperature of 29.9 ± 2.2°C with a humidity content of 77.3 ± 6.2%, while the other is a greenhouse without ventilation and hasn't lime-covered windows, with a temperature of 40.6 ± 4.0°C and humidity of 36.1 ± 8.5%. In addition, it is known that coating the outer surface of greenhouse cover materials with lime reflects solar radiation, thereby reducing the intensity of light entering the interior by 40–45% and, as a result, lowering the internal greenhouse temperature by 3–6°C [10]. Moreover, while the average highest PAR value in the greenhouse without ventilation and without light reflection was approximately 1.400 μmol m^{-2} s^{-1}, the average highest PAR value in the greenhouse with ventilation and light reflection was measured at approximately 480 μmol m^{-2} s^{-1}. Fig. 1 illustrates the views of the greenhouses.

The P2105 variety (Pioneer Hi-Bred, Adana, Türkiye) of maize was planted in August 2025, and after emergence, irrigation was initiated using 50%, 75%, and 100% of the available water capacity (AWC) of the soil was determined as the moisture difference between field capacity (FC) and permanent wilting point (PWP). Irrigation treatments were established at 50%, 75%, and 100% of the AWC. Throughout the experiment, these specific moisture levels were maintained gravimetrically; the pots were weighed regularly using a scale, and the exact amount of water required to reach the target weight was added. Specifically, in the 100% irrigation application, irrigation was applied when the soil moisture content dropped to approximately 60%. Since the aim was to evaluate the effects of microclimate under limited irrigation conditions during the early growth stage, the maize was harvested approximately 40 days after planting during the early stage rather than at maturity. Indeed, the literature reports that nutrient uptake in maize accelerates, particularly during the generative stages, and is directly related to final yield [11].

Figure 1: A greenhouse covered with lime to increase light reflection with air flow from a fan (on the right), and a greenhouse without ventilation and without lime-covered windows (on the left).

2.2 Sampling and Dry Matter Yield

The maize roots were gently separated from the soil and washed using plenty of tap water. After that shoots and roots washed with 1:1000 (w:w) HCl, and finally pure water. They were dried in an oven at 65°C for 48 h, and their dry matter yields were weighed.

2.3 Stem Diameter and Plant Height

Immediately before harvest, stem diameter of maize was measured using a digital caliper (mm), and plant height was recorded with a measuring ruler (cm).

2.4 Water Use Efficiency

Water Use Efficiency (WUE) is usually defined as the total dry matter produced by plants per unit of water used, and WUE has been calculated according to the formula specified below [12].

$$WUE = \frac{D}{W}$$

where D is the mass of dry matter produced (shoot and root) and W is the total volume of water used. Since the soil surfaces of the pots were uncovered and watering was maintained gravimetrically, this water volume (W) accounts for both plant transpiration and soil evaporation, representing total evapotranspiration (ET).

2.5 Maize Nutrition Concentration and Uptake

The total nitrogen content in shoots were determined using the Kjeldahl method, which remains a widely accepted and reliable technique for organic nitrogen quantification in plant samples [13]. The shoot parts of the plant samples were dry-ashed in a muffle furnace at 550°C. The resulting ash was extracted using a 1:3 (w:w) mixture of hydrochloric acid (HCl) and deionized water. The filtrates were then colorimetrically analyzed for phosphorus (P) content using the molybdenum blue method [14], and absorbance was measured with a Shimadzu spectrophotometer at 882 nm. Macro elements (K, Ca and Mg) and Micro elements (Fe, Zn, Cu and Mn) were analyzed by AA-7000 model Shimadzu AAS.

2.6 Statistical Analyses

The findings obtained were analyzed using ANOVA and the least significant difference (LSD) test, with the JMP 8 software package from SAS Institute Inc., Cary, NC. Correlation matrix was analyzed by OriginPro 2024 program.

3 Result

3.1 Dry Weight

Fig. 2 shows the effect of different irrigation levels and different greenhouse conditions on the total dry weight of maize. Fig. 2 demonstrates that plant dry weight statistically significant increases ($p < 0.0001$) under ventilated greenhouse conditions (with 15.9 g pot^{-1}) compared to non-ventilated ones (with 5.1 g pot^{-1}), regardless of irrigation level. In terms of irrigation factor, the highest total dry weight was observed in maize grown under irrigation level I75 conditions (11.5 g per pot); this translates to a 25% water saving. Additionally, greenhouses equipped with ventilation systems and lime-coated glass showed a 68% higher total dry matter yield compared to greenhouses without ventilation or lime treatment. This ratio represents a significant difference. Regarding the greenhouse × irrigation interaction GV and LR × I75 had highest total dry weight with 18.08 g pot^{-1}.

Fig. 3 shows the effects of different greenhouse microclimates and irrigation doses on the root and shoot dry matter weight of maize. In addition, Fig. 3 shows that the greenhouse equipped with ventilation and lime-coated glass panels yielded significantly higher ($p < 0.0001$) root and shoot dry matter weights (4.41 and 11.48 g pot^{-1}, respectively) compared to the unventilated greenhouse that was not subjected to lime treatment (2.15 and 2.93 g pot^{-1} respectively). Under greenhouse conditions with active ventilation and lime-coated glass, the I75 irrigation treatment provided the highest dry matter accumulation in the root and shoot components of maize, at 3.96 and 7.58 g pot^{-1}, respectively.

