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Effects of Zeolite and Deficit Irrigation on Sweet Pepper Growth

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Abstract: The use of zeolites in agriculture as a soil conditioner is becoming an important field of research in crop growth. To study the effect of synthetic zeolites and deficit irrigation on sweet pepper (*Capsicum annuum* L.) cultivation, an experiment was conducted in a controlled environment. In particular, sweet peppers were cultivated in a glasshouse using polypropylene pots filled with sandy loam soil, to which 2% zeolite was added. The zeolite employed in the experiments was obtained using coal fly ash as a raw material. The experiment consisted of two main treatments: (a) soil with a zeolite at 2% (Z) and (b) soil without a zeolite as a control (C). Three subplot treatments consisted of (1) full irrigation at 100% of the available water content (AWC) (100); (2) deficit irrigation at 70% of the AWC (70); and (3) deficit irrigation at 50% of the AWC (50). Sweet pepper cultivation started on 24 April 2023 and lasted until 23 June 2023; during the trial, the environmental data, such as the soil humidity, air temperature, and relative humidity, and some crop parameters, such as the plant height, leaf number, and the SPAD index, were monitored. At the end of the trial, the fresh and dry plant weights, the dry matter content, and the leaf water potential were measured. The results showed that, for the plant fresh weight and dry matter content, no significant differences were observed in the treatments and their interactions, whereas, for the other parameters, the statistical analysis showed significant differences. The study suggests that the soil's structural benefits, resulting from zeolite application, are not followed by an equal positive effect in terms of sweet pepper growth under deficit irrigation conditions.

Keywords: soil amendments; zeolite; available water content; irrigation; water use efficiency

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1. Introduction

One of the main objectives of modern agriculture is to adopt agronomic practices that are as sustainable as possible [1] in order to obtain healthy soils and safe water. In this framework, the use of soil amendments together with the practice of deficit irrigation can play a key role, because they allow one to adequately modify the hydro-physical properties of cultivated soils and obtain safe water. The application of zeolites in agriculture as a soil conditioner has been studied by several researchers [2–5], since their usage solves various soil management problems during crop cultivation.

Zeolites are a group of natural and synthetic crystalline aluminosilicates with a framework of linked TO_4 tetrahedra (where T = Si, Al, or others), each consisting of four O atoms surrounding a cation. The three-dimensional networks containing cavities and channels impart a large surface area and porosity to these minerals, and they are characterized by a high-level ion exchange capacity.

Currently, agriculture is one of the main sectors for the utilization of natural zeolites due to the various positive effects that they can bring to cultivated soil [6]. Several studies have shown the positive advantages related to the use of zeolites in crop cultivation [2]. Zeolites may be used to improve soils contaminated by heavy metals, but also as a slow-release fertilizer [7]. Zeolites improve the soil habitability for root crops and may create an improved soil structure, allowing better water infiltration and water retention, as fully reported by Nakhli et al. (2017) [8] in their review and as shown recently by several other authors [9–11]. In spite of this, the operative implementation of zeolites in agriculture requires a detailed, in-depth understanding of the interaction between the soil's hydro-physical properties [9], soil texture [10], and irrigation management.

Water-saving practices on irrigated crops are mandatory in order to save water, since the farming sector consumes an enormous amount of water, with an estimate of 1300 m^3 per person per year [12,13]. There will be a significant increase in the amount of water needed to produce food by 2050, from 8500 to 11,000 km^3 per year, depending on the extent to which farming systems introduce innovation in irrigation management [13]. Deficit irrigation may be considered an innovative approach in irrigation scheduling in terms of water saving; it consists of deliberately applying a sub-optimal quantity of water during irrigation, without incurring reductions in the yield and, at the same time, increasing the crop water use efficiency [14,15]. Several authors have shown water savings of 43% to 65% under deficit irrigation, with a small impact on the yield and with higher crop quality [16]. The deficit irrigation (DI) strategy may be applied in several forms. Although the traditional one is based on the application of a sub-optimal amount of water throughout the crop cycle, other approaches are characterized by DI only in some stages of the crop cycle (time–space deficit irrigation, TSDI) [17], by the partial root drying (PRD) technique, and recently by the alternate wetting and drying regime (AWD) [18].

Sweet pepper (*Capsicum annuum* L.) is one of the ten most widely cultivated vegetable crops in the world, with very important economic value [19–21]. Its fruits are particularly appreciated, especially for sale in fresh markets, because of their color, pleasant flavor, and high ascorbic acid and mineral content [22,23]. Nevertheless, the application of deficit irrigation to peppers may be problematic, as reductions in the yield and fruit quality have been observed [24,25]. However, other studies have shown a positive impact of deficit irrigation on pepper fruit quality [20]. Recently, some authors [14] have highlighted the need for an integrated approach involving different agronomic practices with the deficit irrigation strategy to further improve the potential of this innovative technique. Hence, the use of a zeolite as a soil conditioner, in combination with the deficit irrigation strategy, may prove to be promising in order to save water and increase the water use efficiency of this crop [20].

This study aimed to verify the combined effects of zeolites and deficit irrigation management on the soil water uptake and growth of sweet peppers.

2. Materials and Methods

2.1. Experimental Description and Research Design

To study the effect of both zeolites synthesized from coal fly ash and deficit irrigation on sweet peppers (*Capsicum annuum* L. cv 'Alceste F1' by Orto Mio S.r.l., Forlì, Italy), an experiment was conducted at the University of Basilicata, Italy (40°31′51″ N, 15°48′35″ E; 736 m a.s.l.) in a temperature-controlled glasshouse. Polypropylene plastic pots with a conical trunk shape (20.0 cm height, 17.0 cm lower diameter, and 20.0 cm upper diameter) with a volume of 7 L were used to cultivate sweet pepper plants. Pots were filled with sandy loam soil collected from a field located in the Basilicata Region, Southern Italy (40°24′45″ N, 16°46′44″ E; 44 m a.s.l.), which was air-dried and passed through a 2 mm sieve, to which a zeolite was added. The soil used in the trial was previously characterized by Comegna et al. (2023) [10], as shown in Table 1. The synthesis of the zeolite (Z) employed in the experiment was performed by a pre-fusion hydrothermal process at 60 °C [26,27] and the final product was Ca-exchanged [28]. A scanning electron microscope (SEM, Zeiss Supra 40) equipped with an energy-dispersive spectrometer (EDS) was used to determine the morphology and chemical composition of the synthetic product (Figure 1).

