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Responses of hybrid bell pepper in the open field with the use of hydrogel and different water regimes

Respostas de pimentão híbrido em campo aberto com o uso de hidrogel e diferentes regimes hídricos

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Efficient water management in water scarcity is essential when irrigating cultivated plants, especially in regions of recurrent drought. This study aimed to evaluate the responses to the application of hydrogel doses and the use of different water regimes in terms of the productivity and water efficiency of bell pepper plants grown in the open field. An experiment was conducted with hybrid bell pepper in subdivided plots, with irrigation levels (50, 75, 100, and 125% of ETc) as the plots and hydrogel doses (0.0, 0.6, 1.2, and 2.4 g pl^{-1}) in the subplots, with four replications. The variables analyzed were fruit yield, water use efficiency, and physiological variables (stomatal conductance and leaf water potential). The doses of hydrogel increased fruit yield and stomatal conductance. The use of hydrogel in bell pepper cultivation ensures stability of physiological variables at 70 days after transplanting, and the dose of 2.4 g pl^{-1} of hydrogel provides greater productivity of bell pepper grown in sandy loam soil. Finally, hydrogel favors the productive performance of hybrid bell pepper with a cumulative irrigation of 683.1 mm in the open field.
Key words: water resources, irrigation management, olericulture.

O manejo eficiente da água em época de escassez hídrica é fundamental na irrigação das plantas cultivadas, especialmente em regiões de seca recorrente. Este estudo teve como objetivo avaliar as respostas à aplicação de doses de hidrogel e a utilização de diferentes regimes hídricos sobre a produtividade e a eficiência hídrica de plantas de pimentão cultivadas em campo aberto. Um experimento foi conduzido com pimentão híbrido em parcela subdividida, os níveis de irrigação (50; 75; 100 e 125% da ETc) como parcelas e nas subparcelas, as doses de hidrogel (0,0; 0,6; 1,2 e 2,4 g pl^{-1}), com quatro repetições. As variáveis analisadas foram produtividade de frutos, eficiência do uso da água e fisiológicas (condutância estomática e potencial hídrico foliar). As doses de hidrogel incrementaram a produtividade de frutos de pimentão e a condutância estomática. O uso de hidrogel no cultivo de pimentão garante estabilidade das variáveis fisiológicas aos 70 dias após o transplantio e a dose de 2,4 g pl^{-1} do hidrogel proporciona maior produtividade do pimentão cultivado em solo franco arenoso. Por fim, o uso de hidrogel favorece o desempenho produtivo de pimentão híbrido com irrigação cumulada de 683,1 mm em campo aberto.
Palavras-chaves: recursos hídricos, manejo de irrigação, olericultura.

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1. INTRODUCTION

Bell pepper (*Capsicum annuum* L.) can be grown throughout the year, preferably with short-cycle cultivars, to reduce costs and water consumption in agriculture. In this sense, irrigation management is essential for the production of this species in semi-arid regions, as it is one of the most sensitive vegetables to water stress [1]. Drip irrigation associated with use of hydrogels in agriculture [2] could boost the efficient use of water in crops in general, especially in the open field, where crops are exposed to constant climatic variations.

Efficient irrigation management can be improved as an alternative that can reduce the amount of water and/or frequency of the irrigation, such as the use of hydrogels so that vegetable growers can increase their profits from the crop. In this sense, according to Souza et al. (2019) [3], the challenge is even greater: to increase the yield of cultivated plants without reducing or at least maintaining their water demands. However, it is important to know the crop's water demand for the different growth stages and even their yields [4].

Plants grown in an open field have smaller and slower growth, with an increase in the time between the different phenological stages and an intense rate of evapotranspiration, as well as other factors when compared to those grown in a protected environment. For this reason, yields in the open field are two to three times lower than those obtained in a protected environment [5]. In field cultivation, the crop is exposed to environmental variations at all times [6].

In the Northeast of Brazil, during the dry season, there is a possibility of very high temperatures, making it difficult to grow bell pepper under glass, causing flower abortion among other problems, which can be overcome by growing them in the open using hydrogel as a way of the improving productivity.

Regarding the effects of hydrogel doses, [7] obtained an increase of up to 69% in the maximum capacity of water absorbed in the hydrogel/soil mixture as the doses of the product increased. [8], evaluating the influence of hydrogel on water retention in two soils of different textures (sandy loam and clay loam), observed that the hydrogel dose of 2.0 g kg^{-1} of soil increased moisture by 40% and 35% for the respective textures, compared to the treatment without hydrogel, and also increased total water availability by 125% for the sandy loam soil and 135% for the clay loam soil. However, there is still a lack of scientific information on the use and effects of hydrogel on the growth and development of vegetables about different water regimes and the soil's physical and water processes.