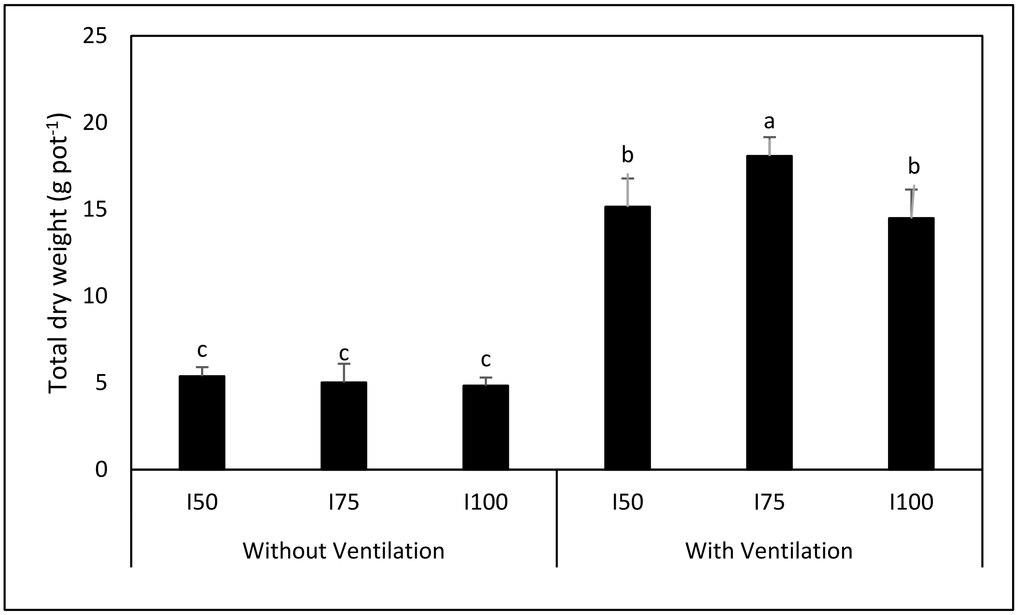

Figure 2: Effect of different irrigation and different greenhouse conditions on total dry weight (g pot^{-1}). GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters on the bars indicate statistically significant differences for the interaction effects according to the LSD test ($p < 0.05$). Bars with no letters indicate that the differences are not statistically significant ($p > 0.05$).

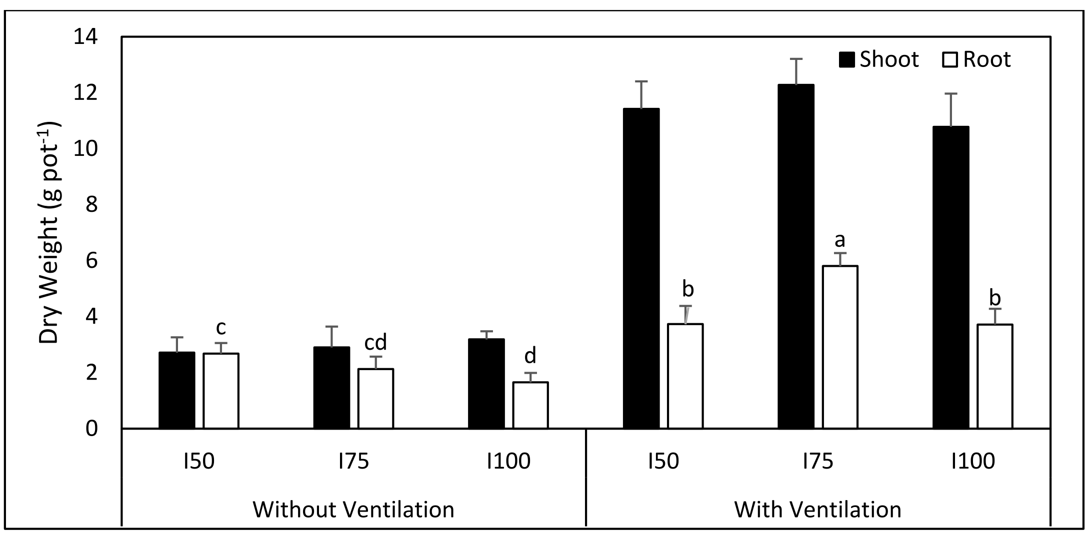

Figure 3: Effect of different irrigation and different greenhouse conditions on shoot and root dry weight (g pot^{-1}). GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters on the bars indicate statistically significant differences for the interaction effects according to the LSD test ($p < 0.05$). Bars with no letters indicate that the differences are not statistically significant ($p > 0.05$).

In addition, Tantau et al. confirm that material selection and surface conditions (such as liming) cause a 20–40% variation in light intensity [15]. In situations where excessive light and heat damage the plant (photoinhibition), this reduction plays a compensatory role. Moreover, although light intensity was reduced in the lime-coated greenhouse, the average temperature in the transparent greenhouse reached 40.6°C. According to Crafts-Brandner and Salvucci, maize photosynthesis is severely inhibited at temperatures exceeding 38°C due to the inactivation of the Rubisco enzyme. In our study, the lime application provided a necessary "thermal shield" by maintaining the plants at 29.9°C, which is the optimal range for Rubisco activity [16]. Consequently, the benefit of temperature stabilization outweighed the effect of reduced light intensity, resulting in the observed increase in dry weight. According to Fig. 4, there is a robust positive correlation between growth parameters (shoot height and stem diameter) and root, shoot, and total dry weight.