Table 1. Principal physical–chemical properties and pedological classification of the studied soil.

Property	Soil	Unit	Method
Sand	53.8	%	Hydrometer method
Silt	34.9	%	Hydrometer method
Clay	11.3	%	Hydrometer method
Texture (USDA classification)	Sandy loam		
Soil pedological classification	Eutric vertisols		
Soil bulk density (ρ_b)	1.10	g cm^{-3}	Core method
Organic matter	17.2	g kg^{-1}	Walkley–Black
ECw	0.74	dSm^{-1}	$BaCl_2$ pH 8.1
pH (in H_2O 1:2.5)	7.9		pH meter
Wilting point (WP)	17.0	% vol	Retention curve (at $h = -1.5$ MPa)
Field capacity (FC)	31.9	% vol	Retention curve (at $h = -0.03$ MPa)

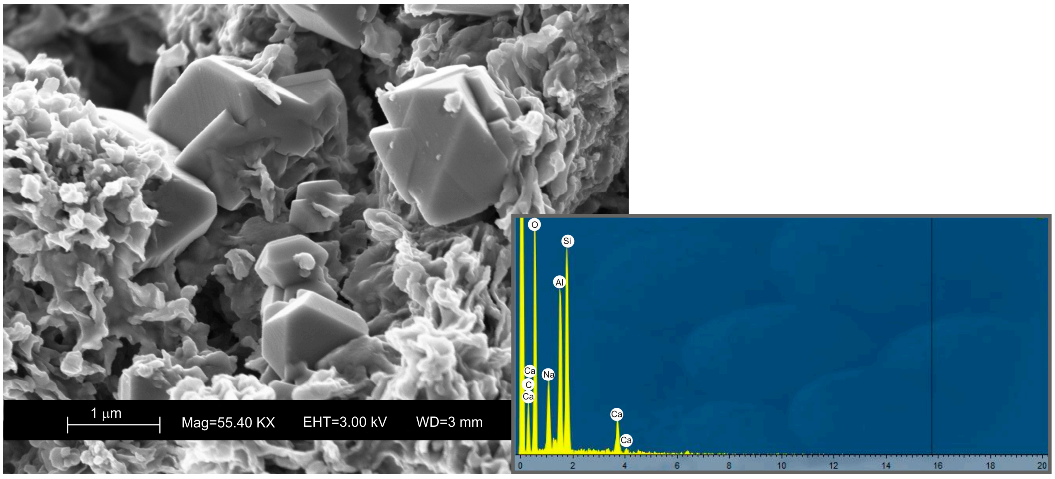

Figure 1. SEM image and EDX data of the synthetic zeolite.

The experiment consisted of two main treatments, namely (1) soil with Z at 2% and (2) soil without Z as a control (C), and three subplot treatments, namely (1) full irrigation at 100% of the available water content (AWC) (100); (2) DI at 70% of the AWC (70); and (3) DI at 50% of the AWC (50). Therefore, a split-plot block design with six treatments, each one consisting of a single pot and with four replicates, was carried out to have a total of 24 pots. Treatments were named Z100 (soil with Z at 2% and full irrigation at 100% of the AWC), Z70 (soil with Z at 2% and DI at 70% of the AWC), Z50 (soil with Z at 2% and DI at 50% of the AWC), C100 (soil without Z and full irrigation at 100% of the AWC), C70 (soil without Z and DI at 70% of the AWC), and C50 (soil without Z and DI at 50% of the AWC). In particular, Z and C were placed in the main plot treatments, and water regimes were placed in the sub-plot treatments. Table 2 shows the soil moisture values at field capacity and wilting point and the different available water content values of the soil with and without zeolites.

Table 2. Soil hydraulic properties: water content at field capacity and at the permanent wilting point, the available water content (AWC), and the air capacity (AC) of the soil with and without zeolites.

Soil Treatments	Field Capacity (%)	Wilting Point (%)	Available Water Content (%)	Air Capacity (%)
Z (2% zeolite)	35.5	15.7	19.8	33.3
C (0% zeolite)	31.9	17.0	14.9	29.1

On 24 April 2023, the pots were irrigated to field capacity (Table 2), and then sweet pepper seedlings at the 3–4th stage of true leaves were transplanted to have 2 plants per pot; successively, one of these was uprooted to have only one plant per each pot. At the first irrigation, when plots were brought to field capacity, fertilization with potassium nitrate 13–46

and diammonium phosphate 18–46 with a total dose of 3 g of N plant^{-1},1 g di P_2O_5, and 5 g of K_2O plant^{-1} was applied. During the experiment, once a week, a graduated cylinder was used to irrigate the plants. The soil moisture content was monitored by soil sensors throughout the trial. Therefore, at the beginning of the trial, Watermark 200SS probes (The Irrometer Company, Inc., Riverside, CA, USA) were installed in all the pots. Before the trial and according to the installation and operating instructions, the Watermark probes were preconditioned [29] and then calibrated according to the methodology proposed by Abbas et al. (2011) [30].

