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ORIGINAL ARTICLE

Water relations and physiology of maize in response to soil moisture levels and greenhouse fertilization systems[1]

Relações hídricas e fisiologia do milho em resposta aos níveis de umidade do solo e formas de adubação em ambiente protegido

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HIGHLIGHTS:

Fertigation ensures better intrinsic water use efficiency.
The fertilization system used affects maize physiology.
The water status of maize plants is influenced by the fertilization system.

ABSTRACT: The water status of crops is directly affected by soil water availability. As such, this study aimed to analyze water relations in maize (double-cross hybrid AG 1051) under different soil moisture contents (80, 90, 100, 110, and 120% of field capacity - FC) and fertilization systems (conventional and fertigation). The experiment was carried out in a greenhouse at the Agricultural Engineering Department of Universidade Federal Rural de Pernambuco, in the municipality of Recife, Pernambuco state, Brazil, from August to October 2019. The experimental design was randomized blocks with a 5 × 2 factorial scheme, four replicates and a total of forty experimental units. At soil moisture levels below 100% of field capacity (100% FC), fertigation increased the relative water content, leaf succulence, leaf water potential, and osmotic adjustment of maize plants. When compared to conventional fertilization, fertigation resulted in higher transpiration rates and better water use efficiency in crops irrigated at 95% of field capacity (95% FC). In plants submitted to soil moisture levels below 100% FC, the fertilization system influenced water, osmotic, and pressure potential, and osmotic adjustment occurred.

Key words: *Zea mays* L., water management, fertilization management, leaf gas exchange, leaf water potential

RESUMO: O status hídrico das plantas é diretamente influenciado pela umidade do solo. Objetivou-se avaliar as relações hídricas de plantas de milho, híbrido Duplo AG 1051, expostos a diferentes níveis de umidades do solo (80; 90; 100; 110 e 120% da umidade equivalente à capacidade de retenção de água no solo) e adubadas de duas maneiras (convencional e via fertirrigação). O experimento foi conduzido em ambiente protegido no Departamento de Engenharia Agrícola da Universidade Federal Rural de Pernambuco, município do Recife-PE, entre os meses de agosto a outubro de 2019. Utilizou-se o delineamento em blocos casualizados, em esquema fatorial 5 × 2, com quatro repetições e um total de quarenta unidades experimentais. Em plantas submetidas ao manejo de irrigação menores que 100% da capacidade de campo, a fertirrigação aumentou o conteúdo relativo de água, a suculência foliar, o potencial hídrico foliar e o ajuste osmótico, quando comparado com a adubação convencional. A fertirrigação resultou em maiores taxas de transpiração e eficiência do uso da água em plantas irrigadas a 95% da capacidade de campo. As estratégias de adubação influenciaram os potenciais hídrico, osmótico e de pressão, e no ajustamento osmótico ocorrido nas plantas sob estratégias de irrigação inferiores a 100% da capacidade de campo.

Palavras-chave: *Zea mays* L., manejo da água, manejo da adubação, trocas gasosas, potencial hídrico foliar

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Introduction

Maize is a cereal of global economic importance due to the nutritional value of its grains, used for human and animal consumption (Erenstein et al., 2022), and its application in ethanol production (Kocak et al., 2022). In Brazil, despite the recent increase in grain production and yield, investment in irrigated areas to improve water use efficiency remains important, especially in the dry season (Cavalcante et al., 2021). Another important factor for crop yield is fertilizer management, particularly soil nitrogen availability throughout the growth cycle (Correndo et al., 2021).

Many studies have investigated strategies to improve nitrogen use efficiency by plants (Pareja-Sánchez et al., 2020; Dimkpa et al., 2020; Mejías et al., 2021) and optimize N, P, and K levels in maize under irrigation (Zamora-Re et al., 2020). Research has also aimed at improving irrigation systems to reduce production costs and increase grain yield (Wang et al., 2021). However, studies (Li et al., 2007) that correlate fertilization and water management with maize water status remain scarce. In this respect, given the importance of optimizing fertigation and irrigation to increase yield and lower production costs, there is a need for studies that correlate fertigation strategies that optimize the N, P and K supply with yield, physiology, and water status in maize cultivation.

Soil water availability can prompt physiological changes in plants, including stomatal closure. This reduces stomatal conductance and transpiration, affecting leaf succulence, relative water content and biomass production, resulting in yield losses (Ahmed et al., 2020). Plant water, osmotic and pressure potential and osmotic adjustment are likely influenced by different irrigation and fertilizer management systems. Under drought stress, plants attempt to reduce their energy potential to continue absorbing water at low soil moisture content while maintaining active solute production, a process known as osmotic adjustment (Bhattacharya, 2021).