3.2 Maize Morphological Parameters

Table 3 shows the effects of different greenhouse microclimates and irrigation applications on maize shoot length (cm) and stem diameter (mm). Maize grown under greenhouse conditions with ventilation and lime-coated glass greenhouse showed significantly greater vegetative growth, with an average plant height of 120.2 cm and a stem diameter 10.9 mm. In contrast, plants grown in unventilated greenhouses without lime-coated glass showed significantly lower values, with an average shoot length of 83.3 cm and a stem diameter 6.8 mm. When plants were grown under ventilated conditions, a 44.3% increase in height and a 60.3% increase in stem thickness were observed. These findings show that well air circulation and optimum light intensity contribute to increased plant growth. The combination of ventilation and light-diffusing lime treatment, especially when combined with optimal irrigation levels, appears to create a more favorable environment for plant growth and stem thickening.

Table 3: Effect of different irrigation and different greenhouse conditions on shoot length (cm) and stem diameter (mm).

Green House Condition	**Irrigation Doses**	**Shoot Length (cm)**	**Stem Diameter (mm)**
GWV and WLR	**I50**	71.7 ± 1.5c	6.6 ± 0.2
	I75	88.0 ± 2.0c	6.9 ± 0.4
	I100	90.3 ± 7.1d	7.0 ± 0.9
GV and LR	**I50**	116.0 ± 6.0b	11.2 ± 0.6
	I75	125.0 ± 5.0a	10.9 ± 1.7
	I100	119.7 ± 1.5ba	10.6 ± 0.0
Green House Condition	**Irrigation Doses**	**Shoot Length (cm)**	**Stem Diameter (mm)**
	Mean I50	93.8B	8.9
	Mean I75	106.5A	8.9
	Mean I100	105.0A	8.8
Mean GWV and WLR		83.3B	6.8B
Mean GV and LR		120.2A	10.9A

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters indicate statistically significant differences for the interaction effects, while different uppercase letters indicate significant differences for the main factors according to the LSD test ($p < 0.05$). For parameters where no statistically significant differences were detected, statistical labels (letters) were omitted according to the LSD test ($p > 0.05$).

3.3 Water Use Efficiency (WUE)

In general, Water Use Efficiency (WUE), defined as the ratio of crop yield to the amount of water applied [17], has shown significant differences between greenhouse microclimate conditions and irrigation levels. The data obtained from this study show that the WUE of maize grown under ventilated greenhouse conditions is significantly higher than that of maize grown under non-ventilated conditions. This also indicates that air circulation and low light intensity increases WUE, likely by reducing heat and moisture stress, and consequently enhances maize development. Different irrigation levels in both greenhouse environments created a significant difference in WUE, and a statistically significant difference was also observed between the greenhouses ($p < 0.0001$). The greenhouse with ventilation and lime-coated features (to reduce light intensity) had a WUE of 4.31 g mm^{-1}, while the unventilated and non-lime-coated greenhouse had a WUE of 0.96 g mm^{-1}, creating a statistically significant difference (Fig. 5). In the non-ventilated greenhouse, WUE decreased as the irrigation dose increased. Furthermore, the WUE of the ventilated greenhouse was higher than that of the non-ventilated greenhouse for all irrigation doses. This indicates that water use efficiency decreases in non-ventilated environments due to high temperatures, which may lead to a decrease in dry weight per unit of water. Furthermore, in the ventilated greenhouse, WUE was highest at I75 (4.76 g mm^{-1}), followed by I50 (4.70 g mm^{-1}) and then I100 (3.48 g mm^{-1}). This pattern suggests that moderate irrigation (I75) under optimal microclimatic conditions strikes a balance between water availability and plant uptake efficiency.

