Australian Journal of
Crop Science
AJCS

AJCS 8(8):1257-1265 (2014) ISSN:1835-2707

$CaSiO_3$ improves water potential and gas exchange but not contribute to the production parameters of maize plants exposed to different irrigation depths

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Abstract

The aim of this study was to evaluate effects of different proportions of calcium silicate ($CaSiO_3$) on leaf water potentials, gas exchange and production parameters in *Zea mays* plants exposed to different irrigation depths. The experiment was organized as factorial scheme in a completely randomized design with five calcium silicate levels (0, 25, 50, 75, and 100% of $CaSiO_3$ indicating the liming of the soil) and five irrigation depths (30, 70, 100, 130, and 160% of necessary to water reposition in this soil). The parameters evaluated in soil were chemical properties before and after the application of calcium silicate and matrix potential, while in plant the water potentials, transpiration rate, stomatal conductance, net photosynthetic rate, grain production, and matter of 100 seeds were measured. The results showed that application of 100% of calcium silicate promoted the values of predawn and midday water potentials. The beneficial effects were also observed in stomatal conductance, net photosynthetic rate and photosynthetic water use efficiency, when applied at the irrigation depths of 70, 100, 130 and 160% of necessary to water reposition in the soil. Despite that calcium silicate significantly promoted the gas exchange, the increment was not transferred to grain production and matter of 100 seeds. This study proved that irrigation depth of 100% is adequate for this crop.

Keywords: *Zea mays* L., silicon, drought, net photosynthetic rate, grain production.
Abbreviations: Ca_calcium, $CaSiO_3$_calcium silicate, $CaCO_3$_calcium carbonate, $CaCl_2$ _calcium chloride, Si_silicon, M100s_matter of 100 seeds, OM_organic matter, UC_uniformity coefficient, Ψw_leaf water potential.

Introduction

The drought is a common environment constraint in regions with agricultural potential, due to occurrence and irregular distribution of rainfall and/or inadequate supply of irrigation (Lobato et al., 2008a). Therefore, the water deficiency serves as limiting factor in several crops (Santos and Carlesso, 1998), such as maize plants. Additionally, the water restriction during vegetative, reproductive, and maturation stages usually result in minor growth and development rates (Lobato et al., 2008b), flower abortion (Pimentel, 2004) and reduction in grain production (Leport et al., 1998).

The irrigation management based on water tension in soil has been frequently used in maize plants (Rivera-Hernández et al., 2009), by which soil is normally filled by water and air, and causes a negative tension state. In addition, water tension in soil, which is called of matrix potential, results a water affinity by soil, under actions of adsorption and capillarity derived of cohesive and adhesives forces (Gomide, 1998).

The use of water status indicators in plant, such as leaf water potential can also be an important approach in monitoring the availability of soil water and irrigation requirements (Bergonci et al., 2000). The water potential is an important and sensitive measure for evaluating water exigency by plants, in which it oscillates in values approximately to zero in plants under adequate water availability (Kramer and Boyer, 1995). The leaf water potential has been used in studies of the water relations in plants (Hsiao, 1973), and it is considered as the standard plant water state.

The silicon (Si) is considered a benefic element to higher plants (Epstein and Bloom, 2004), where the absorption process is active or passive (Ma et al., 2007). Its deposition in cell walls of several organs such as leaf and stem can promote beneficial effects (Cunha et al., 2008). It has been frequently linked to physiological, morphological, nutritional, and molecular aspects in plants (Lobato et al., 2009; Isa et al., 2010). In biochemical level, Silva et al. (2012) described that increase in chlorophyll levels can be caused by silicon application. Isa et al. (2010) reported silicon accumulation in leaf, and this fact is related to higher mechanical resistance from cell wall (Kim et al., 2002), providing better light reception and increasing photosynthesis capacity and CO_2 uptake capacity (Chen et al., 2011).