Thus, the present study aimed to analyze water relations in maize (double-cross hybrid AG 1051) under different soil moisture levels (80, 90, 100, 110, and 120% of soil field capacity-FC) and fertilization systems (conventional and fertigation).

Material and Methods

The study was conducted from August to October 2019 in a greenhouse at the Fertigation and Salinity Laboratory of the Agricultural Engineering Department, at Universidade Federal Rural de Pernambuco, in the municipality of Recife, Pernambuco state (8° 01' 37" S and 34° 56' 53" W, 6.5 m a.s.l.). The treatments consisted of five soil moisture levels (80, 90, 100, 110, and 120% FC) and two fertilization systems: conventional fertilization (CF) and fertigation (F). The experiment used a randomized block design in a 5 × 2 factorial scheme, with four replicates and one plant per pot, totaling forty experimental units.

The initial soil water content was determined by soil samples collected at 0-0.30 m and dried in a microwave oven at maximum power until constant weight (Tavares et al., 2008). Soil water content was used to establish the relevant soil moisture contents for the treatments (Mantovani et al., 2009), which were initiated 15 days after sowing (DAS), with daily irrigation.

For both fertilization strategies, the so-called 5th Aproximacao was used, in accordance with soil analysis (Alvarez et al., 1999). This method is based on soil phosphorus availability (P), which was found to be low in this study. Conventional fertilization (CF) was divided into three applications: before planting (2.14 g P_2O_5 per pot ($NH_4H_2PO_4$), 0.71 g N per pot (Ca $(NO_3)_2$) and 1.43 g K_2O per pot (KNO_3), and when plants reached four and eight fully expanded leaves (0.71 g N per pot $(NH_4)_2SO_4$) and 1.43 g K_2O per pot (KNO_3), respectively). Fertigation (F) was divided into ten parts, applied every four days, namely 1.76 g P_2O_5 per pot ($NH_4H_2PO_4$) and 0.1 g N per pot (Ca $(NO_3)_2$) at all soil moisture levels, and 0.47, 0.45, 0.48, 0.42, and 0.43 g K_2O per pot (KNO_3) in the 80, 90, 100, 110, and 120% FC treatments, respectively, to maintain the soil at field capacity (0.033 m^3 m^{-3}).

The experimental units consisted of 60-L recepientes with a tap at the bottom, connected to a container to collect and measure the drained volume. The recepientes were filled with a 4 cm layer of gravel, which was then covered with Bidim® geotextile, and 62.91 kg of soil compacted to an average density of 1510 kg m^{-3}, as observed in the field. Soil was collected from the 0-0.20 m layer and classified as fluvic Neosol based on the Brazilian Soil Classification System (SIBICS) of Embrapa (Santos et al., 2018) and Fluvents according to the United States Soil Taxonomy system (USDA, 1999). The soil samples were collected in the city of Goiana, Pernambuco state (7° 33' 13" S and 35° 00' 34" W, 11 m a.s.l.). Soil chemical and physical analyses (Table 1) were performed at the Agricultural and Integrated Solutions Laboratory (Soloagri). Soil acidity was corrected to pH 6.0 by applying dolomitic limestone ($CaCO_3$-$MgCO_3$).

Initially, the soil was moistened to its maximum retention capacity, and then three double-cross hybrid AG 1051 maize (*Zea mays* L.) seeds were sown 0.05 m depth, in the center of the pot. Plant health was determined by applying specific insecticides to control the armyworm caterpillar (*Spodoptera frugiperda*). Average daily temperature (°C) and relative humidity (%) were monitored by a portable weather station (Digitech, XC0348 model) installed inside the greenhouse (Figure 1) and reference evapotranspiration (ETo) was

Table 1. Physical and chemical characteristics of the soil used in the study

Textural class	Particle size distribution (g kg^{-1}) Sand	Silt	Clay	Bd (kg m^{-3})	OM (g kg^{-1})	FC (g g^{-1})	PWP (g g^{-1})	ECe (dS m^{-1})
Sand	900	40	60	1,510	47.6	0.06	0.025	0.58
pH (water) 1:2,5	**Ca^{+2} (cmol$_c$ dm^{-3})**	**Mg^{+2}**	**Al^{+3}**	**Na^+**	**K^+**	**H+Al**	**P (mg dm^{-3})**	**C**
4.6	3.9	1.2	0.05	0.06	0.03	3.80	6.81	27.6

Bd - Bulk density; OM - Organic matter; FC - Field capacity; PWP - Permanent wilting point; ECe - Electrical conductivity of the saturated paste extract