Controlled water deficit as a reduction in water supply to improve water use efficiency without affecting plant development and productivity is currently a much-discussed subject [9], but it still needs to be improved.

Technical knowledge about the water needs of plants grown in the open field, combined with a better understanding of how environmental conditions affect agrosystems, is important for expanding the possibilities of professional irrigation management [10]. Alternatively, deficit irrigation presents itself as a challenge to meet the physiological requirements of crop plants [11] and at the same time guarantee productive potential.

The use of irrigation water must be as efficient as possible, since this resource is becoming increasingly scarce in terms of quantity and quality. In addition, factors such as the irregularity of rainfall that occurs in the semi-arid region also need to be taken into account in the agronomic sphere, when it comes to the search for savings and use of water in agriculture [12].

Therefore, this research aimed to evaluate the responses to the application of doses of hydrogel and the use of different water regimes on the productivity and water efficiency of bell pepper plants grown in the open field.

2. MATERIAL AND METHODS

2.1 Experiment area

The experiment was carried out from September to December 2022 in the open field in an area of Neossolo Quartzarênico (Quartzipsamments) belonging to the Instituto Agropolos do Ceará, in the municipality of São Benedito, Ceará, Brazil, (4º 02' 56" S; 40º 51' 54" W and at 903 m). The climate is mild semi-arid hot tropical, classified as BSh according to Alvares et al. (2014) [13], with an average temperature ranging from 22 to 29 ºC and an average annual rainfall of 941.2 mm from January to May [14].

2.2 Soil preparation and irrigation system

The soil in the area was collected at a depth of 0.2 m for chemical and physical characterization before the experiment was set up (Table 1). The methodology for the chemical and physical analyses was suggested by Embrapa (2017) [15], to help manage the fertilization and liming of the hybrid bell pepper *cv*. Dahra RX. The spacing adopted for growing bell pepper was 0.8 m between rows and 0.5 m between plants.

Table 1: Chemical and physical characterization of the soil in the study area.

Depth m	**C** g kg^{-1}	**O.M** g kg^{-1}	**P** mg dm^{-3}	**K** cmol$_c$ dm^{-3}	**Ca** cmol$_c$ dm^{-3}	**Mg** cmol$_c$ dm^{-3}	**pH**	**EC** dS m^{-1}
0 – 0.2	0,57	0,99	3,9	0,25	3,9	1,65	6,6	0,74
	Sand g kg^{-1}	**Silt** g kg^{-1}	**Clay** g kg^{-1}	**Textural Classification**		**SD** g cm^{-3}	**TP** %	**PD** g cm^{-3}
0 – 0.2	741,3	142,5	116,2	Sandy loam		1,25	51	2,55

SD – Soil density; PD – Particle density and TP – Total soil porosity.

The irrigation system adopted was drip irrigation, using polyethylene lines with a diameter of 16 mm, with emitters spaced 0.50 m apart according to the spacing between bell pepper plants, with an actual flow rate of 2.1 L h^{-1} at each plant and a service pressure of 5.0 mca. When evaluating the system application efficiency, it showed a Christiansen uniformity coefficient (CUC) of 91.2%. The irrigation system was equipped with a water tank with a volumetric capacity of 1,000 L with a float-controlled level, a bypass line, manual valves, lateral lines, and a 0.75 CV motor pump. The water used came from a tube well.

The calculation of the plants water consumption was based on the crops daily evapotranspiration (ETc), based on the reference evapotranspiration (ETo), obtained using the "A" Class Tank method, which was installed at the experiment site. The data were collected daily at 9:00 am and then entered into spreadsheets to estimate the ETc. ETo was multiplied by the bell pepper crop coefficient (kc) values proposed by Doorenbos and Kassam (1994) [4], which were 0.4; 0.7; 1.05, and 0.85 for phases I, II, III, and IV, respectively. The water regimes (irrigation levels) were applied according to each treatment.

2.3 Experimental design

The experiment was conducted in subdivided plots with four water regimes: 50, 75, 100, and 125% of ETc (plots) and four doses of polymer in the form of hydrogel: 0.0, 0.60, 1.20, and 2.40 g pl^{-1} (subplots), with four replications and three useful plants per experimental unit, totaling 192 plants.

The different irrigation levels (water regimes in the plot) were applied daily from 25 days after transplanting (DAT). The doses of hydrogel based on acrylamide and potassium acrylate were applied to the hole after hydrating for around 10 minutes until they had fully expanded and then incorporated into the soil around the root of the plant, also at 25 DAT, taking care to leave five to eight centimeters below the surface of the soil in the hole so that there was no loss of hydrogel due to leakage when the polymer expanded.