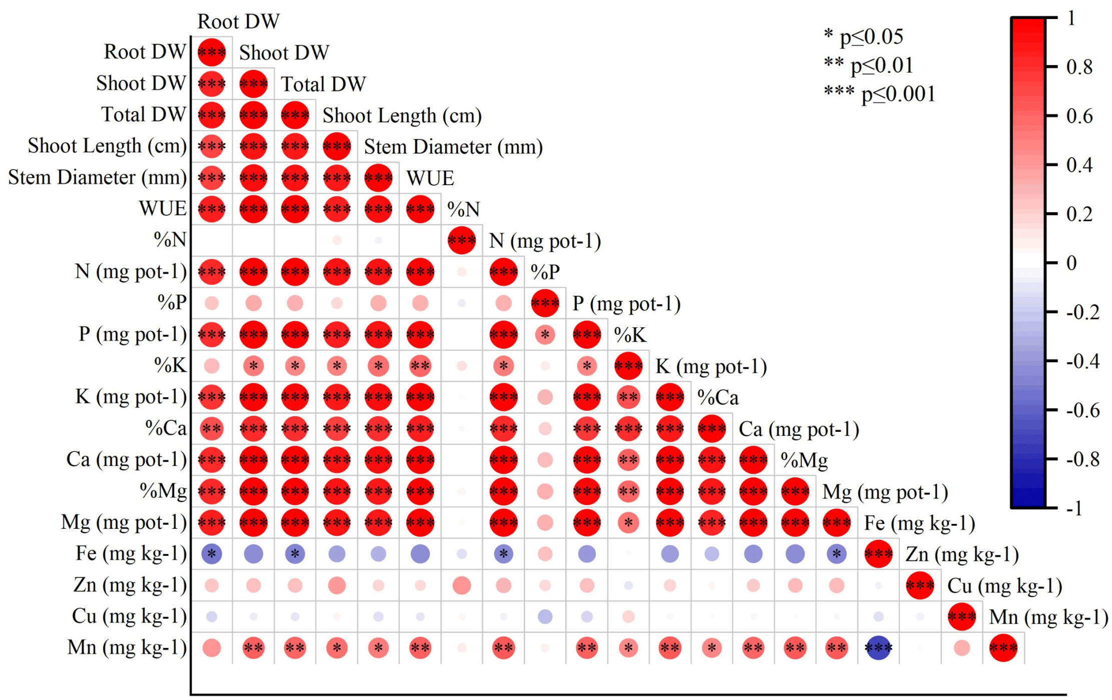

Figure 4: Correlation of shoot dry weight (Shoot DW), total dry weight (Total DW), shoot length (cm), stem diameter (mm), water use efficiency (WUE), shoot nitrogen ratio (%N), shoot nitrogen uptake (N mg pot^{-1}), shoot phosphorus ratio (%P), shoot phosphorus uptake (P mg pot^{-1}), shoot potassium concentration (%K), shoot calcium concentration (%Ca), shoot magnesium concentration (%Mg), uptake of K, Mg and Ca as mg pot^{-1}, and shoot Fe, Zn, Cu and Mn concentration (as mg kg^{-1}).

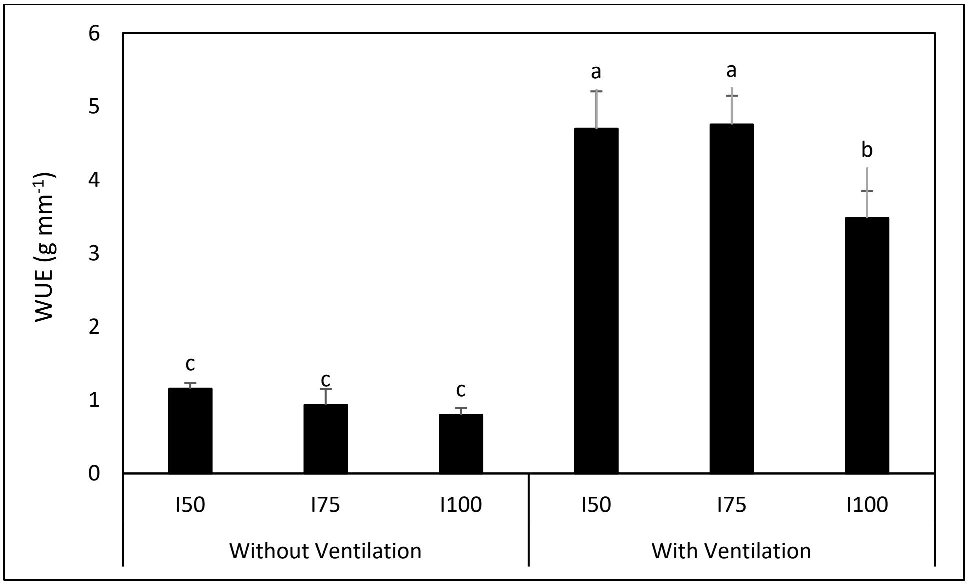

Figure 5: Effect of different irrigation and different greenhouse conditions on WUE (g mm^{-1}). GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters on the bars indicate statistically significant differences for the interaction effects according to the LSD test ($p < 0.05$). Bars with no letters indicate that the differences are not statistically significant ($p > 0.05$).

3.4 Some Nutrition Concentration and Uptake

The effects of different greenhouse and irrigation levels on the nutrient element concentration and nutrient uptake of maize shoots are presented between Tables 4–7. Table 4 shows the effects of different irrigation and greenhouse conditions on N, P, K, Mg, and Ca concentrations of shoot.

Regarding nitrogen (N) concentration, only the Greenhouse × Irrigation interaction led to a noticeable variation, though this effect was not statistically significant. Similarly, phosphorus (P) concentration remained unaffected by the greenhouse environment, irrigation doses, or their interaction. Regarding potassium (%K) concentration, Table 4 shows that all evaluated factors including the Greenhouse × Irrigation interaction, as well as greenhouse and irrigation conditions individually exerted a statistically significant influence. The highest K concentration was obtained under ventilated conditions with the lowest irrigation level (I50) at 10.90%. Additionally, K concentration exhibited a downward trend in response to increasing irrigation rates. For calcium (%Ca) and magnesium (%Mg) concentrations, while the interaction between greenhouse and irrigation did not yield a significant difference, both factors independently had a significant impact. Specifically, the GV and LR greenhouse treatments led to higher Ca (0.51%) and Mg (1.77%) concentrations compared to the GWV and WLR treatments. Additionally, decreasing irrigation doses generally led to a higher accumulation of K, Ca, and Mg in the shoots. While Ca concentration exhibited a downward trend with increasing irrigation dose similar to the pattern observed in K the highest Mg concentration was obtained from the moderate irrigation level, specifically the I75 dose with 1.36%.

When examining the effect of different irrigation and greenhouse conditions on certain nutrient concentrations in shoots (Table 5), while there was no significant difference in terms of the irrigation rate and greenhouse × irrigation rate factors, the greenhouse factor alone resulted in a significant difference (<0.05) for the Mn element. GWV and WLR had a Mn concentration of 31.96 mg kg^{-1}, while GV and LR had a Mn concentration of 37.71 mg kg^{-1}.