This nutrient is assimilated mainly by roots, and its capacity to accumulate in tissues is variable (Chiba et al., 2009). Several monocots such as *Oryza sativa* and *Triticum aestivum* are considered as silicon accumulator, with active absorption by root system, and it exists in amounts higher than 10.0 g kg^{-1} in leaves (Oliveira, 2009). On the other hand, many dicots such as *Phaseolus vulgaris* and *Glycine max* are characterized as silicon non-accumulator. They present passive absorption, with leaf tenors minors than 5.0 g kg^{-1} of Si (Takahashi et al., 1990). The application of silicates of calcium (Ca), such as calcium silicate ($CaSiO_3$) can reduce the soil acidification, due to presence of neutralizing agent like SiO_3 and increases the availabilitiy of Ca (Ramos et., 2006) and Si (Camargo et al., 2007) in soil, which it will reflect in maximization of crop yield.

The aim of this study was to evaluate different proportions of calcium silicate on leaf water potentials, gas exchange and production parameters in *Zea mays* plants exposed to different irrigation depths.

Results

Minimum and maximum temperatures during experiment

The values linked to minimum and maximum temperatures, registered into greenhouse are presented in Fig 1. The temperatures oscillated from 32 to 38 °C (maximum), as well as 17 to 22 °C (minimum) during 112 days of experiment. In this period, the mean temperature varied between 25 and 29 ºC.

Matrix potentials in soil

Fig 2. presents the matrix potentials related to 30, 70 and 100 % of recommended irrigation depths. The higher water tensions in soil verified in treatment with application of 30 % of recommended irrigation depth, oscillating of -90 to -160 kPa. With the application of 70% irrigation depth, the tension varied between -40 and -130 kPa, while treatments exposed to 100 % of recommended irrigation depth, the water tension in soil was kept between -5 and -30 kPa, being lower than that tension in field capacity, in which the values remained in approximately -40 kPa.

Water potentials in leaf

Leaf water potential was associated to different proportions of calcium silicate and different irrigation levels, regardless of the proportions of silicate and time of read (Fig. 3). The highest water potentials were found with addition of calcium silicate. A greater water potential was observed with addition of 100% of calcium silicate.

Modifications in gas exchange

For stomatal conductance, the application of calcium silicate caused increase of the stomatal conductance at 30% of irrigation depth (Fig. 4). In addition, the application of 70 and 100% irrigation depths produced greater values of stomatal conductance under application of 100% calcium silicate. However, under applications of 130 and 160 % irrigation depth more intense increases were occurred under proportions of 50, 75 and 100% of calcium silicate, respectively. The transpiration rate under application of 30 % of the water depth induced intense increases by additions of 25, 50 and 75% of calcium silicate (Fig 4B). Under application of 70 % irrigation depth, the same trend of increase of the transpiration rate observed with the additions of 25, 50, 75 and 100% of calcium silicate. However, under application of 100, 130 and 160% irrigation depth, the transpiration rate was greater with the addition of 50% calcium silicate, showing stability in the proportion of calcium silicate. Under the application of 30 % of irrigation depth, the highest rates of photosynthesis were recorded with the addition of 25 and 75 % of calcium silicate (Fig 4 C). Under application of 70 and 100% of the irrigation depths, similar trends were observed, with higher rates of photosynthesis in the proportions of 25 to 100% calcium silicate. For water applications of 130 and 160 % of the irrigation depth, the best results were obtained at a ratio of 100% calcium silicate. The photosynthetic water use efficiency suffered significant influence from irrigation levels and ratios of calcium silicate applied to the soil (Fig 4 D). Under 30% of the irrigation depth, this parameter was higher in proportions of 25 and 100% of calcium silicate. In addition, under 70% of irrigation depth, the highest value was observed at proportion of 25% calcium silicate. This trend continued until 100% calcium silicate ratio. However, it was observed that application of 100% of calcium silicate was the best in maintaining soil-waters stability under different water applications.

