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TENSIÔMETROS ELETRÔNICOS INTEGRADOS A PLACA MICROCONTROLADORA ARDUINO NO MANEJO DA IRRIGAÇÃO DE ALFACE EM DIFERENTES POTENCIAIS MATRICIAIS CRÍTICOS E TIPOS DE SOLO

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1 RESUMO

O uso racional da água na irrigação é fundamental para a conservação dos recursos hídricos. Nesse sentido, sistemas de automação de irrigação baseados na variação do potencial matricial do solo podem ser empregados como ferramenta para o uso eficiente da água em sistemas irrigados. Objetivou-se avaliar respostas da alface, cv. Wanda, submetida à potenciais matriciais críticos de irrigação controlados por tensiômetros eletrônicos. Os tensiômetros foram integrados a uma placa microcontroladora Arduino para controle da automação de irrigação. Adotou-se o delineamento experimental em blocos completos casualizados com quatro repetições, tendo como potenciais matriciais críticos -15, -20, -25 e -30 kPa em Latossolo Vermelho Amarelo e -10, -15, -20 e -25 kPa em Neossolo Regolítico. Aos 33 dias após o transplantio, foram obtidos parâmetros fenométricos da alface, índice Falker de clorofila e a Eficiência do Uso da Água (EUA). O sistema de automação monitorou e registrou os potenciais ao longo do ciclo da alface, acionou e interrompeu a irrigação de acordo com os potenciais críticos adotados. Os potenciais matriciais apresentaram variações médias em relação aos valores críticos para acionamento e interrupção da irrigação entre 1,45% e 5,50% no Latossolo Vermelho Amarelo e entre 2,90% e 15,50% no Neossolo Regolítico, respectivamente. A adoção de potenciais críticos abaixo de -15 kPa em Neossolo reduz significativamente a frequência de irrigação. O maior peso de matéria fresca foi obtido no potencial matricial de -10 kPa em Neosolo Regolítico e a maior EUA foi obtida na irrigação acionada no potencial de -15 kPa em Latossolo Vermelho Amarelo.

Keywords: tensão de água no solo, automação, irrigação de precisão.

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ELECTRONIC TENSIOMETERS INTEGRATED WITH ARDUINO MICROCONTROLLER IN IRRIGATION MANAGEMENT OF LETTUCE SUBMITTED TO DIFFERENT CRITICAL MATRIC POTENTIALS AND SOIL TYPES

2 ABSTRACT

The rational use of water in irrigation is fundamental for the conservation of water resources. Irrigation automation based on the variation of the soil matrix potential can be used as a tool

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for the efficient water use in irrigation. This study aimed to evaluate lettuce, cv Wanda responses to soil water potentials for irrigation controlled by electronic tensiometers. The tensiometers were integrated with an Arduino microcontroller to control an irrigation automation system. A randomized complete block design with four replications was adopted, with critical potentials of -15, -20, -25, and -30 kPa in Red Yellow Latosol and -10, -15, -20, and -25 kPa in Regolitic Neossol. At 33 days after transplanting, lettuce phenometric parameters, chlorophyll Falker index, and water use efficiency (EUA) were obtained. The automation system monitored and recorded the potentials throughout the lettuce cycle and triggered and stopped the irrigation according to the critical potentials adopted. The soil water potentials showed average variations to the critical values for starting and stopping irrigation between 1.45% and 5.50% in the Oxisol and between 2.90% and 15.50% in the Regolitic Neossol respectively. The adoption of critical potentials above -15 kPa in Neossolo significantly reduces the frequency of irrigation. The highest fresh matter weight was obtained at the matrix potential of -10 kPa in Regolitc Neossol and the highest EUA was obtained in -15 kPa in the Red Yellow Latosol.

Keywords: soil water tension, automation, precision irrigation

3 INTRODUCTION

The rational use of water in vegetable cultivation in the coming years will depend, among other factors, on the efficiency of sensor-controlled irrigation systems that are capable of avoiding losses caused by excessive irrigation or water deficit, which, in inefficient systems, cause water waste and limited plant growth, respectively (MEDICI *et al*., 2010; VALENÇA *et al*., 2018). Lettuce is a short-cycle, fast-growing vegetable with a high demand for water and nutrients; however, it is capable of providing high increases in fresh mass during its cycle (GEISENHOFF *et al*., 2016). Studies involving slow soil drying with subsequent complete wetting in cultivation pots provide a method of imposing water deficit that minimizes most situations in the field, which is recommended for studying the influence of water stress on root development, nutrient uptake, root–shoot interactions, and phenotyping for drought tolerance (TURNER, 2018).