2.4 Analyzed variables

To check the effects of the water regimes and the polymer in the form of a hydrogel on the bell pepper plant, soil moisture was assessed before irrigation in the layer where the hydrogel was inserted (0.0 – 0.15 m) at 65, 73, 80, and 94 DAT. Gas exchange was carried out during the period of greatest water demand by the bell pepper plant (70 DAT), when flowering and fruit formation were taking place. This analysis was carried out between 9:00 and 11:00 am on fully expanded leaves of each plant, using portable infrared gas analysis equipment (IRGA – Infrared Gas Analyzer) model LCpro-SD (ADC BioScientific Ltda.), whose readings were taken on the third or fourth leaf from the apex of the bell pepper plant, before irrigation.

The plant's leaf water potential (Ψw) was determined in the morning (between 4:30 and 5:30 am), also at 70 DAT, using a Scholander pressure pump, Soil-Moisture model 3005 [16]. For this operation, a fully expanded leaf with good plant health was selected and detached from the upper third of each plant, corresponding to each treatment. Pressure was applied until exudation was observed in the cut made in the leaf's petiole.

At 110 DAT, fruit yield (PROD) was assessed and irrigation water use efficiency (WUE) was estimated expressed in kg m^{-3} of water, calculated for all treatments using the ratio between total fruit production on each plant and the accumulated water table in the cycle (unit of water consumed), according to Silva et al. (2010) [17] and Santos et al. (2014) [18].

2.5 Data analysis

The data were subjected to the Shapiro-Wilk test for normality, the F test in the analysis of variance (ANOVA), all at 5% probability, and also to regression analysis for the irrigation levels and the doses of the hydrogel, using SISVAR 5.6 software [19]. In addition, the variables were subjected to principal component analysis (PCA) using the PAST 4.03 software to examine the correlations between treatments and whether there is biological sense, according to Johnson and Wichern (1992) [20].

3. RESULTS AND DISCUSSION

3.1 Soil moisture and plant productivity

The soil moisture for the water regimes and hydrogel doses are shown in an accumulative graph (Figure 1). The data shows a variation in humidity as a function of the treatments (irrigation and hydrogel). The highest water regime (125% of ETc = 683.1 mm) alone differed significantly from the lowest water regime applied (50% of ETc = 273.6 mm), whose humidity increased over the course of the bell pepper cycle (Figure 2A) as the same water regimes occurred for the hydrogel (Figure 1B). It was observed that the lowest water regime (273.6 mm) kept the soil water in a range of 29.4 to 34.8%, possibly associated with hydrogel. The highest water regime (683.1 mm) reached 37.7% moisture, which can be explained by the daily irrigation of the bell pepper based on the crop daily evapotranspiration.

The effects of the water regimes and the hydrogel were similar, as is evident from the coincident increases in the histogram (Figure 1), suggesting that the irrigation events associated with the hydrogel treatments were similar for the water content in the sandy loam soil at the 0.0 – 0.15 m depth. It was observed that for the different treatments, soil moisture varied from 29.8% (control dose) to 39% for 2.4 g of hydrogel per plant (Figure 1B), differing statistically by the Tukey test, and there was also a gradual increase in soil moisture as the doses of hydrogel increased. Similar results were reported by Oliveira et al. (2004) [8], who observed that a hydrogel dose of 2.0 g kg^{-1} of soil increased moisture by 40% (sandy loam) and 35% (clay loam). This may be related to the fact that the hydrogel helps to keep water in the soil for longer, consequently increasing the plant's tolerance to drought [21], especially in regions with reduced water availability, such as semi-arid regions.

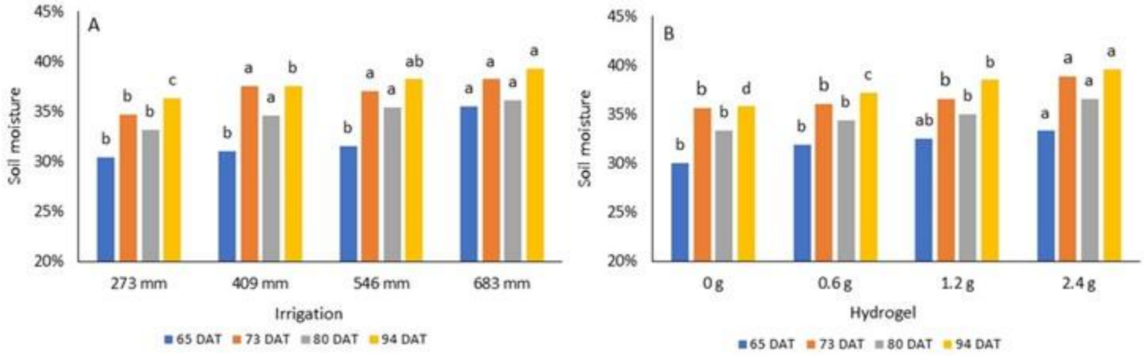

Figure 1: Cumulative histogram of sandy loam soil moisture for the water regimes and hydrogel for the four readings at a depth of 0 – 0.15 m: A) water regimes B) hydrogel treatments in bell pepper cultivation. Equal letters do not differ by Tukey test at 5% significance.