Grain production and matter of 100 seeds

The grain production (Fig 5) revealed an increase tendency, proportional to the irrigation depth. For the irrigation of 30%, the higher productions were occurred to proportions of 50, 75 and 100% of calcium silicate, respectively. While at 70% of the irrigation depth, the higher grain production was found in the proportions of 50 and 75% of calcium silicate. These results indicate that silicon attenuated the negative effects provoked by water deficit in maize plants. For applications of 100, 130 and 160% of irrigation depth, there was no significant difference in maize production at different ratios of calcium silicate. Fig 5B. shows the results for the matter of 100 seeds. The interaction between the irrigation and proportion of calcium silicate does not significantly affect the matter of 100 seeds. It was observed that the matter of 100 seeds responds positively to increased irrigation depth in all proportions of calcium silicate. Additionally, responded positively to increase of irrigation depth, in turn, aiming to increase the production.

Discussion

In relation to minimum and maximum temperatures, the climatic data reveal that the air mean temperatures frequently oscillated near 24 ºC, being considered adequate for crop development due to maize plants better performance under moderate temperatures of 18-25 °C (Didonet et al. 2002). High night temperatures during night period are not beneficial for the production of maize, provoking accentuated reduction of the plant cycle, due to thermal sum (Fancelli and Gold Neto, 2004).

The reductions in irrigation depths frequently induced increases water tensions and matrix potentials in soil. In other words, the increase in water tension is the indicator of lower water amount and consequently minor water availability of soil to plants. Resende et al. (2008) and Rivera-Hernández et al. (2009) were used as references for the water conditions reported in the experiment. They described that the potential of -70 kPa provides a water restriction in intensity sufficient to affect the production in higher plants. Therefore, the irrigation depths of 30 and 70% were effective to induce water deficit conditions. This effect was more pronounced during the application of 30% of the recommended irrigation depth.

When 100% of calcium silicate applied, the water potentials increased in values linked to predawn and midday times, noting that this treatment is statistically better in all five irrigation depths of our study.

Table 1. Chemical and physical compositions of the soil used in this study.

		Chemical^1															
pH	P	K	Si	Zn	Cu	Mn	S	B	Fe	EP	Ca	Mg	Al	H+Al	T	m	V
	(mg dm^{-3})									(mg L^{-1})	(cmol dm^{-3})					(%)	
5.0	53.7	20.0	2.7	0.6	1.3	17.7	6.7	0.1	31.1	36.3	1.5	0.4	0.5	3.6	5.6	20.4	35.1
		Physical^2															
Sand				Silt						Clay				OM			
					(%)									(dag kg^{-1})			
49				13						38				2.1			

[1] pH in water (1:2.5), P and K by Mehlich I extraction, Mg and Al extractable by 1 M KCl solution [21]; P in the equilibrium solution (EP) according to Álvarez *et al.* [22]; level of organic matter (OM) according to Anne [23]. T = Cation exchange capacity at pH 7.0; t= Cation exchange capacity effective; m = Aluminum saturation index; V = Base saturation index. [2] The soil granulometry was determined by the pipette method [25].

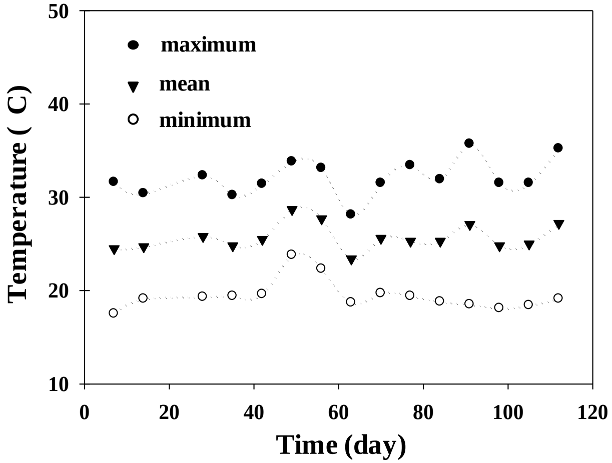

Fig 1. Maximum, mean, and minimum temperatures obtained during experimental period.