Table 4: Effect of different irrigation and different greenhouse conditions on shoot macro nutrient concentration.

Green House Condition	Irrigation Doses	N	P	K	Ca	Mg
		(%)				
Without Ventilation	I50	2.35 ± 0.10b	0.18 ± 0.07	8.11 ± 0.13cd	0.40 ± 0.00	0.82 ± 0.04
	I75	2.58 ± 0.18a	0.15 ± 0.03	8.80 ± 0.55bc	0.37 ± 0.02	0.80 ± 0.03
	I100	2.29 ± 0.12b	0.13 ± 0.05	7.81 ± 0.24d	0.36 ± 0.05	0.73 ± 0.11
With Ventilation	I50	2.40 ± 0.03ab	0.18 ± 0.02	10.90 ± 0.71a	0.55 ± 0.05	1.77 ± 0.09
	I75	2.39 ± 0.21ab	0.17 ± 0.01	9.06 ± 0.52b	0.53 ± 0.03	1.92 ± 0.22
	I100	2.48 ± 0.03ba	0.20 ± 0.02	8.37 ± 0.36bcd	0.45 ± 0.00	1.62 ± 0.04
Green House Condition	**Irrigation Doses**	**N**	**P**	**K**	**Ca**	**Mg**
		(%)				
	Mean I50	2.37	0.18	9.50A	0.48A	1.29BA
	Mean I75	2.49	0.16	8.93B	0.45A	1.36A
	Mean I100	2.38	0.16	8.09C	0.40B	1.17B
		N	**P**	**K**	**Ca**	**Mg**
		(%)				
Mean GWV and WLR		2.40	0.15	8.24B	0.38B	0.78B
Mean GV and LR		2.42	0.18	9.45A	0.51A	1.77A

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters indicate statistically significant differences for the interaction effects, while different uppercase letters indicate significant differences for the main factors according to the LSD test ($p < 0.05$). For parameters where no statistically significant differences were detected, statistical labels (letters) were omitted according to the LSD test ($p > 0.05$).

Table 5: Effect of different irrigation and different greenhouse conditions on shoot micro nutrient concentration.

Green House Condition	Irrigation Doses	Fe	Zn	Cu	Mn
		(mg kg^{-1})			
Without Ventilation	I50	50.97 ± 2.0	45.48 ± 2.6	17.72 ± 0.7	30.54 ± 3.6
	I75	51.35 ± 0.1	48.16 ± 1.2	24.31 ± 5.2	33.35 ± 4.1
	I100	51.13 ± 0.6	50.78 ± 10.2	20.82 ± 3.1	32.01 ± 1.5
With Ventilation	I50	50.53 ± 1.6	44.62 ± 4.6	20.31 ± 0.7	39.60 ± 6.8
	I75	50.00 ± 0.7	55.70 ± 8.7	20.73 ± 3.6	35.69 ± 3.7
	I100	50.09 ± 1.4	56.14 ± 4.8	19.41 ± 5.5	37.85 ± 2.7
Green House Condition	**Irrigation Doses**	**Fe**	**Zn**	**Cu**	**Mn**
		(mg kg^{-1})			
	Mean I50	50.75	45.05	19.01	35.07
	Mean I75	50.68	51.93	22.52	34.52
	Mean I100	50.61	53.46	20.11	34.93
Green House Condition	**Irrigation Doses**	**Fe**	**Zn**	**Cu**	**Mn**
		(mg kg^{-1})			
Mean GWV and WLR		51.15	48.14	20.95	31.96B
Mean GV and LR		50.21	52.15	20.15	37.71A

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters indicate statistically significant differences for the interaction effects, while different uppercase letters indicate significant differences for the main factors according to the LSD test ($p < 0.05$). For parameters where no statistically significant differences were detected, statistical labels (letters) were omitted according to the LSD test ($p > 0.05$).

In terms of N uptake (as seen Table 6), only the greenhouse factor showed a statistically significant different. Precisely, the greenhouse with ventilation GV and light reflection LR treatments resulted in significantly higher nitrogen uptake (277.87 mg pot^{-1}) compared to greenhouse without ventilation GWV and without light reflection WLR treatments (70.51 mg pot^{-1}). When examining the effects of different greenhouse and irrigation practices on phosphorus uptake, only the greenhouse factor created a statistically significant difference in phosphorus uptake ($p < 0.0001$). Similar to the trend observed in nitrogen uptake, the GV and LR treatments resulted in significantly higher phosphorus uptake (20.85 mg pot^{-1}) compared to the GWV and WLR treatments (4.49 mg pot^{-1}).

In terms of macro nutrient uptake (mg pot^{-1}), data presented in Table 6 reveals that potassium (K) and magnesium (Mg) accumulation in maize shoots were significantly influenced by the Greenhouse × Irrigation interaction. The highest K uptake (1239.56 mg pot^{-1}) was achieved under GV and LR conditions combined with the I50 irrigation level, whereas the maximum Mg uptake (235.61 mg pot^{-1}) was recorded in the same greenhouse condition but with the I75 treatment. Conversely, the interaction between greenhouse types and irrigation doses did not significantly alter calcium (Ca) uptake. However, both factors independently exerted a significant impact on Ca accumulation; the GV and LR treatments resulted in a substantially higher Ca uptake (58.65 mg pot^{-1}) than the GWV and WLR treatments. Furthermore, regarding the main effects of irrigation, lowering the water application to I50 and I75 levels led to significantly greater Ca and K uptake compared to full irrigation (I100).