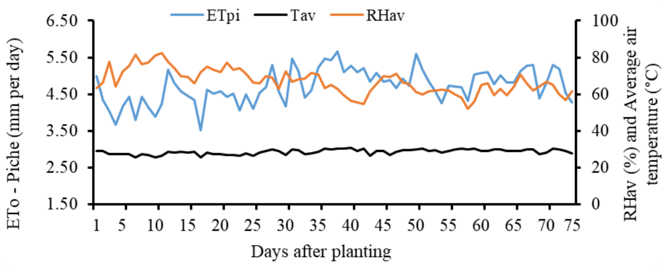


Figure 1. Average daily temperature - Tav (°C), average relative humidity of air - RH av (%), and average Piche evaporation - Piche - ETpi (mm per day) inside the protected environment during the study period (August 10 to October 25, 2019)

estimated by a Piche evaporimeter model (Vescove & Turco, 2005). The evaporimeter was installed in the center of the greenhouse, 1.5 m above the ground, and Piché evaporation (EToPi) was determined by computing the difference in water level between two consecutive days.

The following variables were analyzed: (i) peeled ear fresh weight (PEFW), (ii) ear diameter (ED), (iii) water stress index - WSI calculated by Eq. 1 according to Jackson et al. (1981); (iv) leaf succulence - LS [g H_2O dm^{-2}]; (v) stomatal conductance - gs [mmol H_2O m^{-2} s^{-1}], (vi) transpiration - E [mmol H_2O m^{-2} s^{-1}], and (vii) intrinsic water use efficiency - IWUE [(μmol de CO_2 m^{-2} s^{-1}) (mmol H_2O m^{-2} s^{-1})$^{-1}$]. The last three variables were determined between 9 and 11 a.m. on the first leaf below and opposite the uppermost ear, 58 days after sowing (DAS), when the plants had reached physiological maturity, using an infrared gas analyzer (IRGA, Li-6400xt model, LI-COR) at a photosynthetic photon flux of 1,500 μmol m^{-2} s^{-1}.

$$WSI = \frac{(T_c - T_{air}) - T_{wet}}{T_{dry} - T_{wet}} \quad (1)$$

where:

T_c - leaf canopy temperature;
T_{air} - air temperature;
T_{wet} - non-water stressed baseline; and,
T_{dry} - water stress baseline.

In addition, (viii) leaf water - Ψh, (ix) osmotic - Ψo, and (x) pressure potentials - Ψp (this last based on the difference between Ψh and Ψo), as well as (xi) osmotic adjustment (OA) and relative water content (RWC) were determined using the disc method proposed by Weatherley (1950).

Ψh was measured with a Scholander pressure chamber (1515D Pressure Chamber Instrument model - PMS Instrument Company), between 1:30 and 4:30 a.m., on the first leaf below the uppermost ear of each plant sampled, during the reproductive stage (R1). The leaves were then exposed to increasing pressures until the overflow pressure was obtained.

For Ψo, the leaves used in Ψh analysis were wrapped in aluminum foil and stored at 4 °C for 24 hours. Next, they were ground with a mortar and pestle and the sap obtained was filtered and centrifuged at 10,000 RPM at 4 °C. Tissue osmolality was determined in a vapor pressure osmometer (Vapro Wescor Model 5600) in a 10 μL aliquot of the supernatant (Souza et al., 2012). The values obtained in millimoles per kilogram were transformed into the osmotic potential using the van't Hoff equation (Eq.2).

$$\psi o = -R \times T \times C \quad (2)$$

where:

R - general gas constant (0.008314 MPa kg K^{-1} mol^{-1});
T - temperature (K); and,
C - solute concentration expressed in mol kg^{-1}.

OA was measured on the second leaf below and opposite the first ear insertion node, collected at the same time as the leaves used to determine water potential. In the laboratory, they were saturated in Petri dishes (filled with distilled water) in the dark for 24 hours, at 4 °C. After reaching complete turgor, the leaves were dried with paper towels and ground with a mortar and pestle in liquid nitrogen. The sap extracted was filtered, placed in a microtube and centrifuged at 10,000 RPM for 10 minutes at 4 °C.

Osmolality was read with an osmometer (Vapro Wescor Model 5600) in a 10 μL aliquot of the supernatant remaining from centrifugation (Silveira et al., 2009), and the values obtained in millimoles per kilogram were transformed into MPa using the van't Hoff equation. OA was determined based on the difference between the osmotic potential of control and stressed plants, using the following equation (Eq. 3).

$$OA = \left(\psi_{oc}^{100} - \psi_{os}^{100}\right) \quad (3)$$

where:

OA - osmotic adjustment;
ψ_{oc}^{100} - osmotic potential of control plants at full turgor - corresponding to 100% of field capacity; and
ψ_{os}^{100} - osmotic potential of stressed plants at full turgor.