The approach that uses soil water status monitoring makes irrigation decisions more efficient, as it is related to water availability to plants and can be supported by real-time measurements (MONTESANO; VAN IERSEL; PARENTE, 2016). Currently, several irrigation controllers on the market that regulate the soil water content on the basis of sensor measurements exist. These controllers trigger irrigation when sensors detect values below a predefined lower soil moisture limit and irrigate until a value defined as an upper moisture limit is detected. Generally, the soil moisture reference for these controllers is established using soil moisture at field capacity (ROMERO *et al*., 2012).

Recently, advances in open-source hardware components, such as the Arduino electronics prototyping platform, have introduced new soil moisture measurement devices that can be interconnected with data storage, transmission, and automation systems (BITELLA *et al*., 2014). The Arduino microcontroller runs an open-source program capable of operationalizing electronic components in an electrical circuit. Currently, in the context of open-source electronics, a wide variety of sensors and auxiliary components, such as data storage and communication modules, can be applied to automation and variable monitoring systems linked to irrigated production systems (MASSERONI *et al*., 2016; TARGA; SILVA; CEZAR, 2019). Controlling irrigation automation on the basis of soil matric potential monitoring with low-cost electronics could be a viable alternative for incorporating this technology into commercial vegetable production (VALENÇA *et al*., 2018). Electronic tensiometers coupled to the Arduino platform use pressure transducers as a reading mechanism, which, integrated into a control circuit, enables the automation of irrigation on the basis of direct readings of the soil matric potential (PEREIRA *et al*., 2020) .

In view of the above, the present work evaluated the responses of lettuce crops grown in cultivation pots subjected to different critical matrix potentials of water replacement in an irrigation automation system controlled by an Arduino microcontroller integrated with electronic tensiometers.

4 MATERIALS AND METHODS

4.1 Experimental location

The study was conducted in a greenhouse at the Biology Experimental Station of the University of Brasília (UnB), located at coordinates 15°44'08.7" S and 47°52'58.2" W. The climate of the region, according to Köppen-Geiger, is Aw, characterized as tropical, with a dry season in winter, average annual rainfall of 1360 mm, average maximum annual temperature of 26.7°C and average annual minimum of 16.1°C (CARDOSO; MARCUZZO; BARROS, 2014). The greenhouse is 30 m long and 13 m wide and has an evaporative air cooling system consisting of an expanded clay panel associated with a motor pump set responsible for pumping water to the upper part of the panel and 8 exhaust fans with a removal capacity of 450 m^3 air min^{-1}. The cooling system's actuation control used the internal air temperature, which was set at 27°C by a thermostat installed in the central part of the greenhouse, 2 m above the ground. A shade net with 50% brightness was installed at the ceiling height.

4.2 Physical-hydric and chemical characterization of Red–Yellow Latosol (LVA) and Regolithic Neosol (NR) and preparation of cultivation pots

For the cultivation of lettuce (*Lactuca sativa* L.) cv. Wanda, 11-L pots filled with Red–Yellow Latosol (LVA) with a clayey texture collected in the 0–0.20 m layer in an annual crop area (15°56'56.32" S; 47°55'46.16" W) and with Regolithic Neosol (NR) with a sandy texture collected in the 0–0.20 m layer in a natural Cerrado area (15°58'48.27" S; 47°56'57.54" W) were used. Undisturbed soil samples were used to determine the physical properties (Table 1). Both soils were sieved with a #2.0 mm mesh and air-dried. After drying, five single samples of each soil type were collected to determine their chemical and granulometric properties (Table 2).

Table 1. Physical characteristics of the Red–Yellow Latosol (LVA) and Regolithic Noeosol (NR).