During the trial, a portable Escort Junior temperature and humidity data logger was used to record the greenhouse air temperature and relative humidity (Escort Messtechnik AG, Aesch bei Birmensdorf, Switzerland). Data were acquired every hour and the probe was placed only over the sweet pepper canopy. Figure 2 shows the mean air temperature and the relative humidity patterns monitored throughout the experiment. From transplanting to the first fruit ripening (i.e., end of the trial), the plant height, leaf number, and leaf greenness index, the latter measured using a SPAD meter (SPAD-502, Konica Minolta Corporation, Ltd., Tokyo, Japan), were recorded weekly.

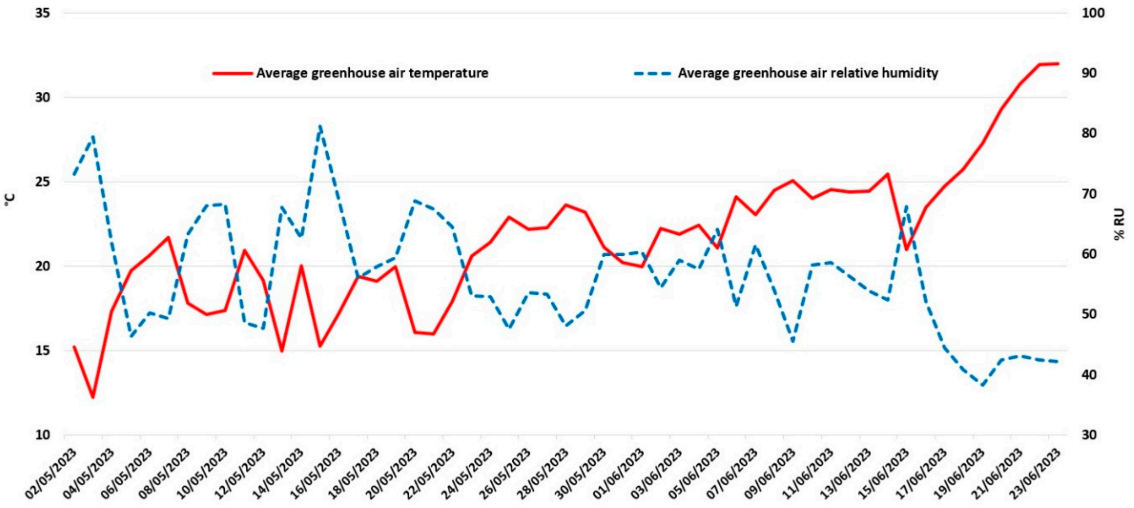

Figure 2. Mean air temperature (°C) and relative air humidity (%) patterns monitored during the trial.

On 23 June, at the end of the trial, per each treatment, the leaf area was measured through an electronic area meter (3100 area meter, LI-Cor, Inc., Lincoln, NE, USA). Moreover, by means of the pressure chamber technique and according to Scholander et al. (1965) [31], the leaf water potential (Ψ) was measured on the youngest uppermost fully expanded leaf of three plants per treatment at midday. Furthermore, the sweet pepper fresh and dry weight were determined by drying the samples in a ventilated oven at 75 °C until a constant weight was reached, and therefore the dry matter content was calculated. Lastly, the irrigation water use efficiency (iWUE) was calculated as the ratio between the assimilated total dry weight (g) and the irrigation volume (g L^{-1}).

2.2. Statistical Analysis

Before performing the analysis of variance (ANOVA), the Shapiro–Wilk ($p \leq 0.05$) and Bartlett ($p \leq 0.05$) tests were applied to test the normality and homogeneity of variances, respectively. Afterward, data were subjected to an analysis of variance (two-way ANOVA) according to the split-plot experimental design. The mean values were separated with the Student–Newman–Keuls (SNK) test, at the significance level of $p \leq 0.05$.

Moreover, a principal component analysis (PCA) was performed to evaluate correlations between the treatments, the soil volumetric water content, and some morphological and quantitative sweet pepper traits.

All the statistical procedures were computed using the software RStudio: Integrated Development for R, version 2023.06.2 Build 561 [32].

3. Results

3.1. Soil Water Content

The soil water content varied during the trial according to watering. Figure 3a shows the water volumetric soil content values in the three irrigation treatments in soil with zeolites. This parameter recorded higher values in the Z100 and lower ones in the Z50 treatment. During the experiment, in all treatments with the zeolite, the soil volumetric content never dropped below the wilting point (15.7%). Figure 3b shows the water volumetric soil content values in the three irrigation treatments in the soil without the zeolite. As shown, differences between the irrigation treatments were observable only in the first 30 days of the experiment, when the sweet pepper was at the beginning of the flowering stage and the greenhouse air temperature started to become warmer. It is important to underline that in the two soil treatments, the AWC range was different, according to the effect of the zeolite on the soil hydraulic properties (Table 2, Figure 4). Figure 5a shows that a greater amount of water was applied to the Z100 treatment. Consequently, the irrigation water use efficiency (iWUE) was lower in this treatment, as well as in all the Z ones (Figure 5b). In contrast, the C50 treatment showed lower water use (Figure 5a) and a higher value of iWUE (Figure 5b).