The data were submitted to the Shapiro-Wilk normality test and analysis of variance by the F test at $p \leq 0.05$ and $p \leq 0.01$, using SISVAR statistical software (Ferreira, 2011). For cases in which soil moisture (%FC) showed a significant effect, the results were compared by regression analysis, and when the fertilization system (A) significantly influenced the variables, by the F test.

Results and Discussion

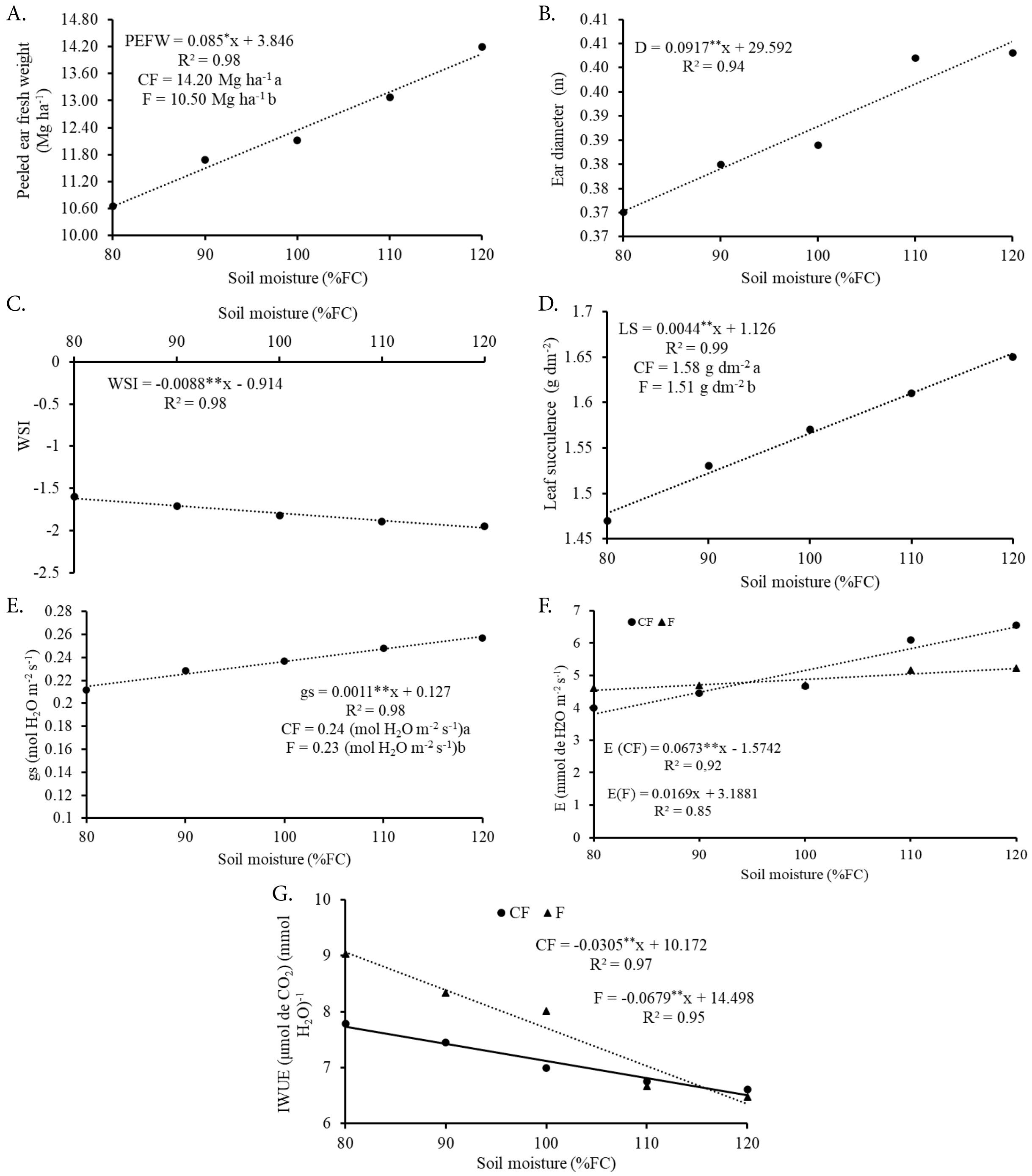
Significant differences ($p \leq 0.01$) were observed for peeled ear fresh weight (PEFW), ear diameter (ED), water stress index (WSI), relative water content (RWC), leaf succulence (LS), stomatal conductance (gs), transpiration (E), and intrinsic water use efficiency (IWUE) at the soil moisture levels analyzed. Fertilization system also influenced ($p < 0.01$ or $p < 0.05$) these variables, except for ED and WSI, and interaction between soil moisture and fertilization system ($p < 0.01$) influenced E and IWE (Table 2).