The humidities observed for the hydrogel treatments also resulted in high values but without negatively affecting the development of Dahra RX bell pepper. This behavior can also be explained by the presence of 14.15% silt and 11.62% clay, as well as 51% pores in this soil (Table 1), which may have favored water retention associated with the presence of hydrogel, since according to Schattman et al. (2023) [22], the physical characteristics of the soil affect soil-water-plant relations. In this case, the behavior observed here, using hydrogel associated with this soil texture, can prevent water loss and increase irrigation efficiency, promoting water savings. Therefore, this practice of using superabsorbent hydrogel benefits plants with greater water storage.

It can be seen that the hydrogel guarantees an increase in the maintenance of the water content in the soil, consequently improving the availability of water to the plants, which is reflected in the improvement in the productivity of bell pepper. According to Navroski et al. (2016) [23], the hydrogel added to the soil allows for greater real water capacity in the system, and Beniwal et al. (2010) [24] add that soil treated with hydrogel can mitigate the effects of some stress on plants.

Similar results were reported by Akhter et al. (2011) [25], who concluded that the hydrogel increased the soil's ability to retain water, which helped plant growth. In addition, the phenomenon of constant hydration of the hydrogel in the soil by daily irrigation may also justify the gradual increase in soil water content above field capacity. According to Albalasmeh et al. (2022) [21], hydrogel concentrations largely affect and increase the amount of water retained in sandy-textured soil. Therefore, the application of hydrogel could reduce irrigation times and help crops resist drought and rainfall irregularities in semi-arid regions [26]. In this way, reducing water consumption in agriculture and ensuring the sustainability of water resources in the semi-arid region.

Thus, hydrogel presents itself as a potential for use in areas where irrigation is limited, and it is therefore essential to store more available water for plant establishment [27]. Because hydrogel absorbs and stores water hundreds of times its weight, 400 to 1600 g of water per dry gram of hydrogel [28]. Finally, the use of 2.4 g pl^{-1} of hydrogel in sandy loam soil associated with daily irrigation without the occurrence of deep-water percolation in the 0 – 0.15 m layer is justified.

The isolated effect of the doses of hydrogel on bell pepper yield resulted in a linear increase of 6.8 t ha^{-1} for each increase in the dose of hydrogel applied, an increase of 28.4% compared to the control dose, reaching a maximum yield of 77.4 t ha^{-1} (Figure 2). However, there was no significant effect of irrigation on this variable, possibly because the hydrogel canceled out the effect of water regimes on productivity, and there was no significant interaction ($p \geq 0.05$) between the factors. This may also be associated with an increase in the number of fruits as a result of the hydrogel. This finding indicates that the use of hydrogel can help to increase the productivity of the bell pepper crop under conditions of deficit irrigation. These results were higher than those found by Sezen et al. (2011) [29], as these authors observed higher bell pepper yields with 100% irrigation (47.8 t ha^{-1}), while those with 50 and 75% irrigation showed 36 and 47.2 t ha^{-1}, respectively. It is clear that the dose of 2.4 g pl^{-1} has an effect on the availability of water to the plant in the growth phase and guarantees a good yield in bell pepper.

Ahmed and Fahmy (2019) [30], when studying the application of hydrogel to overcome water scarcity on the yield and quality of tomato fruits, observed that an increase in yield was recorded when hydrogel was applied under full irrigation (100% of field capacity), whose increase reached 13.7; 14.7 and 20.5% compared to the absence of hydrogel and 2.2; 3.8 and 5.4% under scarce irrigation (75% of field capacity) compared to the control without hydrogel (100% of field capacity).

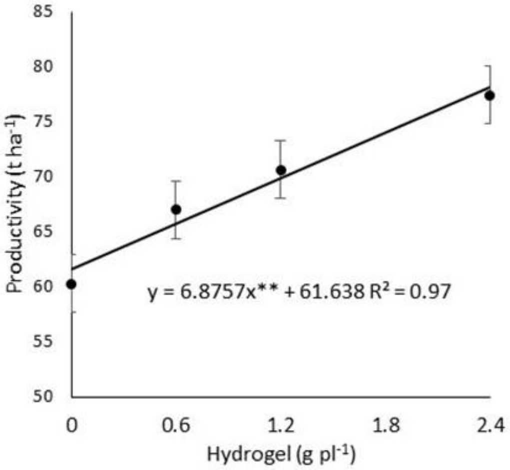

*Figure 2: Productivity of bell pepper at 110 DAT subjected to different doses of hydrogel in the open field. **, significant at the 1% probability level using the t-test, respectively.*