Table 2. Amounts of $CaSiO_3$, $CaCO_3$, and $CaCl_2$ used to liming of the soil.

Proportion	$CaSiO_3$	$CaCO_3$	$CaCl_2$
(%)		(g pot^{-1})	
0	0.00	10.50	4.12
25	3.05	7.88	3.09
75	9.15	2.63	1.03
100	12.20	0.00	0.00

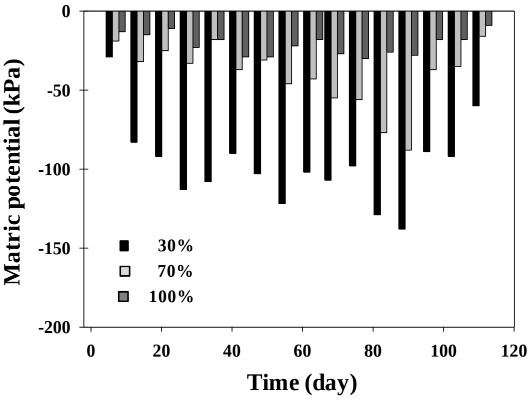

Fig 2. Matrix potential in soil obtained with irrigation depths of 30, 70, and 100 % of necessary to water reposition in this soil during experimental period.

Table 3. Nutrients, recommended amounts, and sources used in fertilization of this study.

Nutrient	Concentration (mg kg of soil^{-1})	Source
N	300	$NH_4H_2PO_4$
P	300	KH_2PO_4
K	200	KH_2PO_4
S	40	K_2SO_4
Mg	46	$MgSO_4 \cdot 7H_2O$
B	2.5	H_3BO_3
Cu	7.5	$CUSO_4 \cdot 5H_2O$
Mo	0.5	$(NH_4)_6MO_7O_{24} \cdot 4\ H_2O$
Zn	2.5	$ZNSO_4 \cdot 7H_2O$

The stomata are sensitive to leaf water potential, in which stomatal mechanism promotes stomatal closure with decreasing leaf water potential and opening of this structure with increasing water potential. The values of leaf water potential ranges between -0.3 and -0.5 MPa, which are usually considered suitable for development of *Zea mays* plants, while values less than -0.8 MPa will cause inhibition of photosynthesis rate. The lower rates are attributed to the development and expansion of leaf. The values below -1.5 MPa are frequently found at the permanent wilting points in *Zea mays* specie (Salah and Tardieu, 1997; Porto et al., 1998). Bergonci et al. (2000) reported values of leaf water potential between -1.2 and -1.5 MPa in irrigated *Zea mays* plants, as well as -1.6 and -2.0 MPa in non-irrigated plants.

In gas exchange, it was observed that proportion of 100% of calcium silicate promoted beneficial effects in relation to stomatal conductance, net photosynthetic rate and photosynthetic water use efficiency, when applied at the irrigation depths of 70, 100, 130 and 160%. Additionally, the silicon accumulation in stomata caused the formation of a double layer of cuticle silica, which reduces transpiration (Datnoff et al. 2001) and eventually plant's water requirement. This fact is of importance extreme to growing crops that are exposed to periods of limited water availability. Around 95% of the total water absorbed by the plant is consumed to maintain thermal equilibrium by transpiration. Therefore, the variation in transpiration will be affected directly by the plant temperature, more specifically the leaf temperature (Qiu et al. 2000).

The grain production and matter of 100 seeds were influenced by increase in irrigation depths, but the application of calcium silicate not significantly promoted these parameters. The performance of *Zea mays* plants under conditions of water restriction is much lower, when compared to cultivation in optimal condition, which can be explained by the low tolerance of this species to water deficit (Silva et al., 1984).