PEFW (Figure 2A) and ED (Figure 2B) increased at a rate of 0.085 Mg ha^{-1} and 0.0917 m, respectively, per unit increase in soil moisture, as also reported by Huang et al. (2022).

Table 2. Summary of analysis of variance for peeled ear fresh weight (PEFW), ear diameter (ED), water stress index (WSI), leaf succulence (LS), stomatal conductance (gs), transpiration (E) and intrinsic water use efficiency (IWUE) in double-cross hybrid AG 1051 maize, under different soil moisture levels and fertilization systems (conventional and fertigation)

Source of variation	DF	Mean squares						
		PEFW	ED	WSI	LS	gs	E	IWUE
SM (%FC)	4	2087.34*	17.811**	0.161**	0.040**	0.002**	3.807**	4.958**
Linear R.	1	8211.17**	65.359**	0.635**	0.161**	0.009**	14.339**	19.320**
Quad R	1	40.93ns	0.385ns	0.010ns	0.001ns	0.0001ns	0.191ns	0.054ns
Fertil (A)	1	19411.51**	1.734ns	0.116ns	0.02*	0.002*	0.601*	3.376**
%FC × A	4	898.69ns	0.323ns	0.003ns	0.001ns	0.0002ns	1.376**	0.844**
Residual	27	587.30	3.110	0.038	0.002	0.0003	0.099	0.307
CV (%)	---	16.49	4.55	10.90	3.02	7.69	6.26	7.47

** - Significant at $p \leq 0.01$; * - Significant at $p \leq 0.05$; ns - Not significant according to the F test at 0.05 probability; DF - Degrees of freedom; SM - Soil moisture (% field capacity); Fertil - Fertilization system; CV (%) - Coefficient of variation. Residual analyses were performed for all significant regressions with results in the normal range (3; -3)



CF - Conventional fertilization; F - Fertigation; * - Significant at $p \leq 0.05$ according to the F-test; ** - Significant at $p \leq 0.01$ by F-test; FC - field capacity

Figure 2. Peeled ear fresh weight - PEFW (A), ear diameter - ED (B), water stress index - WSI (C), leaf succulence - LS (D), stomatal conductance - gs (E), transpiration - E (F) and intrinsic water use efficiency - IWUE (G) in double-cross hybrid AG 1051 maize, under different soil moisture contents and fertilization systems

However, in the present study, WSI (Figure 2C) declined linearly in maize plants by 0.0088 for each unit increase in soil moisture, with an absolute reduction of 21.6%, when compared to the WSI of plants under 80 (-1.62) and 120% FC (-1.97). This reduction had a significant effect on WSI values when comparing 80 and 120% FC. Plants exposed to water stress exhibited lower average ear weight and leaf succulence.

The amount of water applied influenced plants water status. Nevertheless, the negative WSI values obtained make it possible to infer that leaf surface temperature was lower than the air temperature, characterizing no water stress (Brewer et al., 2022). This is evident in the increasing yield gains, as also reported by Carroll et al. (2017).

In addition to the yield effects observed, the relationship between greater water availability and reduced WSI has also been reported in bean (Rai et al., 2020), sugarcane (Dhansu et al., 2021), and maize (Brewer et al., 2022), and is considered an important parameter in assessing plant water status.

Leaf succulence increased linearly with the rise in soil moisture, at a rate of 0.0044 g H_2O dm^{-2} (Figure 2D). Plants exhibited an LS of 1.48 and 1.65 g H_2O dm^{-2} in those under 80 and 120% FC, respectively. When compared with the 100% FC treatment, LS declined by 5.73% in plants at 80% FC and increased by 11.48% (1.65 g H_2O dm^{-2}) at 120% FC.

Although conventionally fertilized plants obtained 4.43% higher LS than their fertigated counterparts, corroborating the findings of Silva et al. (2009), who reported average LS values greater than 1.51 g H_2O dm^{-2}. Sousa et al. (2024) observed higher leaf succulence (0.017 to 0.020 g H_2O cm^{-2}) in *Gossypium hirsutum* L. plants under irrigation at 60% FC when compared to the other treatments.

Stomatal conductance increased linearly at 0.001 mol H_2O m^{-2} s^{-1} per unit increase in soil moisture (Figure 2E), resulting in increased gas exchange by the stomata, favoring transpiration and regulating water entry via the roots (Bhattacharya, 2021).

Plants under 80% FC displayed lower stomatal conductance (Figure 2E) than those submitted to 100 and 120% FC, which obtained approximately 10 and 20%, respectively, indicating that despite the water deficit, stress was insufficient to affect ear development.