Features	LVA	NR
Bulk density of soil (g cm^{-3})	0.962	1,292
Total porosity (m^3 m^{-3})	0.636	0.512
Macroporosity (m^3 m^{-3})	0.144	0.200
Microporosity (m^3 m^{-3})	0.492	0.312

Source: Authors (2020)

Table 2. Chemical attributes and soil granulometry in the 0–0.20 m layer of the Red–Yellow Latosol (LVA) and Regolithic Noeosol (NR).

Features	LVA	NR	Features	LVA	NR
pH in $CaCl_2$	5.6	4.2	H + Al (cmolc dm^{-3})	3.7	5.5
P (mg dm^{-3})	7.8	4.1	SB (cmolc dm^{-3})	4.7	1.0
K (mg dm^{-3})	62	45	t (cmolc dm^{-3})	4.7	1.7
Ca^{2+} (cmolc dm^{-3})	3.5	0.6	T (cmolc dm^{-3})	8.4	6.6
Mg^{2+} (cmolc dm^{-3})	1.0	0.2	V (%)	56.4	15.9
Al^{3+} (cmolc dm^{-3})	0.01	0.68	m (%)	0.2	39.3
Sand	4.1%	77.2%			
Silt	36.7%	8.5%			
Clay	59.2%	14.3%			

t = effective CEC, T = CEC at pH = 7.0, m = aluminum saturation, V = base saturation, SB = sum of exchangeable bases. **Source**: Authors (2020)

were used. A nonwoven synthetic mat was placed at the inner base of each pot, and a 0.02 m layer of #2.0 gravel was added to aid drainage. Lettuce seedlings were grown in 200-cell expanded polystyrene trays filled with a commercial substrate composed of coconut fiber and vermiculite. One seedling per pot was transplanted when the seedlings had, on average, five definitive leaves.

The experimental design was a randomized complete block design with four replications. Each experimental plot consisted of four pots with 1.0 m row spacing and 0.4 m plant spacing. Fifty-two border pots were planted in the area, resulting in a total of 180 pots. Fertilization was performed manually by broadcasting (Table 3), converting the recommended amount, in kg ha -1, to g pot $^{-1}$, considering the cross-sectional area of each pot (530 cm ^{2}), fertility analysis (Table 2), and dosages according to the recommendation proposed by Ribeiro, Guimarães, and Alvares (1999).

Table 3. Fertilization was performed in pots filled with LVA and NR.

Nutrient	Recommendation (kg ha^{-1}) LVA	Recommendation (kg ha^{-1}) NR	Total quantity per pot (g) LVA	Total quantity per pot (g) NR	Planting	1st application	2nd application	3rd application
N	150	150	21.2	21.2	20%	20%	30%	30%
P_2O_5	300	400	92.9	123.8	100%	-	-	-
K_2O	90	120	9.6	13.0	20%	20%	30%	30%

Source: Authors (2020)

Before the seedlings were transplanted into the pots, 25 mm of water was applied in three applications, which was sufficient for water drainage through the bottom of the pots and soil settlement inside. Then, undisturbed samples were taken to develop the soil water retention characteristic curve via the Richards pressure chamber method. The water retention equations for LVA and NR were adjusted on the basis of the model proposed by Van Genuchten (1980), using the Mualem restriction and the RETC software (VA GENUCHTEN; LEIJ; YATES, 1991), as well as soil moisture at field capacity (Θcc) at potentials of -10 kPa for LVA and -

5 kPa for NR and the permanent wilting point (ϴpmp) at a potential of -1500 kPa for both soils (Table 4).

Table 4. Fitted equations of soil water retention curves according to Van Genuchten, moisture content at field capacity (ϴcc) and permanent wilting point (ϴpmp) for LVA and NR.

Soil type	Fitted equation	R^2	ϴcc ($cm^3\ cm^{-3}$)	ϴpmp ($cm^3\ cm^{-3}$)
LVA	$\theta = 0.159 + 0.674/[1+(0.178\ h)^{1.23}]^{0.18}$	0.99**	0.55	0.23
NR	$\theta = 0.113 + 0.445/[1+(0.069\ h)^{1.89}]^{0.47}$	0.98**	0.40	0.11

ϴ: volumetric moisture content ($cm^3\ cm^{-3}$); h: Matric potential (kPa); ϴcc: moisture content at field capacity on a volume basis ($cm^3\ cm^{-3}$); ϴpmp: soil moisture at the permanent wilting point on a volume basis ($cm^3\ cm^{-3}$); **Significant at $p < 0.05$. **Source**: Authors (2020)