The Si absorption promotes benefits in several crops and also in *Zea mays* plants (Lima et al., 2011), such as increased resistance to lodging (Fallah, 2012) and photosynthesis rate (Ali et al., 2013). Silicon is a chemical element involved in physical functions of evapotranspiration regulation. Also, it can form a mechanical barrier against pathogen invasion to internal part of the plant. Besides, it prevents insect attacks (Costa and Moraes, 2009; Romero et al., 2011). Faria (2000) revealed that the lower the value linked to field capacity of the soil, the higher was the plant response to silicon.

Despite the fact that calcium silicate significantly promotes the photosynthesis rate, the increment does not transfer towards grain production. The photosynthesis plays an important role in crop production (Wullschleger and Oosterhuis, 1990) because the yield is directly influenced by the intensity of the accumulation rate of carbohydrates

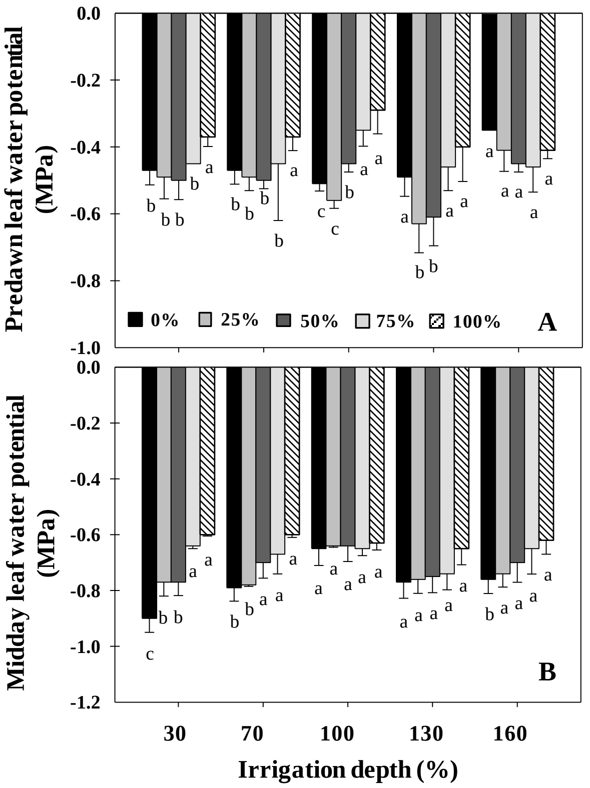

Fig 3. Predawn leaf water potential (A) and midday leaf water potential (B) in *Zea mays* plants (cv. BR 106) exposed to five calcium silicate levels (0, 25, 50, 75, and 100% of $CaSiO_3$ indicated to liming of the soil) and five irrigation depths (30, 70, 100, 130, and 160% of necessary to water reposition in this soil). Means followed by the same letter to each irrigation depth are not significantly different by the Scott-Knott test at 5% of probability (P > 0.05). The bars represent the mean standard error.

(Crafts-Brandner and Poneleit, 1992). Results described by Jordan (1983) and Pimentel (1999) revealed that water deficit can affect the transport and utilization of carbon skeletons, because these molecules are maintained in leaf, and consequently will not be available to grain (Oliveira Neto et al., 2009). Drought causes changes in the partition of carbohydrates into plant, such as sucrose and starch (Lobato et al., 2008a), which it can perform key roles in the mechanisms of adaptation and tolerance of the plant in water deficit conditions (Villadsen et al., 2005).