On the other hand, analysis of the results indicated greater transpiration (E) in plants submitted to water stress (below 100% FC), which may be due to stomatal behavior (stomatal opening and closing) (Fanourakis et al., 2020). Plant transpiration increased at 0.0169 and 0.0673 mmol H_2O m^{-2} s^{-1} per unit increase in soil moisture in fertigated and conventionally fertilized plants, respectively (Figure 2F).

The higher yields resulting from the increase in soil moisture and evident in PEFW and ED analysis were corroborated by the increase in LS, gs, and E.

Moreover, under conventional fertilization, there was a 19% greater increase in transpiration when compared to fertigated plants. In other words, in the present study, the direct relationship between soil water availability and plant transpiration (Nie et al., 2021) was influenced by the fertilization system. These results suggest that nutrient supply via fertigation increased transpiration efficiency when compared to conventional fertilization, thereby reducing water loss through the leaves.

IWUE declined linearly at 0.0679 and 0.0305 μmol de CO_2 mmol H_2O per unit increase in soil moisture in fertigated and conventionally fertilized plants, respectively (Figure 2G). Under conventional fertilization, IWUE was 2.5% lower than that recorded in fertigated plants, indicating that the fertilization strategies (Urban et al., 2017) influenced water use efficiency in the present study. Santos et al. (2014) studied maize performance in response to water and nutrient management and reported behavior similar to that observed here.

With respect to the fertilization strategies used in the present study, IWUE was better in fertigated than conventionally fertilized plants. This is likely because better nutrient use by the maize plants, especially of potassium, combined with high values for RWC, LS and the different plant potentials, resulted in greater transpiration, which would justify the increased IWUE in fertigated plants (Cano et al., 2019).

Interaction between soil moisture and the fertilization system influenced ($p < 0.01$) water potential (ψw) and OA and soil moisture variations and the fertilization strategy affected ($p < 0.01$) RWC, ψw, ψo, and OA (Table 3).

RWC increased linearly at 0.1239% per unit increase in soil moisture and remained above 91% in all the treatments (Figure 3A). However, there was an estimated 6.64% decline in RWC in plants at 80% FC when compared to 100% FC (Figure 3B). As such, the relationship between WSI and RWC is evident (Tejeda et al., 2020), since a decline leaf water content is associated with increased water stress (Moro et al., 2015).

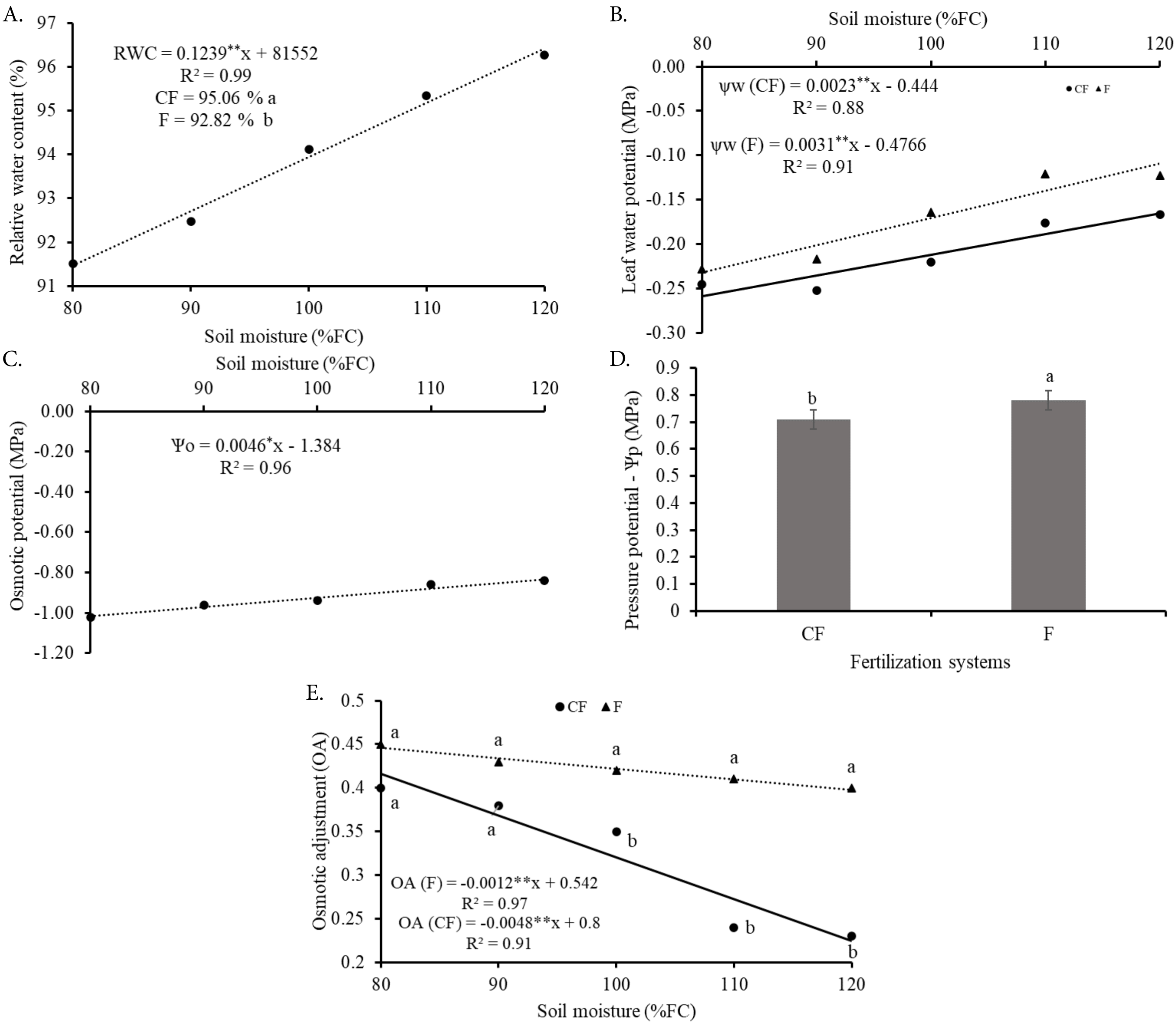
Conventionally fertilized plants exhibited a 2.24% higher RWC than their fertigated counterparts (Figure 3A), as observed in another study (Hessini et al., 2019).