When studying the productivity of Carliston bell pepper under different irrigation levels, Kara and Yildirim (2015) [31] found maximum yields of 21.57 t ha^{-1}, for irrigation corresponding to 80% of ETc. On the other hand, Padrón et al. (2015) [32], reported maximum yields of 34.2 t ha^{-1} with approximately 70% of ETc in the open field. These results differ from those found in this research due to the genetic characteristics of each material, as well as the management conditions in each experiment, such as the use of hydrogel associated with irrigation, which could improve the availability of water and its efficient use in the cultivation of Dahra RX hybrid bell pepper, thus increasing the productivity of this crop under hydrogel (Figure 2). The use of information related to productivity is important for strategic water management and irrigation planning, associated with the use of a soil conditioner such as a polymer in the form of a hydrogel, which has a real capacity to help increase total crop productivity.

The productivity results found in this study are higher than those found by local producers. This is due to the efficient use of irrigation water, coupled with the efficient application of mineralized fertilizers supplied at the appropriate dosage and time, as well as the plant management treatments, which consequently improved the productivity of the bell pepper (Figure 2). In addition, this process may have been influenced by the greater water retention in the soil with the presence of the hydrogel (Figure 2), as Navroski et al. (2016) [23] reported that there was an improvement in the chemical characteristics of the substrate with the addition of hydrogel, as well as the availability of nutrients to the seedlings of forest species. In short, the hydrogel seems to have fulfilled this function. According to Padrón et al. (2015) [32], a uniform supply of water in the soil during growth is necessary to ensure uniformity in fruit size and to improve production.

3.2 Stomatal conductance, leaf water potential and water use efficiency

Water deficiency in cultivated plants directly influences both growth and physiological characteristics, such as decreasing photosynthetic rate (A) and stomatal conductance (gs) according to Ramos et al. (2021) [33]. Gao et al. (2020) [34], add that water deficit alters morphophysiological and biochemical factors, but in the present study, in general, it was not possible to notice these morphological and/or physiological changes in plants subjected to deficit irrigation associated with hydrogel. For example, gas exchange measured at 70 DAT using IRGA was not significantly influenced ($p \geq 0.05$), except for stomatal conductance (gs), which was influenced by the hydrogel alone.

This finding reflects the absence of water deficit during the reading (irrigation corresponding to 50% of ETc) in the bell pepper plants during their cycle. In other words, it is possible that the doses of hydrogel had a positive effect on deficit irrigation (50% and 75% of ETc), allowing water to be made available to the plants since they did not interfere with the bell pepper photosynthetic apparatus and, consequently, did not reduce its physiological characteristics, including photosynthetic rate, as well as morphological variables and total productivity, a fact that may also be associated with daily irrigation, which favors constant hydration of the hydrogel to store and make water available in the soil.

According to Taiz et al. (2017) [35], reducing water loss through transpiration is essential for the plant to remain hydrated and for leaf thermal control. According to Dutra et al. (2015) [36], reduced stomatal conductance and lower transpiration result in less water loss, favoring greater plant tolerance to stress. Thus, it was observed that transpiration measured at 70 DAT (flowering and fruit formation period) did not differ statistically ($p \geq 0.05$) between treatments with water regimes or with hydrogel, possibly because the use of hydrogel together with daily water replacement, even with a deficit, allowed the bell pepper plants to transpirate normally at this vegetative stage, on the day the reading was taken at 70 days after transplanting and 45 days after treatment.

Stomatal opening increased as the dose of hydrogel was increased, with a dose of 2.4 g pl^{-1} providing greater stomatal opening (0.281 mol of H_2O m^{-2} s^{-1}) with a 30% increase compared to the control dose (Figure 3). It is known that the opening and closing of the stomata control the entry and exit of CO_2 and H_2O in the leaves and that these processes can be measured by reading the stomatal conductance (*gs*) in the plants, thus justifying the expressiveness of the morphological results of the bell pepper evaluated in this research, especially at the dose of 2.4 g of hydrogel per plant, as well as the improvement in water use efficiency at the lower irrigation levels, allowing the plant to carry out its physiological processes correctly since the plant's stomatal movement is related to the availability of water. Under water deficit, plants close their stomata in response to the lack of water to reduce transpiration and avoid losing water to the atmosphere [37], which is probably why there was no statistically significant difference between transpiration and the different water regimes tested in this study.

These findings are innovative and reinforce the direct relationship between the availability of water in the soil and the stomatal behavior of the bell pepper plant, showing that hydrogel can be a strategic ally in mitigating the effects of water deficit in semi-arid regions. These results were not addressed by Pereira et al. (2019) [10], Albalasmeh et al. (2020) [21], Gao et al. (2020) [26], Suresh et al. (2018) [28] and Kara and Yildirim (2015) [31].