Table 6: Effect of different irrigation and different greenhouse conditions on shoot macro nutrient uptake.

Green House Condition	Irrigation Doses	N	P	K	Ca	Mg
				(mg pot^{-1})		
GWV and WLR	I50	63.40 ± 12.29	5.02 ± 2.23	219.54 ± 43.74d	10.88 ± 2.24	22.22 ± 4.93c
	I75	75.34 ± 23.49	4.25 ± 0.86	253.37 ± 55.86d	10.65 ± 2.37	23.02 ± 5.36c
	I100	72.79 ± 8.17	4.19 ± 1.62	248.43 ± 22.99d	11.37 ± 1.76	23.21 ± 3.95c
GV and LR	I50	273.51 ± 20.15	20.48 ± 3.60	1239.56 ± 27.17a	62.88 ± 0.36	202.48 ± 28.12ba
	I75	293.27 ± 32.86	20.81 ± 1.91	1111.89 ± 102.52b	64.99 ± 6.23	235.61 ± 31.46a
	I100	266.84 ± 26.61	21.25 ± 1.53	900.38 ± 73.11c	48.10 ± 5.30	174.12 ± 16.41b
Green House Condition	**Irrigation Doses**	**N**	**P**	**K**	**Ca**	**Mg**
				(mg pot^{-1})		
	Mean I50	168.45	12.75	729.55A	36.88A	112.35
	Mean I75	184.31	12.53	682.63A	37.82A	129.32
	Mean I100	169.81	12.72	574.41B	29.73B	98.67
Green House Condition	**Irrigation Doses**	**N**	**P**	**K**	**Ca**	**Mg**
				(mg pot^{-1})		
Mean GWV and WLR		70.51B	4.49B	240.45B	10.96B	22.82B
Mean GV and LR		277.87A	20.85A	1083.94B	58.65A	204.07A

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters indicate statistically significant differences for the interaction effects, while different uppercase letters indicate significant differences for the main factors according to the LSD test ($p < 0.05$). For parameters where no statistically significant differences were detected, statistical labels (letters) were omitted according to the LSD test ($p > 0.05$).

There was a statistically significant difference in the levels of Fe, Zn, Cu, and Mn uptake from maize due to the greenhouse factor; the treatments GV and LR had the highest micronutrient contents, at 0.58 mg Fe pot^{-1}, 0.60 mg Zn pot^{-1}, 0.23 mg Cu pot^{-1}, and 0.43 mg Mn pot^{-1}, respectively (Table 7). In addition, Fig. 4 shows a robust positive correlation among biomass parameters (total dry weight, height, diameter) and WUE, moreover these growth indicators exhibited a positive correlation with manganese concentration in the shoots. When the effect of irrigation levels on microelement concentrations was examined, no statistically significant differences were found; however, in terms of the amount of elements uptake (mg pot^{-1}), a significant difference was observed only for zinc. The irrigation treatment resulted in a significant difference in terms of the amount of Zn removed (mg Zn pot^{-1}); the I75 irrigation treatment had the highest Zn content at 0.41 mg Zn pot^{-1}, followed by I100 at 0.38 mg Zn pot^{-1} and I50 at 0.31 mg Zn pot^{-1}.

Table 7: Effect of different irrigation and different greenhouse conditions on shoot micro nutrient uptake.

Green House Condition	Irrigation Doses	Fe	Zn	Cu	Mn
		(mg pot^{-1})			
GWV and WLR	I50	0.138 ± 0.030	0.123 ± 0.024	0.048 ± 0.010	0.082 ± 0.016
	I75	0.149 ± 0.038	0.139 ± 0.034	0.069 ± 0.015	0.095 ± 0.019
	I100	0.163 ± 0.015	0.162 ± 0.039	0.066 ± 0.011	0.102 ± 0.010
GV and LR	I50	0.576 ± 0.032	0.506 ± 0.009	0.231 ± 0.012	0.457 ± 0.116
	I75	0.614 ± 0.049	0.683 ± 0.118	0.254 ± 0.048	0.438 ± 0.055
	I100	0.539 ± 0.049	0.602 ± 0.043	0.212 ± 0.081	0.409 ± 0.071
Green House Condition	**Irrigation Doses**	**Fe**	**Zn**	**Cu**	**Mn**
		(mg pot^{-1})			
	Mean I50	0.36	0.31B	0.14	0.27
	Mean I75	0.38	0.41A	0.16	0.27
	Mean I100	0.35	0.38AB	0.14	0.26
Green House Condition	**Irrigation Doses**	**Fe**	**Zn**	**Cu**	**Mn**
		(mg pot^{-1})			
Mean GWV and WLR		0.15B	0.14B	0.06B	0.09B
Mean GV and LR		0.58A	0.60A	0.23A	0.43A

GWV and WLR mean a greenhouse without ventilation and without light reflection; GV and LR mean a greenhouse with ventilation and light reflection. I50: 50% of available water, I75: 75% of available water, and I100: 100% of available water. Different lowercase letters indicate statistically significant differences for the interaction effects, while different uppercase letters indicate significant differences for the main factors according to the LSD test ($p < 0.05$). For parameters where no statistically significant differences were detected, statistical labels (letters) were omitted according to the LSD test ($p > 0.05$).