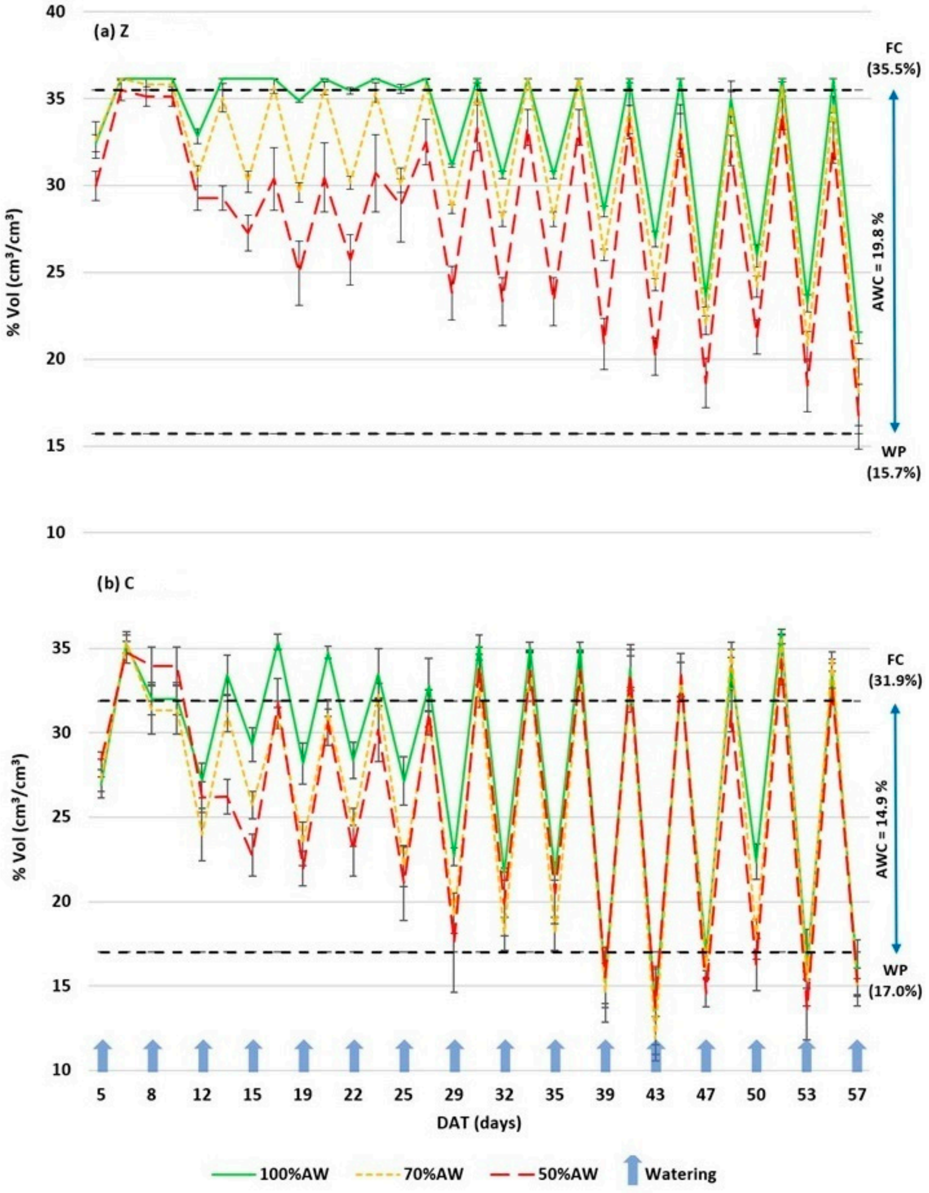

Figure 3. Volumetric water content trend for (**a**) soil with zeolite (Z) and (**b**) soil without zeolite (C).

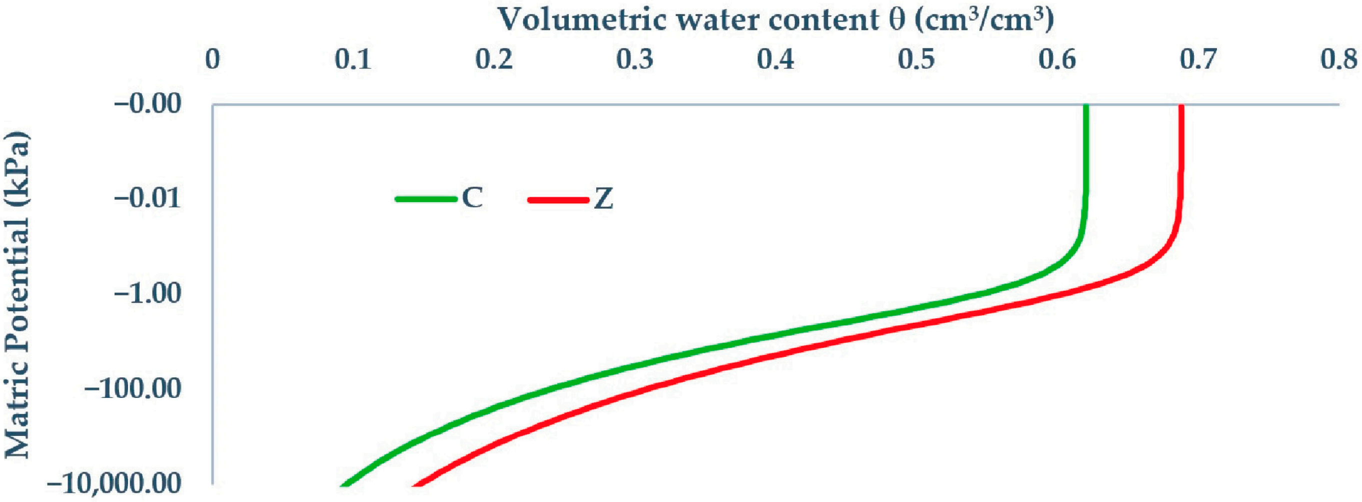

Figure 4. Soil water retention curves of Z and C soils, modified from Comegna et al. (2023) [10].