Leaf water potential increased linearly by 0.0023 and 0.0031 MPa per unit increase in soil moisture in conventionally fertilized

Table 3. Summary of analysis of variance for relative water content (RWC), water potential (Ψw), osmotic potential (Ψo), pressure potential (Ψp), and osmotic adjustment (OA) in fertigated and conventionally fertilized double-cross hybrid AG 1051 maize under increasing soil moisture levels and fertilization systems

Source of variation	DF	Mean squares				
		RWC	Ψw	Ψo	Ψp	OA
Soil moisture (%FC)	4	30.955^{**}	0.019^{**}	0.039^{*}	0.013^{ns}	0.018^{**}
Linear Regression	1	122.719^{**}	0.035^{**}	0.156^{**}	0.071^{**}	0.068^{*}
Quadratic Regression	1	0.145^{ns}	0.000^{ns}	0.0003^{ns}	0.0009^{ns}	0.0003^{ns}
Fertilization system (A)	1	50.349^{**}	0.033^{**}	0.06^{ns}	0.059^{*}	0.113^{**}
%FC × A	3	1.859^{ns}	0.004^{**}	0.005^{ns}	0.005^{ns}	0.009^{**}
Residual	27	0.956	0.00002	0.010	0.007	0.002
CV (%)	---	1.04	2.23	10.94	11.14	11.17

** - Significant at p ≤ 0.01, * - Significant at p ≤ 0.05%, ns - Not significant according to the F test at 0.05 probability; DF - Degrees of freedom; SM - Soil moisture (% field capacity); CV (%) - Coefficient of variation. Residual analyses were performed for all significant regressions with results in the normal range (3; -3)



CF - Conventional fertilization; F - Fertigation; * - Significant at $p \leq 0.05$ according to the F-test; ** - Significant at $p \leq 0.01$ according to the F-test; FC - Field capacity

Figure 3. Relative water content - RWC (A), leaf water potential - ψw (B), osmotic potential - Ψo (C), pressure potential - Ψp (D), and osmotic adjustment - OA in fertigated and conventionally fertilized double-cross hybrid AG 1051 maize under increasing soil moisture levels

and fertigated plants, respectively (Figure 3B). This parameter became less negative because water is retained with less energy.

The ψw values obtained are similar to the previously presented WSI and E results and consistent with yield gains. Moreover, they suggest that the 80% FC treatment did not cause water stress in the maize plants studied (Boyer, 1970; Bergonci et al., 2000).

In this respect, fertigation resulted in ψw values closer to 0 MPa, indicating good hydration (Bianchi et al., 2005), even when compared with the soil moisture treatments (Figure 3B).

According to Boyer et al. (1970), ideal Ψw values for maize are between -0.6 and -0.8 MPa. However, Bergonci et al. (2000) and Bianchi et al. (2005) recommended minimum values of -1.2 to -1.5 MPa in irrigated maize plants. After stomatal closure, values below -1.5 MPa can be used as an indicator of water stress in maize (Bianchi et al., 2005).