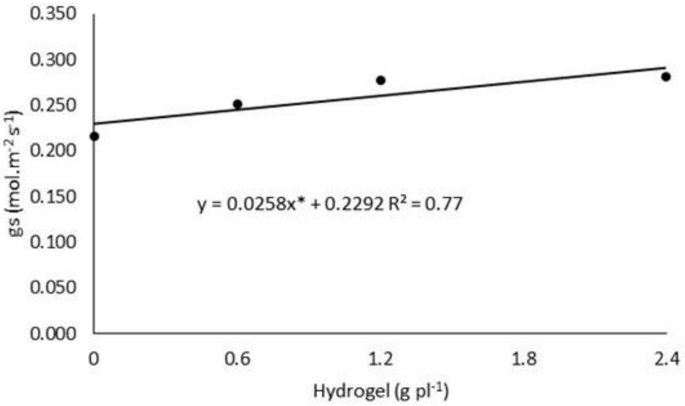

*Figure 3: Stomatal conductance (gs) at 70 DAT in leaves of bell pepper plants in the open field subjected to doses of hydrogel. *, significant at the 5% probability level using the t-test.*

Water deficit causes several negative effects on sensitive plants, including a decrease in leaf water potential (Ψw), but these effects on bell pepper plants were almost imperceptible or practically stable at 70 DAT, as there was a decrease reaching only -0.0064 MPa in a downward trend with irrigation levels (273.2 mm) and the absence of hydrogel doses (Figure 4). From this simultaneous interaction between irrigation levels and doses of hydrogel, it was observed that the water potential in the bell pepper leaf showed an upward trend as irrigation levels increased until it reached 571.7 mm at up to 2.4 g of hydrogel per plant, with a maximum value of -0.0042 MPa. This behavior justifies the maximum value of stomatal conductance observed at the dose of 2.4 g pl^{-1} (Figure 3), indicating that there is a high leaf water content (turgidity) in the bell pepper leaf, and therefore no water deficit in the plant despite daily deficit irrigation, showing that the use of hydrogel did improve the transport of water from the roots to the aerial part of the Dahra RX bell pepper.

According to Taiz and Zeiger (2013) [38], this allowed the plant to synthesize and accumulate solutes to be used at times of low water availability to reduce the water potential and maintain cell hydration. It is interesting to note that the water potential as a function of irrigation levels followed the same behavior as stomatal conductance, since according to Atteya (2003) [39], a reduction in conductance is associated with a decline in water potential. This will logically result in a lower transpiration rate for the plant.

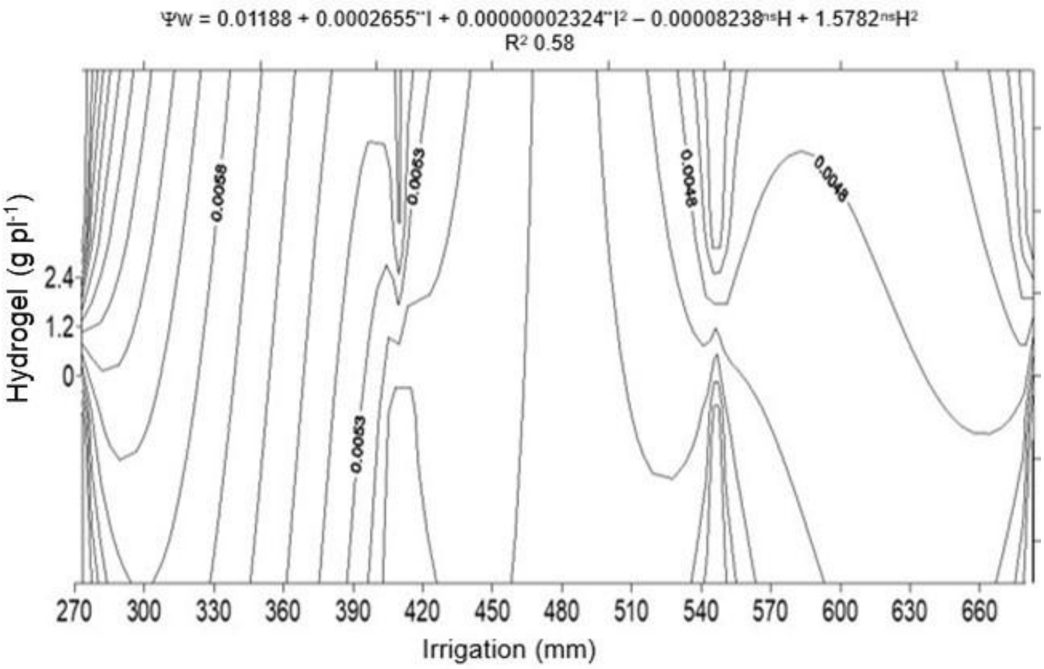

Figure 4: Effect of the interaction between irrigation rates and hydrogel doses on leaf water potential (Ψw) at 70 DAT in bell pepper plants in the open field.