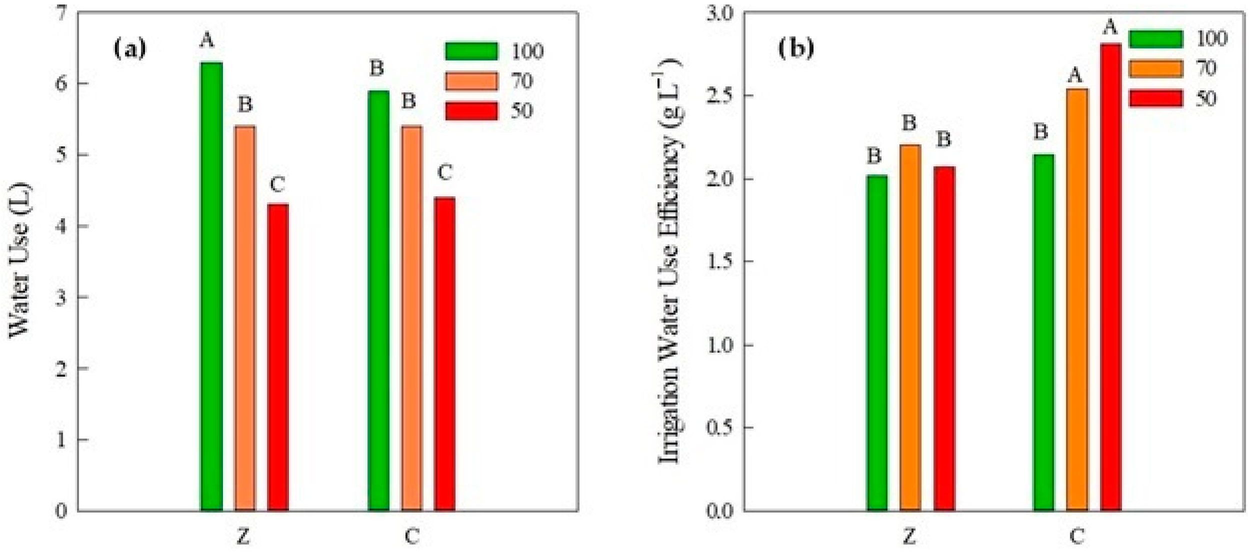

Figure 5. Irrigation volume (**a**) and irrigation water use efficiency (**b**) measured for studied treatments. Mean values (n = 4) within a column followed by different letters are significantly different at $p < 0.01$, according to the SNK test.

3.2. Plant Growth

Table 3 reports the two-way ANOVA results for the sweet pepper growth parameters. No significant differences were shown by the treatments and their interactions for the plant fresh weight and the dry matter content, whereas, for the other parameters, the statistical analysis revealed significant differences (Table 3). A larger value for the plant height, equal to 58.0 cm, was observed in the Z100 treatment, and a lower one was obtained for Z50, with 47.5 cm. A significant reduction in the leaf number and the leaf area from the Z70 to Z50 treatments was observed (Table 3). Regarding the leaf number, the decreasing effect of the zeolite was even clearer when looking at the temporal trend of this parameter (Figure 6a,b). Moreover, a negative interaction effect of the zeolite on the SPAD index was also observed (Table 3). The SPAD index's temporal trend showed the negative effect of the zeolite in the soil (Figure 7a,b). Relative to the leaf water potential, the interaction of the two treatments was significant, with a more negative value for Z50 (−1.48 MPa). Meanwhile, in the control (C100) as well as in the C70 treatment, the water status was better (−0.95 MPa).

Table 3. Effects of the zeolite and the water regimes on some morphological and physiological traits of sweet pepper.

Treatments (1)	Plant Height	Leaf Number	SPAD Index	Leaf Area	Leaf Water Potential (Ψ)	Plant Fresh Weight	Plant Dry Weight	Dry Matter Content
	(cm)	(n.)		(cm^2)	(MPa)	(g)	(g)	(%)
Z 100	58.00 a	48.75 a	50.88 ab	1574.00 a	−1.08 b	104.05	12.83 a	12.77
Z 70	51.25 ab	43.50 b	52.05 ab	1314.00 b	−1.23 c	93.45	11.88 a	12.72
Z 50	47.50 b	37.00 c	54.55 a	1066.75 c	−1.48 e	77.37	8.89 b	11.58
C 100	53.25 ab	54.25 a	44.80 b	1628.75 a	−0.95 a	99.18	12.60 a	13.10
C70	54.00 ab	51.50 a	47.23 ab	1579.00 a	−0.95 a	94.05	13.72 a	14.56
C50	51.00 ab	43.00 b	51.55 ab	1403.75 a	−1.38 d	90.85	12.23 a	13.82
Significance (2)	*	**	*	**	**	n.s.	*	n.s.
Zeolite (Z)								
Z	52.25	43.08 b	52.49 a	1318.25 b	−1.26 ab	91.62	11.20	12.35
C	52.75	49.58 a	47.86 b	1537.17 a	−1.09 a	94.69	12.85	13.83
Significance	n.s.	*	**	*	*	n.s.	n.s.	n.s.
Water regimes (W)								
100	55.63 a	51.50 a	47.83 b	1601.38 a	−1.01 a	101.61	12.71 a	12.93
70	52.62 a	47.50 a	49.64 ab	1446.50 b	−1.09 a	93.75	12.80 a	13.64
50	49.25 b	40.00 b	53.05 a	1235.25 c	−1.42 b	84.11	10.56 b	12.70
Significance	*	**	*	**	**	n.s.	*	n.s.
Interaction								
Z × W	*	**	*	**	**	n.s.	*	n.s.

(1) Mean values in a column followed by a different letter are significantly different at $p \leq 0.05$, according to the SNK test. (2) n.s., no significant difference; *, significance at $p \leq 0.05$; **, significance at $p \leq 0.01$.