Materials and Methods

Localisation, environment conditions, plant material, and soil characteristics

The study was carried out in Departamento de Ciência do Solo from Universidade Federal de Lavas, Minas Gerais, Brasil (21°14' S; 45°00' W; 915 m asl), where the experiment was conducted under conditions of greenhouse. The maximum, mean, and minimum temperatures were described during experimental period in Figure 1. Seed of *Zea mays* L. (cv. BR 106) was used as plant material. This cultivar has favourite agronomical characteristic such as the plant height of 2.4 m, ear length of 0.16 m, and yield of 5.5 ton ha^{-1}, which is adapted to the Brazilian conditions (Embrapa, 2004). The soil was classified as Oxisol, (Embrapa, 2006) and collected from depth of 0-20 cm, then allowed to dry, crushed to pass through a 5 mm sieve and finally mixed. The chemical and physical compositions were described in Table 1.

Experimental design and treatments

The experiment was organized in factorial scheme in a completely randomized design with five calcium silicate levels (0, 25, 50, 75, and 100% of $CaSiO_3$ indicated to liming of the soil) and five irrigation depths (30, 70, 100, 130, and 160% of necessary to water reposition in this soil), composed by 4 replications. The volume of each pot was 15 L.

Treatment application and fertilization

Table 2 described the amounts of calcium silicate ($CaSiO_3$) and calcium carbonate ($CaCO_3$) present to liming of the soil. The calcium was applied in the form of calcium chloride ($CaCl_2$), aiming to equilibrate the amount of this element in treatments. After the treatment application, the soil was kept under incubation for 45 days. The fertilization using macro and micronutrients was carried out as described by Novais et al. (1991), with some modifications (Table 3). After treatment applications and fertilization, the soil was analyzed and results are expressed in Table 4.

Curve of water retention and field capacity

The curve of water retention was used to water characterization of the soil, and data were applied in formulas $\theta = 0.4215 \text{ x } [1 + (0.2040 \text{ x } (\Psi_m)^{1.8757}]^{-0.4669} + 0.2670$ and $\Psi_m = [1/\alpha \ (1/m) \ 1/n]$, in agreement with Genuchten (1980), Where, θ = humidity current ($cm^3 \ cm^{-3}$), Ψ_m= tension in soil (kPa), as well as α, m, and n are parameters linked to equation adjustment in model proposed by Genuchten. The field capacity was estimated by equation $\theta_i = (\theta_s - \theta_r) \text{ x } [1+1/m]^{-m} + \theta_r$, as proposed by Dexter (2004), Where, θ_i = humidity in inflexion point of the curve ($cm^3 \ cm^{-3}$), θ_s = humidity of saturation ($cm^3 \ cm^{-3}$), and θ_r = humidity residual ($cm^3 \ cm^{-3}$). The value of humidity calculated in field capacity of this study was 0.3458 $cm^3 \ cm^{-3}$ to tension of - 40 kPa.

Irrigation depths and water volume

The irrigation was carried out based on curve of water retention linked to soil and tensiometer measurements which was installed at 0.15 m. The irrigation was implemented when the water tension in soil reached the value of – 40 kPa, and to each irrigation depth (30, 70, 100, 130, and 160% of necessary to water reposition in this soil).

All measurements were carried on a daily basis at 17:00 h, and soil moisture meters (Watermark, model 200SS-5) were installed to quantify the matrix potential (Fig 2) only in three higher tensions (30, 70, and 100 of ideal depth to soil). The water volume applied to irrigation was calculated by equation: $V = (\theta_c - \theta_{treat}.) \text{ x } V_{soil}$, where V = water volume to be applied (mL), θ_c = humidity in yield capacity ($cm^3. \ cm^{-3}$), θ_{treat} = humidity in treatment ($cm^3. \ cm^{-3}$), and V_{soil} = volume of soil (mL).

Irrigation application system and flow water

For application of depths, a drip irrigation system with auto compensating drippers and water flow of 4 h h^{-1} was installed.

Table 4. Chemical composition of the soil after application of $CaSiO_3$.