4.3 Irrigation system

A drip irrigation system was used with on-line emitters installed in 16 mm outer diameter LDPE pipes, one emitter per cultivation pot, and a flow rate of 4.0 L h^{-1} at a working pressure of 10 mca maintained by a pressure regulator. A 125 micron disc filter, pressure taps installed after the solenoid valves, a Bourdon pressure gauge with a glycerin accuracy of 0.1 kgf cm^{-2}, ball valves, hydraulic connections, and a 1000 L reservoir were used. At the beginning of the experiment, the flow rates of the 16 drippers were measured in triplicate for a collection time of 2 min, and the coefficient of distribution uniformity (CUD) was 97.06%.

4.4 Automation and monitoring system for micrometeorological variables

The monitoring of the soil matric potential was performed by electronic tensiometers coupled to MPX5700DP pressure transducers, which converted the partial vacuum inside the tensiometer into an electrical signal and transmitted it to the Arduino microcontroller board. The Arduino MEGA 2560 board integrates tensiometers with other system components, including the *real-time clock (RTC*) module, *the data logger (SD-Card*) module, relay modules, ½" solenoid valves, and a 1/3 hp single-phase motor pump. Each relay module has four channels; therefore, two relay modules were used to drive eight solenoid valves, and an additional single-channel relay was used to drive the motor pump. Eight analog ports on the Arduino board were used to connect the pressure transducers. A 7.5 V DC source was used to power the Arduino board, and a 5 V DC source was used for the pressure transducers and relay modules. All sources were connected to a power strip connected to the conventional power grid, which operates at 220 V. Figure 1A shows the arrangement of the vessels with the tensiometers, and Figure 1B shows an electronic tensiometer.

Figure 1. General arrangement of vessels and electronic tensiometers (A); detail of the electronic tensiometer installed in the vessel (B).

Source: Authors (2020)

For irrigation automation programming, a programming code was developed containing a main code and subroutines to execute the following procedures: i) measurement of the matrix potential provided in each reading with its respective date and time of acquisition; ii) storage of the readings in a *.txt file* at 60-s intervals; and iii) comparison of the read values of the matrix potential with critical values defined by the user so that the system would act in activating the motor pump and opening and closing solenoid valves. The critical mechanical potentials (PMc) were obtained from the characteristic water retention curves of each soil, where from the field capacity values of -10 kPa for LVa and -5 kPa for NR, PMc values of -15, -20, -25 and -30 kPa were adopted for LVA, called LVA/-15 kPa, LVA/-20 kPa, LVA/-25 kPa and LVA/-30 kPa, respectively, and -10, -15, -20 and -25 kPa for NR, called NR/-10 kPa, NR/-15 kPa, NR/-20 kPa and NR/-25 kPa, respectively. For the end of a given irrigation shift, the time required to reestablish moisture at field capacity in each soil was specified via Equation (1), which is indicated for localized irrigation via tensiometry and adapted from Braga and Calgaro (2010).

$$Ti=\frac{Lb*Dm}{n*Q} \quad (1)$$

where Ti = irrigation time (min); Lb = gross application depth (mm); Dm = diameter wetted by the dripper (0.057 m); n = number of drippers per pot (1); and Q = dripper flow rate (0.066 L min $^{-1}$).

The temperature and relative humidity were obtained via the DHT-22 conjugate sensor, which was integrated into an Arduino UNO board. The sensor is capable of reading a relative humidity between 0 and 100% and an air temperature between -40 and 125°C, with readings every 60 seconds, and storing the data in a text file via the SD-Card module (*Data Logger*). For this purpose, it was installed in the central part of the experiment at a height of 1.0 m from the ground.