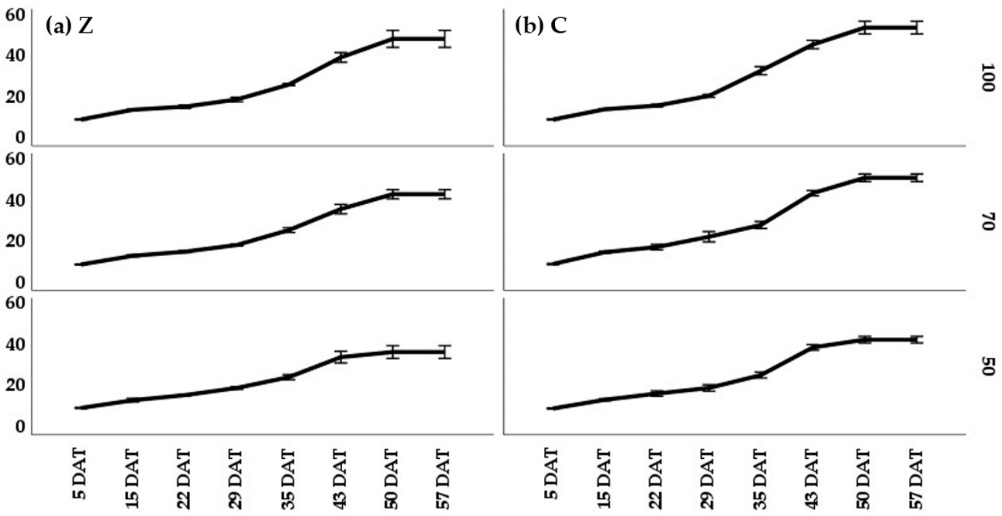

Figure 6. Temporal trend (days after transplant, DAT) of leaf number in (**a**) Z and (**b**) C treatments; mean values (n = 4) and standard error are reported.

Lastly, a greater value of the plant dry weight was observed in the C70 treatment, reaching 13.72 g, whilst a lower one, equal to 8.89 g, was obtained for Z50. In any case, as expected according to deficit irrigation management, for this parameter, there was no significant difference between treatments, except for the Z50 one.

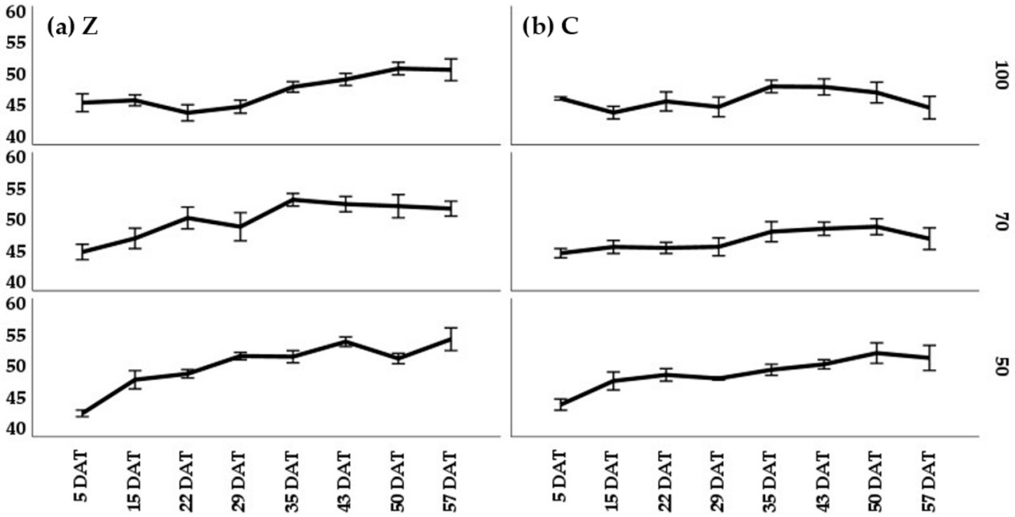

Figure 7. Temporal trend (days after transplant, DAT) of SPAD index in (**a**) Z and (**b**) C treatments; mean values (n = 4) and standard error are reported.

3.3. Principal Component Analysis

To achieve a complete evaluation of the zeolite soil content and watering regimes' effects on some morphological and quantitative traits of sweet pepper, a principal component analysis (PCA) was carried out. By employing PCA, nine original variables were reduced to two principal components, representing 90.31% of the total variability. In particular, the first component (PC 1) explained 71.48% of the total variability, and the second one (PC 2) accounted for the remaining 18.83%. PC 1 was highly and positively correlated with the leaf area, the leaf number, the plant dry weigh, the leaf water potential, the plant fresh weight, the plant height, and the dry matter content. In fact, in the loading plot (Figure 8), these variables were placed far from the origin of PC 1, close together and, therefore, positively correlated. Inversely, PC 1 was characterized by a negative relationship with the SPAD index. On the other hand, PC 2 was positively correlated with the iWUE and the dry matter content (Figure 8).

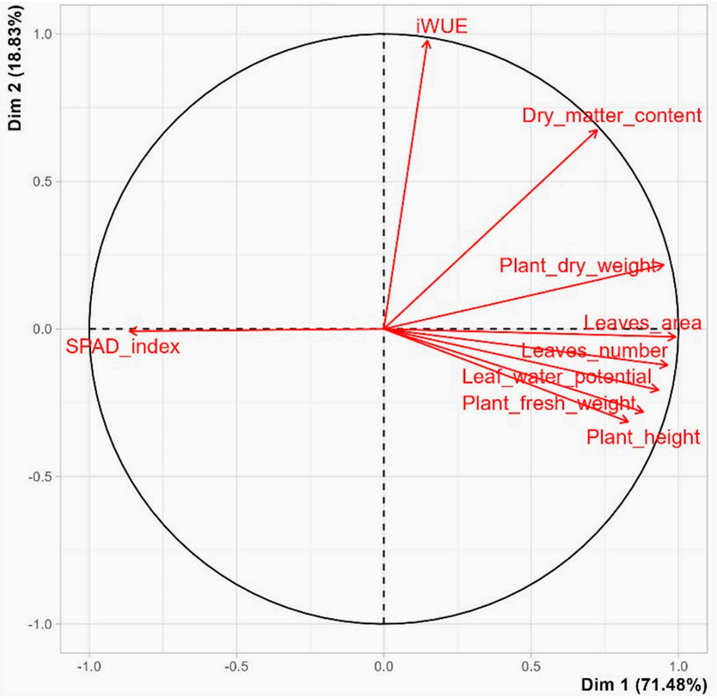

Figure 8. Loading plot of variables in the two-dimensional space (Dim 1 = PC 1 and Dim 2 = PC 2).