Water use efficiency (WUE) was significantly influenced ($p < 0.01$) by the water regime alone, with an overall production average of 5.82 kg m^{-3} of water. The increase in the water applied over the 110-day cycle led to a 58.4% reduction in the efficient use of water until it reached 3.65 kg m^{-3} at the 683.1 mm irrigation level, corresponding to 125% of ETc (Figure 5). On the other hand, the highest WUE value was 8.79 kg m^{-3} of water for 273.2 mm at 50% of the evapotranspiration water, i.e. water use efficiency was improved in the conditions of deficit irrigation on the bell pepper plants. This signifies a satisfactory response by the Dahra RX hybrid bell pepper to the conditions of low water availability tested here, indicating that the plant efficiently used the water received to promote phytomass production and good total productivity. The reduction in WUE with increasing irrigation levels is possibly due to water loss due to the low storage capacity in the root zone or nutrient leaching in this sandy loam soil caused by excess water during irrigation daily [40].

From the view of water management, Marouelli and Silva (2012) [41] stated that the water demand of bell pepper is around 450 to 650 mm, depending on the management system, the cycle, and the irrigation system adopted. Furthermore, for a drip irrigation system with water application of less than 546.45 mm (100% of ETc) associated with the use of hydrogel (2.4 g pl^{-1}) for open field conditions, it can be concluded that there is an efficient use of water, resulting in water savings in the bell pepper crop for a 110-day cycle. This finding reinforces the use of hydrogel in sandy loam soils in the semi-arid region to improve WUE in the bell pepper crop, as was found in tomato cultivation under water scarcity by Ahmed and Fahmy (2019) [30].

Considering that the bell pepper was grown in open fields during the dry season, according to Waraich et al. (2011) [42], it is very important to improve the efficiency of water use in agriculture, which is an important technique for alleviating water scarcity. Therefore, given that the highest yield (77.4 t ha^{-1}) was observed with the highest dose of hydrogel (2.4 g pl^{-1}). It is up to the grower to combine the use of a water-retaining polymer in the form of a hydrogel to improve water availability and savings, paying attention to the costs of water and hydrogel for the production of Dahra RX hybrid bell pepper under conditions of low water availability.

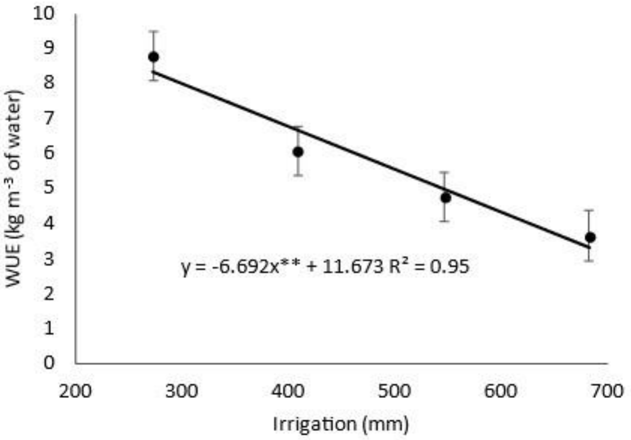

*Figure 5: Water use efficiency (WUE) as a function of different water regimes for growing peppers in the open field. ** significant at 1% probability level by t-test.*

Similar results were observed in Carliston bell pepper by Kara and Yildirim (2015) [31], whose WUE values were 6.0, 4.1, 3.6, 2.7, and 2.1 kg m^{-3} of water for water levels corresponding to 20, 50, 80, 100 and 120% of ETc, respectively. In this way, the results of this study confirm those found by Padrón et al. (2015) [32] when growing bell pepper under different water regimes. The authors also noted a reduction in water productivity with increasing irrigation levels. The findings here partially corroborate those found by Sezen et al. (2015) [29], who previously reported water productivity ranging from 6.9 to 5.7 kg m^{-3} of water for cumulative irrigation of 570.4 mm over the entire bell pepper crop cycle with an interval of 3.0 to 6.0 days.

Finally, considering the water requirement of bell pepper according to Marouelli and Silva (2012) [41] of up to 650 mm in the short cycle and up to 1,200 mm in the long cycle [41], therefore, the results found in this research by Sezen et al. (2015) [29], and Padrón et al. (2015) [32] show that water consumption in bell pepper production can be 681 mm for a 110-day cycle without drastically affecting productivity, especially when associated with hydrogel.