4 Discussion

4.1 Dry Weight

The research findings of this study show that microclimate conditions have an almost threefold effect on maize dry matter yield, and that maize grown in ventilated and lime-coated greenhouses has a higher dry weight than maize grown in non-ventilated and non-lime-coated greenhouses. The ventilated greenhouse had lime-coated glass, which likely reduced light intensity and temperature peaks, contributing to a more stable microclimate. Studies have shown that ventilation improves air exchange and reduces humidity loss; while whitewashing glass can mitigate heat stress and excessive transpiration [18,19]. Together, these factors create a favorable environment for photosynthesis and biomass accumulation, especially when water supply is balanced.

It should be noted that whitewashing the greenhouse glass naturally reduced the incoming light intensity alongside lowering the internal temperature. Because these environmental variables are coupled under natural greenhouse conditions, the exact individual contribution of temperature, humidity, or light intensity cannot be perfectly isolated in this experimental setup. Therefore, the observed improvements in maize growth and WUE should be interpreted as the result of the combined, synergistic effect of the modified microclimate system as a whole.

In the study, different irrigation levels did not produce a significant difference in maize dry matter yield under either microclimate condition. Although there was no significant difference in the dry matter yields of maize grown in ventilated and lime-coated greenhouses, on average, the I75 application had the highest dry weight. A three-year field study conducted in Bangladesh investigated the effects of different limited irrigation strategies on wheat yield, water productivity, and economic returns. The study reported no statistically significant difference in yield between full irrigation and deficit irrigation applied during one or two growth stages of wheat [20]. Also, in China's semi-arid Guanzhong Plain, implementing reduced irrigation strategies in maize cultivation can increase yield and water use efficiency. Specifically, the study found that a 80% irrigation level (I80) yielded higher yields compared to full irrigation [21]. In another study conducted under greenhouse conditions in Türkiye, the effects of different irrigation levels (50%, 75%, and 100%), different biochar materials and doses, and different mycorrhizal inoculations on maize dry matter weight and WUE were investigated. The research findings indicate that there is no significant difference between the I75 and I100 applications as dry weight [22]. These studies support our research findings.

4.2 Maize Morphological Parameters

As seen Table 3 greenhouse microclimate and different irrigation doses significantly impact maize growth (as maize shoot length and stem diameter). Maize grown in ventilated greenhouses covered with lime-coated glass exhibited superior growth, achieving the highest shoot lengths and stem diameters at all irrigation levels. Ahmed et al. reported that fresh and dry biomass increased by 48.9% and 58.6%, respectively, as light intensity increased. They also found that air circulation facilitated CO_2 transport, increasing gas exchange and photosynthetic efficiency. Furthermore, the combined effect of increased light intensity and air movement synergistically supported plant growth. Their findings support the results obtained in our study [23]. The plant development observed in the ventilated and whitewashed greenhouse characterized by increased shoot length and stem diameter stems from a physiological optimization. The active air movement likely minimized the boundary layer resistance at the leaf-atmosphere interface, thereby streamlining CO_2 diffusion and bolstering gas exchange efficiency. This mechanism aligns with the principles established by Ahmed et al., where enhanced air velocity was shown to maintain photosynthetic stability under environmental pressure.

In another study, it was observed that increasing irrigation levels led to improvements in plant morphological characteristics such as plant height and related growth parameters [24]. Additionally, Singh et al. reported that the ventilation rate directly affects plant physiology and morphology by regulating greenhouse temperature, humidity, and CO_2 levels. Furthermore, they reported that natural ventilation provided by wind helps maintain the internal temperature within the range of 15–35°C, thereby creating an environment conducive to cell division and growth in plants [4]. This study partially supports our research findings.

4.3 Water Use Efficiency (WUE)

This study examined the critical effect of greenhouse microclimate and irrigation levels on WUE. Ventilated greenhouses likely have more efficient WUE for plants due to improved air circulation and reduced stress. Reflective surfaces further enhance this effect and also increase plant yield and growth. Under non-aerated conditions, excessive irrigation can cause suffocation in the root zone, negatively affect nutrient uptake, and lead to high evapotranspiration. However, under aerated conditions, optimal irrigation maintains a balance between water availability in the root zone and plant water use efficiency (WUE).

For example, tomatoes grown in cooler greenhouse conditions are found to be of higher quality in terms of firmness and sugar content compared to those grown in warmer greenhouses. Although the study in question focuses primarily on crop yield and fruit quality parameters, it demonstrates that regulating greenhouse microclimate (such as reducing temperature and humidity stress) through optimized ventilation and irrigation strategies leads to significant improvements in both fruit quality and plant growth conditions [25]. Cold greenhouses, or greenhouses equipped with cooling systems, have shown increases in yield and WUE [26,27] for plants.

Excessive and uncontrolled irrigation has been shown to reduce water use efficiency (WUE) due to nutrient leaching and reduced aeration in the root zone, and that this situation disrupts the plant's nutrition and transpiration activities [22,28,29]. Furthermore, Katsoulas et al. effectively regulated the internal temperature and humidity of semi-closed greenhouses equipped with cooling systems, thereby reducing plant stress, increasing plant photosynthetic activity, and leading to increased yields [30]. These studies support the findings of our research.