The correlation between variables is clearly illustrated in the correlation matrix (Figure 9). The matrix highlights the positive correlations between all variables except for the SPAD index and, less markedly, for the iWUE.

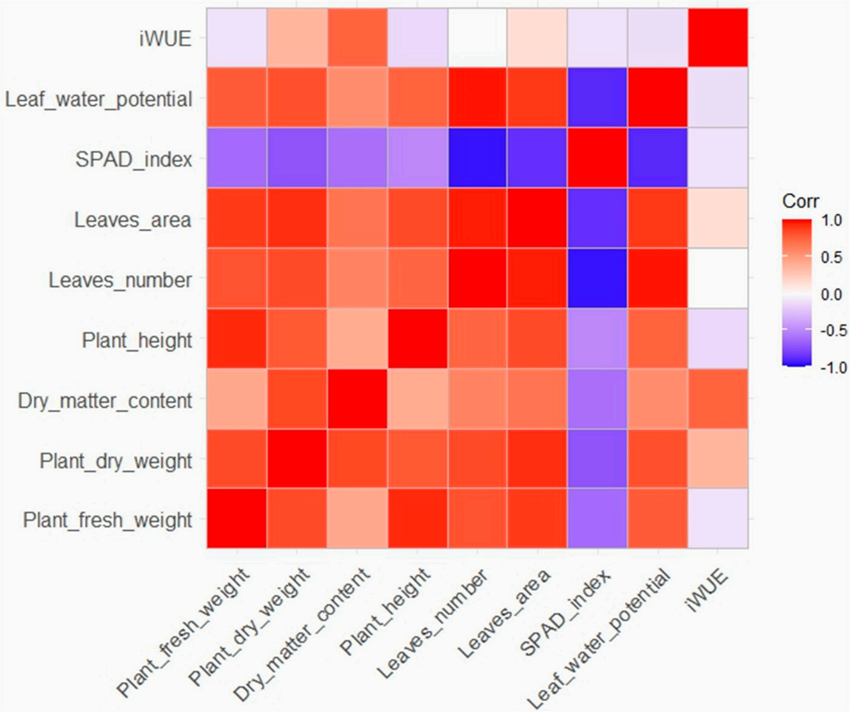

Figure 9. Heat map results of variables (plant fresh weight, plant dry weight, dry matter content, plant height, leaf number, leaf area, SPAD index, leaf water potential, and iWUE).

The score plot (Figure 10) highlights the good separation between treatments. In particular, the Z100, C100, and C70 treatments, plotted on the positive side of PC 1, were found to be more efficient for the investigated sweet pepper's morphological and physiological traits. In contrast, the Z70, Z50, and C50 treatments, located on the negative side of PC 1, were found to be less efficient regarding the investigated traits. This was also confirmed by the biplot of the loadings and scores, in which all the loadings but the SPAD index were near the more efficient treatments (Figure 11).

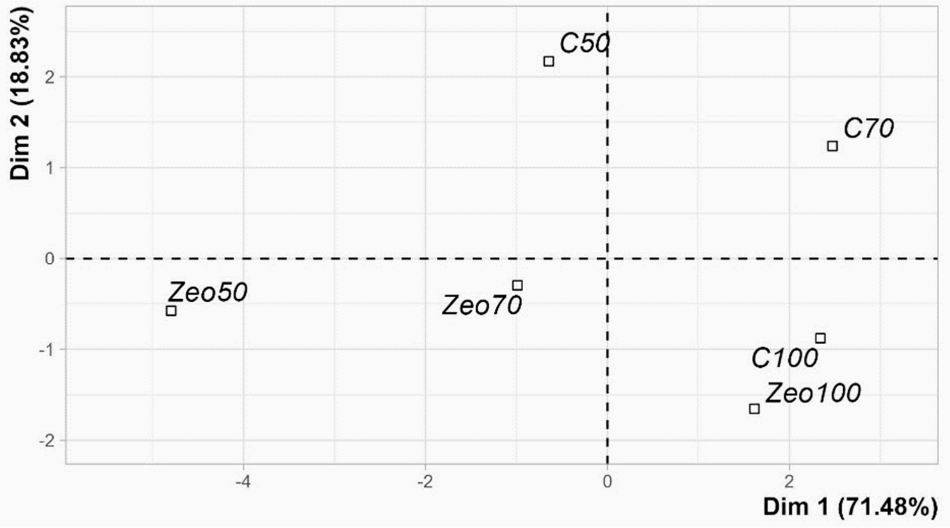

Figure 10. Score plot of the treatments in the two-dimensional space.