Proportions		Measurements											
$CaSiO_3$	$CaCO_3$	pH	P	K	EP	Ca	Mg	Al	H+Al	T	m	V	OM
(%)			(mg dm^{-3})		(mg L^{-1})	(cmol dm^{-3})					(%)		(dag kg^{-1})
0	100	5.2	121.5	150	37.2	2.5	1.0	0.1	4.0	8.0	2.5	49.4	2.6
25	75	5.3	125.0	109	39.4	2.9	1.0	0.1	3.6	7.8	2.4	53.4	2.6
50	50	5.1	143.6	131	38.3	3.2	1.2	0.1	3.6	8.4	2.1	56.8	2.6
75	25	5.2	114.7	122	34.1	3.5	1.1	0.1	3.6	8.6	2.0	57.8	2.6
100	0	5.3	118.1	139	27.3	3.5	1.1	0.1	3.6	8.6	2.0	57.8	2.6

[1]pH in water (1:2.5), P and K by Mehlich I extraction, Mg and Al extractable by 1 M KCl solution [21]; P in the equilibrium solution (EP) according to Álvarez *et al.* [22]; level of organic matter (OM) according to Anne [23]. T = Cation exchange capacity at pH 7.0; t= Cation exchange capacity effective; m = Aluminum saturation index; V = Base saturation index. [2]The soil granulometry was determined by the pipette method [25].

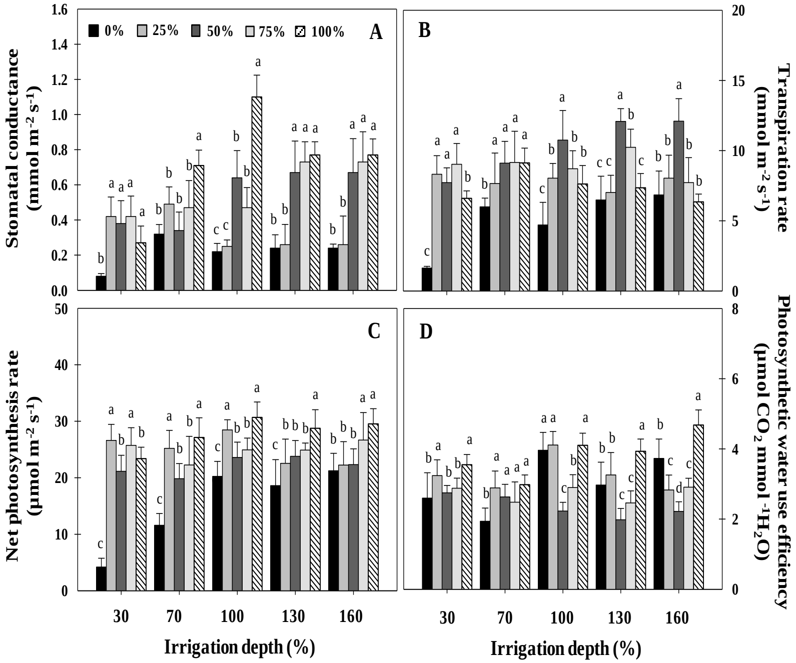

Fig 4. Stomatal conductance (A), transpiration rate (B), net photosynthetic rate (C), and photosynthetic water use efficiency (D) in *Zea mays* plants (cv. BR 106) exposed to five calcium silicate levels (0, 25, 50, 75, and 100% of $CaSiO_3$ indicated to liming of the soil) and five irrigation depths (30, 70, 100, 130, and 160% of necessary to water reposition in this soil). Means followed by the same letter to each irrigation depth are not significantly different by the Scott-Knott test at 5% of probability ($P > 0.05$). The bars represent the mean standard error.