The optimization of environmental and biological processes has become a central theme in sustainable agriculture, urban planning, and bioengineering. In the agricultural domain, water management remains a critical factor for crop productivity, particularly in arid regions. Yi et al. demonstrated that precise assessment of soil water balance can significantly optimize irrigation schedules in flood-irrigated maize fields, highlighting the importance of understanding soil properties and cultivation history to improve water-use efficiency [31]. This approach aligns with broader trends in precision agriculture, where integrating environmental data allows for targeted interventions that enhance crop performance.

4.4 Some Plant Nutrition Concentration and Uptake

The results show that greenhouse with hotter conditions significantly affect plant nutrient uptake in shoots, mainly for N and P. While irrigation application alone did not show a harmonious effect on nutrient concentration, the combination of ventilation and light reflection in glasshouses markedly enhanced nutrient uptake. This enhancement is probably due to better root-zone aeration and microclimatic stability, which support root respiration and nutrient absorption. Previous studies also confirm that rhizosphere ventilation and cooling systems can optimize root exertion and metabolic processes, further promoting effective nutrient accession. These findings punctuate the significance of integrated hothouse design in perfecting plant nutritive performance.

Niu et al. explored the effects of different rhizosphere ventilation treatments on water and nutrient absorption in maize. Their findings demonstrated that ventilation markedly improved the uptake of nitrogen and phosphorus. This enhancement was primarily attributed to increased oxygen concentration in the root zone, which stimulated root respiration and metabolic activity. As a result, the roots exhibited greater efficiency in absorbing water and nutrients from the soil [32]. The study concluded that optimizing greenhouse microclimate through engineering solutions can be an effective agronomic strategy to improve crop performance. Specifically, it was reported that equipping semi-closed greenhouses with cooling systems significantly reduced plant thermal stress and improved microclimatic conditions, thereby enhancing water use efficiency and yield [30]. These enhanced conditions indirectly promoted nutrient uptake by increasing root activity and improving metabolic processes.

Interestingly, while restricted irrigation reduced total K uptake, it maintained or even elevated the K concentration (%) in the shoots. This discrepancy is consistent with the findings of Liu et al. [33], who noted that deficit irrigation triggers a concentration effect due to reduced biomass accumulation often referred to as the lack of dilution effect. Furthermore, maintaining a higher tissue K concentration under moisture stress serves as an adaptive mechanism for osmotic adjustment, helping the plant regulate stomatal conductance and preserve cell turgor despite limited water availability. Our results regarding the distinct behaviors of mineral concentration versus total uptake under moisture deficits are strongly supported by the concepts outlined by Jarrell and Beverly [34]. Their study underscores that while deficit irrigation significantly shifts the absolute elemental composition and partitioning within the plant system due to altered transpiration pull and mass flow, the proportional density of individual ions like Ca, Mg, and K can remain robust. This indicates that while the absolute nutrient sink strength (mg pot^{-1}) is suppressed by water-limited conditions, the plant's physiological adjustments prevent a proportional drop in nutritional quality, stabilizing tissue concentrations through a closely regulated ion-balance mechanism under stress.

As shown in Table 5, this study indicates that the interaction between irrigation and the greenhouse environment did not result in a statistically significant difference ($p > 0.05$) in the concentrations of micronutrients (Fe, Zn, Cu, and Mn). Manganese is a key cofactor in the water-splitting complex of photosystem II and enhances photosynthetic efficiency [35,36]. This may explain the positive correlation between Mn concentration and shoot dry weight and water use efficiency (WUE) in maize (as seen Fig. 4). Zn is an element transported by diffusion in the root zone [37], and the presence of water directly influences this process. Indeed, since optimal moisture conditions were provided at the I75 irrigation level, the maize plant took up more Zn from the soil.

However, these early nutritional advantages should be evaluated with caution, as this study was strictly limited to the first 40 days of vegetative growth under restricted pot volumes. In pot experiments, spatial root constraints can artificially affect the depletion zone of less mobile ions, a limitation extensively documented by Marschner [38] and Barber [39]. Therefore, while microclimate optimization successfully maintains transpiration pull and nutrient acquisition during the juvenile stage, long-term trials extending to physiological maturity are required to validate whether these vegetative benefits successfully translate into final grain yield.

5 Conclusion

This study examined the effect of limited irrigation conditions on maize dry weight, growth, and N, P, K, Ca, Mg, Fe, Zn, Cu, and Mn nutrition in greenhouses with different microclimates condition. The research findings show that the microclimate of the greenhouse significantly affects maize dry weight production, nutrient uptake, and WUE under limited irrigation conditions. Ventilated and lime-coated greenhouses significantly increased dry weight and WUE, especially at the 75% irrigation level. These findings demonstrate that ventilated and lime-coated (light-attenuating) microclimate environments can increase plant dry weight by saving water, which is vital for saving water resources among rising temperatures and deficit water supplies due to global warming. Moreover, the research findings support hypothesis I and hypothesis II, while partly supporting hypothesis III. Minimizing boundary layer resistance and managing structural humidity not only secure biomass formation but also guarantee the upward mass-flow and diffusion of essential macro and micronutrients.

Farmers and greenhouse operators can safely reduce irrigation levels to 75% of available water capacity without facing significant early vegetative growth penalties, provided that internal temperatures are thermally shielded via reflective coatings and adequate air circulation. It is important to note that the findings of this study regarding WUE and nutrient dynamics are strictly limited to the early vegetative stage (almost first 40 days). Future field and greenhouse studies monitoring the full crop cycle through to physiological maturity are required to fully understand the long-term impacts of microclimate engineering on final grain yield and reproductive sustainability under changing climate scenarios.

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