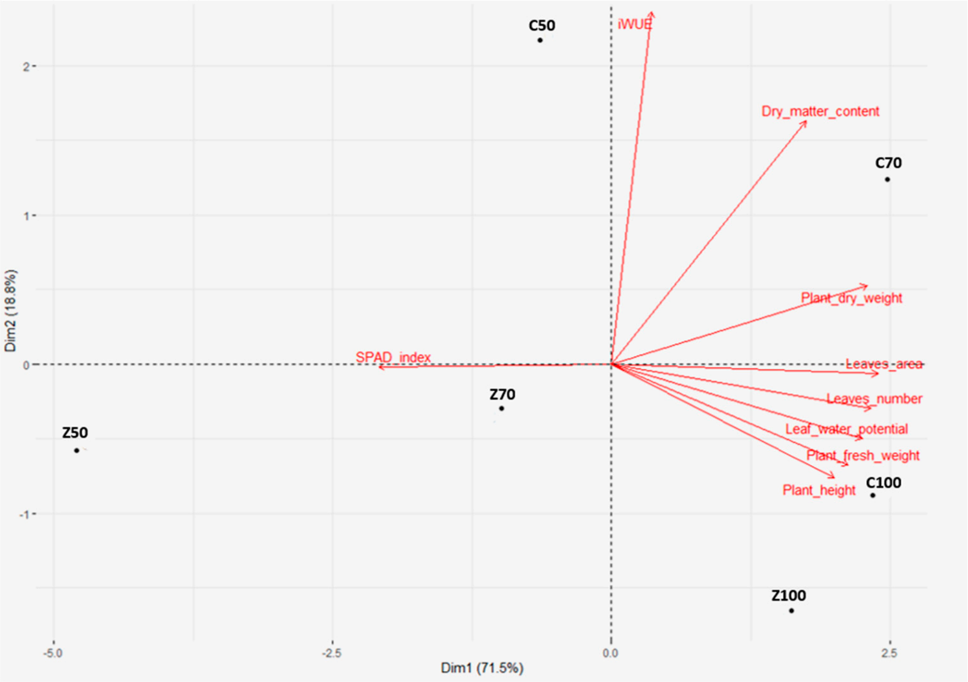

Figure 11. Biplot of loadings and scores in the two-dimensional space.

4. Discussion

There are numerous advantages arising from the use of zeolites in agriculture [2], and one of these is closely linked to the ability of this material to retain a large amount of water. This aspect plays an important role during periods of water scarcity, in areas where water availability is limited or water losses are substantial [33]. In this experiment, we observed the capacity of a zeolite added to a sandy loam soil to widen the range of available water in the soil and to retain water, although at more negative matric potential values, due to narrower pores [10], compared to the conditions of the soil without the zeolite (Table 2, Figures 3 and 4). The soil water content values during the trial showed that when sub-optimal irrigation water is applied (Z70 and Z50 treatments) on sandy loam soil added with 2% zeolite, water is available for sweet pepper crops but at lower matric potential (Figure 4). These results are in agreement with Al Busaidi et al. (2008) and Ippolito et al. (2011) [34,35]. On sandy loam soil, 2% zeolite addition also improves the air capacity from 29.1 to 33.3% (Table 2), creating better soil habitability and aeration for the growth of the plant's root systems. However, this improvement is not enough. The mentioned aspects highlight the complex effects that zeolite addition can cause in a soil. These are both in relation to its texture [9,36] as well as to deficit irrigation management with respect to some sweet pepper traits, such as the leaf number, leaf area, and dry weight. These results regarding water retention in soil are consistent with other studies [34,37–39]. Further authors have underlined that the high water absorption by zeolites causes damage to crops as dry zeolites block the water in their structure [6]. Crop growth is negatively correlated with the zeolite amount added to the soil because of a reduction in the drainage capacity and a shift in the water availability range towards higher soil humidity values [9].

However, in the literature, there is not information about the combined effect of adding zeolites to the soil and deficit irrigation management on sweet pepper. In our experiment, sweet pepper growth with a deficit irrigation strategy (Z70 treatment, Table 3 and Figure 4) allowed for savings in water, as expected. No benefits regarding the iWUE arising from the application of deficit irrigation in the treatments with the zeolite were observed (Figure 5b). However, it is worth underlining that the sweet pepper crop is not very suitable for deficit irrigation, as it has a yield response to water (Ky) greater than 1.0 (Ky = 1.1 [40,41]), and the use of this irrigation strategy may be inefficient as reductions in yield and fruit quality may occur [24,25,42,43]. Hence, the use of zeolites as soil conditioners, in combination with the deficit irrigation strategy, could mitigate the poor applicability of deficit irrigation in sweet pepper. In our research, the greater quantity of available water that the zeolite allowed to be retained in the soil did not translate into an advantage, because this water was retained by the narrower pores with more negative matric potential values. This means that the sweet pepper subjected to sub-optimal irrigation, in order to limit the water loss, reduces the leaf transpiration surface, having a lower leaf number, leaf area, and plant dry weight (Table 3, Figure 6). Moreover, the crop needs to allocate more resources for water uptake. The greater effort in water uptake is also confirmed by the more negative leaf water potential and higher SPAD index values observed in the Z treatments (Table 3, Figure 7). The PCA analysis briefly confirmed what has been reported above: the Z100, C100, and C70 treatments were found to be more efficient for the sweet pepper's morphological and physiological traits (Figure 10). The results presented here indicate that, in sweet pepper, the combined use of a zeolite and deficit irrigation is not an effective strategy. These results disagree with other studies showing that zeolites and deficit irrigation increase the yield, even if on other crops [18]. This is due to the particular response of the sweet pepper to deficit irrigation and to the soil texture used in this experiment. In other words, the results of this research suggest that the soil structural benefits resulting from zeolite application are not followed by an equally positive effect in terms of sweet pepper growth under deficit irrigation conditions. However, according to other authors [18], the combination of zeolites and deficit irrigation management may be an innovative and effective strategy to improve water storage and increase yields in other soil texture conditions, where the positive effect of adding zeolites to the soil becomes prevalent and therefore effective.

5. Conclusions

Recently, there has been great interest in using zeolites in agriculture due to the innumerable controversial effects of this soil conditioner on all the aspects that contribute to obtaining crop yields. Furthermore, as far as the deficit irrigation technique is concerned, although it has been known and studied for some years, it still needs to be used since it is a valid methodology to save water. Combining zeolites and deficit irrigation management may be an innovative and effective strategy to improve water storage and increase crop yields, in soils where the positive effect of adding zeolites becomes prevalent and effective. In our experiment, the ability of the zeolite added to a sandy loam soil to retain water and then to widen the range of available water was observed. Sweet pepper subjected to sub-optimal irrigation reduces the water use surface and this, consequently, reduces crop growth. These results suggest that the soil structural benefits resulting from the studied zeolite's application have a positive effect but do not follow it in terms of sweet pepper growth under deficit irrigation conditions. Further research could clarify the possibility of combining zeolites and deficit irrigation in different soil texture conditions to improve the yield and quality of crops.

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