4.5 Lettuce phenometric parameters, water use efficiency and Falker total chlorophyll index

At 33 days after transplanting (DAT), the number of leaves (NF), stem height (AC), stem diameter (DC), fresh shoot mass (MFPA), fresh root mass (MFR), dry shoot mass (MSPA), dry root mass (MSR), Falker index of chlorophyll a (CLA), chlorophyll b (CLB), total chlorophyll (CLT) and water use efficiency (WUE) were determined. For all the variables obtained, four useful plants per replicate were considered, totaling 16 plants per treatment. In the NF count, only expanded leaves with a minimum length of 5 cm and a typical green color of the cultivar were considered, discarding dry leaves close to the ground (VIANA *et al*., 2004) and those whose leaf blade was damaged by more than 50% due to various injuries. The CA was defined after leaf removal by measuring the distance between the plant collar and the insertion of the sheath of the first (youngest) leaf via a digital caliper with a precision of 0.01 mm. The DC was measured in the plant collar region after all the leaves were removed, with readings in mm taken with the aid of calipers. The MFPA was obtained by weighing the leaves and stems, and the MFR was obtained by weighing the roots sectioned from the collar of each plant. The MSPA and MSR were subsequently obtained by weighing the leaves, stems, and roots after drying in a forced circulation oven at 65°C for 72 hours. Both fresh and dry mass measurements were taken on a precision balance with a precision of 0.01 g.

The chlorophyll values were indirectly determined via a ClorofiLOG® model CFL 1030 chlorophyll meter. On the basis of the results of the chlorophyll a (CLA), chlorophyll b (CLB) and total (CLT) indices, linear regression models were adjusted to describe the relationships between the critical potentials and the average chlorophyll indices obtained in each water replacement treatment. The water use efficiency (WUE) was obtained considering the MFPA and the total irrigation depth (mm) applied per treatment from the MFPA/total depth ratio.

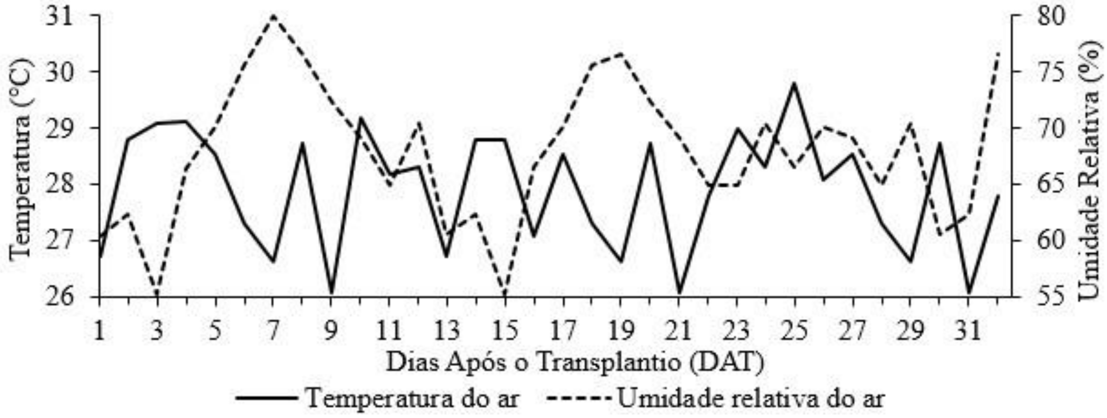
The results were subjected to analysis of variance via the 'F' test, where in cases of significance, the Tukey test was performed to compare means for the phenometric variables of the plants and regression analysis for the chlorophyll index, both at the significance level of $p < 0.05$. Additionally, the phenometric data were subjected to principal component analysis. For the statistical analyses, RStudio v. 1.3.1073 software was used.

5 RESULTS AND DISCUSSION

5.1 Irrigation automation system and micrometeorological variables

The average values of air temperature and relative humidity during the crop cycle were 27.9°C and 68%, respectively (Figure 2). The maximum tolerable temperature for lettuce is approximately 30°C for most cultivars (DIAMANTE *et al*., 2013). These data are similar to those reported by Villas Boas *et al*. (2008), who recorded average values of 25°C and 66.5% for air temperature and relative humidity, respectively, in a greenhouse.