3.3 Principal component analysis for the responses of measured parameters in bell pepper under water regimes and hydrogel

The associations between the variables analyzed in Dahra RX bell pepper using principal component analysis are shown in Figure 6. Component 1 explains 52.4% and component 2 explains 28.2%, totaling 80.6% of the total variations in the parameters analyzed under water regimes and hydrogel doses.

Water use efficiency (WUE) differed from the higher irrigation levels, indicating a greater association with the deficit irrigation level (50% of ETc = 273.22 mm), thus showing that WUE is important for peppers under deficit irrigation conditions, confirming what has already been discussed in Figure 5. The fresh mass of the aerial part (MFPA), the number of fruits (NF), and the average weight of the bell pepper (PMF) are highly associated with irrigations of 100% (546.4 mm) and 125% (683.1 mm) of ETc, i.e. the production of phytomass depends on the water available in the soil. On the other hand, the physiological variables such as photosynthetic rate (*A*), transpiration (*E*), internal CO_2 concentration (*Ci*), and stomatal conductance (*gs*) are associated with the doses of 1.2 and 2.4 g pl^{-1}, which justifies the stability of these variables, such behavior possibly being related to the availability of water in the soil associated with these doses of hydrogel, i.e. the water-retaining polymer fulfills the function of retaining and making water available to the plants.

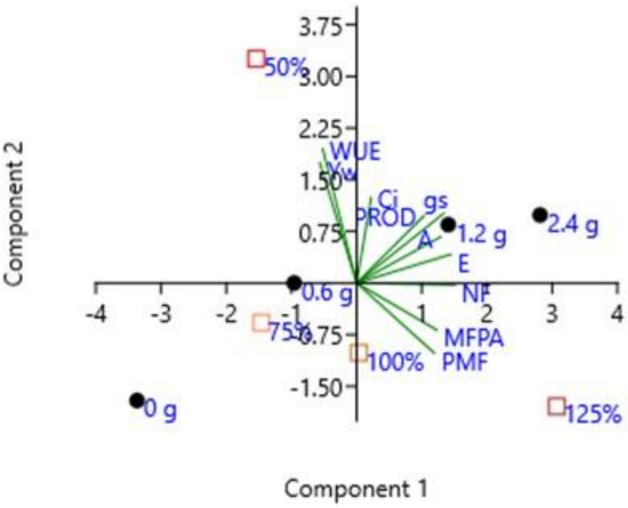

Figure 6: Scatter plot for the first two components of the different variables analyzed in peppers under water regimes and hydrogel doses. The variables number of fruits per plant (NF), average fruit weight (PMF), productivity (PROD), fresh mass part area (MFPA); water use efficiency (WUE), internal carbon (Ci), photosynthetic rate (A), transpiration (E), stomatal conductance (gs) and leaf water potential (Ψw).

It is worth noting that the control treatment (0.0 g of hydrogel), being isolated, shows no association between the measured variables, as does the 0.6 g pl^{-1} dose. The productivity of the bell pepper (PROD) was in the same quadrant as the physiological variables, so there may be an association depending on the WUE with the use of hydrogel, the doses of which were between 1.2 and 2.4 g pl^{-1}, as a way of maintaining the productivity of the bell pepper, as seen in Figure 3. Thus, corroborating the importance of alternatives such as the use of hydrogel to improve water saving in the cultivation of bell pepper *cv*. Dahra RX in sandy loam soil.

Therefore, the hydrogel shows relevant agronomic benefits under water deficit, retaining more water in sandy loam soil, promoting improvements in plant physiology and productivity in bell pepper cultivation, thus with the potential to be used in agriculture for better water management in the semi-arid region as a way of guaranteeing food security and sustainability in this region. According to Kumari et al. (2023) [43], hydrogels increase water retention capacity and also particle aggregation in sandy soils, however, there is a need to improve studies that report their effectiveness. However, there is still a lack of scientific information on the use and effects of hydrogels on the growth and development of other vegetables related to different water regimes and the physical water processes of soil with different textures [44].

4. CONCLUSIONS

The results showed that the use of hydrogel at up to 2.4 g pl^{-1} in the cultivation of Dahra RX bell pepper allows for an increase in fruit productivity in the open field, indicating an alternative for its use associated with deficit irrigation in regions with water restrictions for irrigation.

The hydrogel sustains the productive performance of bell pepper of 77.4 t ha^{-1} during 110 days under deficit irrigation in sandy loam soil with accumulated irrigation of 681.3 mm, improving the efficiency of irrigation water use in bell pepper in the open field.

Despite the benefits of using hydrogel in agriculture, the initial cost of the product may limit its adoption by small farmers. A detailed economic analysis is needed to associate the most efficient irrigation level with the technical dose of hydrogel.

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