Leaf water potential is an important factor in assessing plant water status, since this parameter declines under severe or moderate water stress, making it difficult for plants to absorb water (Parkash & Singh, 2020). However, it is important to underscore that the parameters used to characterize water status decrease with increased water loss due to transpiration, thereby reducing cell expansion, growth, and photosynthesis (Taiz & Zeiger, 2017). However, this did not occur in the present study, indicating good water status in plants at the different soil moisture levels studied.

At 80% FC, Ψo was -1.02 MPa, representing a difference of approximately 18% in relation to the Ψo of plants at 120% FC. In general, this increase was 0.0046 MPa per unit increment in soil moisture (Figure 3C).

The Ψo results presented here classify the maize plants as hydrated, since Ψo in the protoplasm of irrigated plants, can reach - 0.5 MPa, although values of - 0.8 to -1.2 MPa are more common (Taiz & Zeiger, 2017). Notably, plants under water stress accumulate soluble organic compounds and exhibit more negative osmotic potential when compared to non-stressed plants.

Although the fertilization system used did not affect Ψo ($p > 0.05$) some studies (Santos et al., 2022; Oller et al., 2023) suggest that Ψo may be influenced by factors such as the cultivation system or nitrogen source.

Our findings corroborate those of Bianchi et al. (2005), who reported a lower Ψo in non-irrigated than irrigated plants on most days. On the other hand, Hessini et al. (2019) reported the sensitivity of Ψo to the presence of ammonium in fertigation in the form of ammonium sulfate, demonstrating that the salt content of fertilizers affects the occurrence of abiotic stress.

Although the plant potentials obtained are within the average range for turgid plants, and there were productive gains, these results demonstrate that osmotic adjustment occurred under both fertilization strategies, albeit more intense under the conventional system.

It is possible that soil N concentrations caused OA. High salt concentrations can induce toxicity symptoms, including leaf necrosis, chloroplast membrane breakdown, and altered osmotic potential (Hessini et al., 2019).

Average pressure potential was higher in fertigated maize plants when compared to their conventionally fertilized counterparts, with values of 0.78 and 0.71 MPa, respectively (Figure 3D). These results indicate that the lowest ψp under conventional fertilization may have influenced cell growth, given that cell expansion depends on pressure potential (Boyer, 1970). In this respect, Bianchi et al. (2005) reported positive pressure potentials in maize plants under satisfactory water conditions, in contrast to plants under water stress, which presented close to zero or null.

Osmotic adjustment decreased linearly with the increase in soil moisture at rates of 0.0048 0.0012 MPa under conventional fertilization and fertigation, respectively (Figure 3E). The maximum decline in OA was observed at 120% FC, with 0.22 MPa under conventional fertilization and 0.40 MPa for fertigation.

There was a significant difference in water potential in fertigated plants at irrigation depths of 100, 110, and 120% FC. This demonstrates greater OA and good agronomic performance in fertigated AG 1051 maize plants at the lowest soil moisture level. Although PEFW declined by 24.21 at 80% FC in relation to 120% FC, the values obtained exceeded 10 Mg ha^{-1}, indicating good yield under the lowest soil moisture content studied.

Although the soil moisture levels used in the present study did not characterize a situation of stress for the maize crop, the data obtained show that, for the shallowest depths, osmotic adjustment occurred. Similarly, Bianchi et al. (2005) reported OA between 0.4 and 0.18 MPa in maize under conventional and no-till systems, respectively. On the other hand, Tejeda et al. (2020) found that different maize cultivars submitted to abiotic stresses exhibited osmotic stress (reduced osmotic potential), with a reduction in turgor, cell wall extension, and photosynthetic rate.

According to our findings, fertigation produced higher gas exchange values (gs and E) and plant potentials in maize irrigated at 80 to 95% FC, suggesting yield was less compromised in this moisture range when compared to conventional fertilization.

In this respect, higher pressure potentials were also observed in fertigated plants (higher average), indicating greater cell expansion. Lower water potential, likely due to higher cell pressure and osmotic potential, did not differ between the fertilization systems used. Thus, it is interesting to note that OA was higher in fertigated plants and influenced the maintenance of leaf water potential, since these plants experienced greater osmotic pressure than their conventionally fertigated counterparts.

Conclusions

1. Peeled ear fresh weight and ear diameter increased with irrigation depth up to 120% FC. Plants under 80% FC experienced water stress, evident in the higher water stress index and osmotic adjustment values obtained, and a decline in ear fresh weight and diameter when compared to plants at 100% FC.
2. Irrigation at field capacity below 100% resulted in higher intrinsic water use efficiency but lower ear fresh weight, indicating low photoassimilate conversion and, consequently, stress in the maize plants studied.
3. Leaf water, osmotic, and pressure potential and osmotic adjustment were influenced by fertigation.

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