Figure 2. Average daily variations in air temperature and relative humidity during the cycle

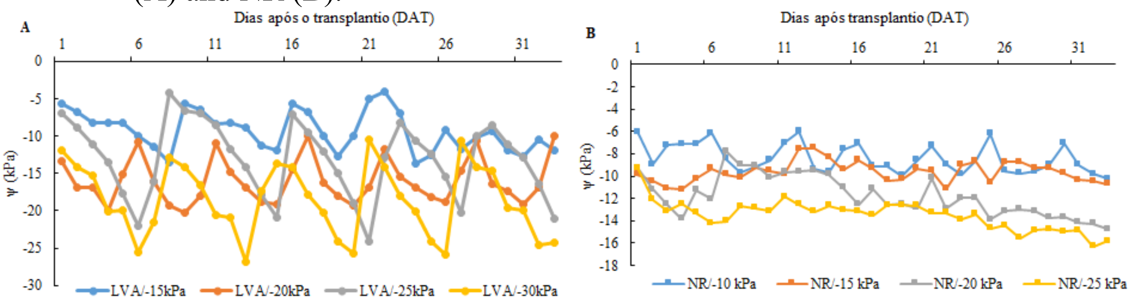


Source: Authors (2020)

Each PMc presents a distinct temporal dynamic, in which the LVA/-15 kPa (Figure 3A) maintained values close to -10 kPa, with some occurrences of daily average values close to -5 kPa, which indicates excessive soil moisture on these days since the field capacity potential for the LVA is -10 kPa. The PMc LVA/-20 kPa varied between -10 and -20 kPa throughout the lettuce cycle. The LVA/-25 and LVA/-30 kPa of the PMc maintained daily average values above the critical values adopted for triggering; however, the LVA/-30 kPa presented average values below -15 kPa most of the time, indicating that moisture was maintained below field capacity.

In NR (Figure 3B), the PMc NR/-10 kPa maintained average values between -6 and -10 kPa during the lettuce cycle. The matric potential (PM) at field capacity for NR was -5 kPa, and when observing the average variation in the other PMcs, it was verified that the daily average values did not reach this value throughout the cycle. The higher irrigation frequency at a PMc of -10/kPa (Table 9) was decisive for maintaining the daily average PM closer to the established field capacity. The NR/-25 kPa PMc maintained daily average potential values below -10 kPa, indicating the maintenance of soil moisture at values below field capacity throughout the lettuce cycle for this PMc.

Figure 3. Average daily variation in matric potential throughout the lettuce cycle under LVA (A) and NR (B).



Source: Authors (2020)

The performance of irrigation control via matric potential is considered satisfactory when the potentials are maintained at values close to the limits adopted for irrigation activation and interruption, considering a maximum tolerance of 20% (ALMEIDA *et al.*, 2017). On the basis of these criteria, the potentials of LVA and NR remained within acceptable limits throughout the crop cycle (Figure 3). However, in NR, there was greater variation in the potential readings at the time of activation and mainly after the end of irrigation, with this variation being above 20% in NR/- 10 kPa (Table 5). Soils that drain water more quickly are generally those with greater macroporosity, whereas those that drain more slowly are soils in which micropores constitute the majority of the total porosity. Thus, as is well known, sandy soil conducts water more quickly than clayey soil does (HILLEL, 1998). Therefore, the greater variation in potential in NR may have been influenced by this soil characteristic, which has a macroporosity of 20% and a sand percentage of 77%, whereas LVA has 14% macroporosity and 4% sand (Table 1).

Table 5. Average matric potential for irrigation activation (PMa), average matric potential for irrigation interruption (PMi), standard deviation (SD) and coefficient of variation (CV) for critical matric potential (PMc) in LVA and NR.

Soil type	PMc (kPa)	PMa (kPa)	CV (%)	SD (kPa)	PMi (kPa)	CV (%)	SD (kPa)
LVA	-15	15.52	2.77	0.42	5.81	3.88	0.24
	-20	21.95	0.87	0.16	12.40	2.34	0.30
	-25	25.46	0.89	0.22	10.19	7.52	0.76
	-30	31.08	1.27	0.37	9.34	8.36	0.78
NR	-10	10.51	4.34	0.45	4.52	25.73	1.16
	-15	15.78	3.41	0.53	5.40	11.64	0.62
	-20	20.62	2.02	0.41	4.93	13.58	0.67
	-25	25.66	2.11	0.54	4.88	11.43	0.55

LVA: Red Yellow Latosol (LVA) and NR: Regolithic Neosol. **Source**: Authors (2020)