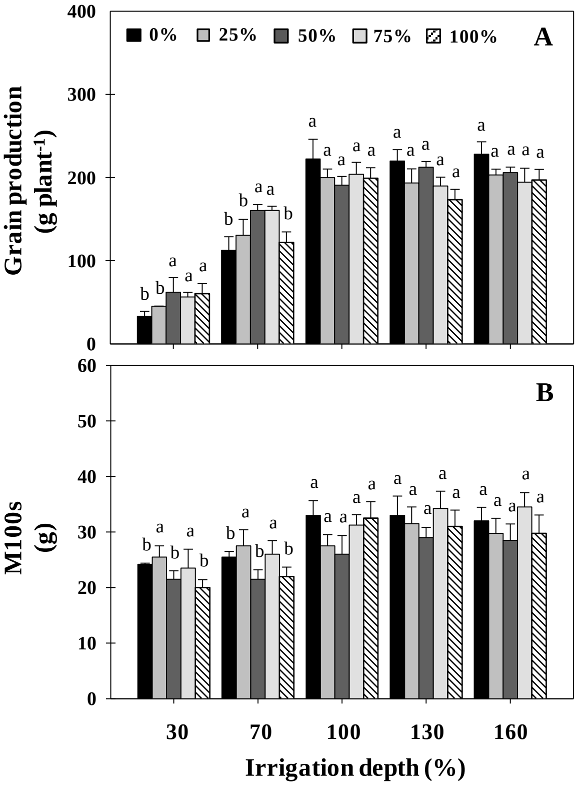

Fig 5. Grain production (A), and matter of 100 seeds (B) in *Zea mays* plants (cv. BR 106) exposed to calcium silicate levels (0, 25, 50, 75, and 100% of $CaSiO_3$ indicated to liming of the soil) and five irrigation depths (30, 70, 100, 130, and 160% of necessary to water reposition in this soil). Means followed by the same letter to each irrigation depth are not significantly different by the Scott-Knott test at 5% of probability ($P > 0.05$). The bars represent the mean standard error

The flexible tubes with 80 cm of length were used in side lines, initiated from distribution control, and water was pressurized by gravity. The uniformity coefficient linked to flow water was measured by formula: CU = ($q_{25\%}$ / $q_{average}$) proposed by Bralts and Kesner (1978). Where, UC = uniformity coefficient, $q_{25\%}$ = average of 25% of minor flows (L h^{-1}), and $q_{average}$ = average total (L h^{-1}). In this study the value to UC was 0.93.

Leaf water potential

The leaf water potentials (Ψw) were measured in fully expanded leaves under light during period between 05:00 to 06:30 h, and 11:30 to 13:00 h corresponding to predawn and midday potentials, respectively, using an analogue plant moisture system (Skye Instruments, model SKPM 1405/50). It is based on technical of pressure chamber (Scholander et al. 1964), according to the procedure of Turner (1988).

Gas exchange

The transpiration rate, stomatal conductance, and net photosynthetic rate were evaluated using an infra-red gas analyser (LICOR, model LI-6400), in adaxial surface of fully expanded leaves, located in median region of each leaf analysed. The photosynthetic water use efficiency was estimated according to Osmond et al. (1980). The gas exchange was evaluated between 9:00 and 12:00 h, in all plants of the experiment, being the irradiance kept in 1000 µmol m^{-2} s^{-1} during the measurements.

Data analysis

Data were subjected to variance analysis and when significant differences occurred; Scott-Knott test at 5% level of error probability was applied (Steel et al., 2006). Standard errors were calculated for all means. All statistical procedures were carried out with the SAS software (SAS, 1996).

Conclusion

The irrigation depths used in this study were effectives to induce water deficit in maize plants. The application of 100% of calcium silicate promoted increase in values of predawn and midday water potentials. Furthermore, the calcium silicate promoted beneficial effects of stomatal conductance, net photosynthetic rate and photosynthetic water use efficiency, when applied at irrigation depths of 70, 100, 130 and 160%. However, despite the effect of calcium silicate to promote significant gas exchange, the increment was not transferred to grain production and matter of 100 seeds.

Acknowledgements

This research financially supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/Brazil) to Lobato AKS, as well as Marques DJ was supported by graduate scholarship also from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/Brazil).

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