PMc readings may also be related to the electrical signal transmitted by the pressure transducer connected to the tensiometer. Each soil drying and wetting cycle alters the air volume inside the tensiometer, which can cause small variations in the electrical signal output from the pressure transducer (AZEVEDO, 2017). Considering the available water capacity (AWC) as the soil moisture range between the permanent wilting point (-1500 kPa) and the field capacity (-10 kPa for LVA and -5 kPa for NR), the automation system in LVA controlled 13, 21, 27 and 32% of the AWC in the PMc's LVA/-15, LVA/-20, LVA/-25 and LVA/-30 kPa, respectively, and in NR, it controlled 46, 62, 76 and 77% of the AWC in the PMc's NR/-10, NR/-15, NR/-20 and NR/-25 kPa, respectively.

Tensiometers generally have a matric potential reading capability of up to -100 kPa, below which the equipment loses its prime and stops recording matric potentials properly (BIANCHI *et al*., 2017). Up to -100 kPa, it is possible to monitor approximately 70% of the available water capacity (AWC) in sandy soil, whereas in clayey soil, up to 40% of the AWC can be monitored (BRAGA; CALGARO, 2010). Furthermore, good controller performance depends on proper maintenance and correct installation of the tensiometer to ensure the best possible contact between the porous capsule and the soil. Maintenance, which mainly consists of refilling the tensiometer with water, was more frequent in the MPcs in NR, especially at potentials below -15 kPa in NR.

5.2 Phenometric parameters of lettuce

In the phenometric analysis of lettuce, the coefficients of variation (CVs) ranged from 14.34 to 54.24%, with the greatest variations for MFPA and MFR (Table 6), which are directly related to fresh phytomass production. When the difference between MFPA and MSPA was applied, the average percentage of water in lettuce in the PMc in LVA was 91.2%, and in NR, it was 92.1%. Lettuce has, on average, 94% water in its composition; thus, part of the crop variability occurs due to variations in water content from one plant to another, resulting in a higher CV in MFPA (GUIMARÃES *et al*., 2019).

The NR/-25 kPa PMc presented the lowest values for most of the phenometric variables evaluated (Table 6). The greatest phenometric reduction in NR/-25 kPa was observed for MFPA, where in relation to NR/-10 kPa, MFPA was 67% lower and in relation to LVA/-30 kPa, the reduction was 29%. The difference in moisture content between the PMc NR/-25 kPA and NR/-10 kPa treatments was approximately 10%, and the irrigation frequency in the NR/-25 kPa treatment was 60% lower than that in the NR/-10 kPa treatment (Table 7). The MFPA results at NR/-10 kPa follow the trend observed by Geisenhoff *et al*. (2016), in which the highest productivity of crisp lettuce in protected cultivation was obtained when irrigation was carried out at critical potentials close to -12 kPa.

The reduction in NF as a function of PMc was significant in NR from NR/-15 kPa, whereas in LVA, NF did not significantly differ between the PMcs evaluated. The highest DP values occurred in NR/-10 kPa and did not differ in the PMcs in LVA. The DP reductions in NR were 6.1, 5.3, and 9.1 cm for PMcs NR/-15, NR/-20, and NR/-25 kPa, respectively (Table 6). On the basis of these NR results, the average DP reduction was 0.04 cm per unit increase in the PMc adopted. This result is lower than that reported by Geisenhoff *et al*. (2016), who used PMc values between -12 and -70 kPa in medium-textured soil and reported a reduction of 0.08 cm (DP) per unit increase in the critical irrigation potential adopted.

MPc values between -15 and -30 kPa did not significantly alter the phenometric responses of lettuce crops to LVA. Bianchi *et al*. (2017) reported high variability in the MPc values of lettuce crops, which depend on factors such as species and varieties, soil texture, irrigation system, type of matric potential monitoring device, and tensiometer installation depth. In general, for lettuce crops, considering tensiometers installed to a depth of 0.15 m in sandy soils and drip irrigation, ideal MPc values can reach -20 kPa. For clayey soils under the same irrigation system, the authors reported ideal PMc values of up to -30 kPa.

Table 6. Number of leaves (NF), stem diameter (DC), stem height (AC) and plant diameter (DP), fresh shoot mass (MFPA), fresh root mass (MFR), dry shoot mass (MSPA) and dry root mass (MSR) for critical matric potential (PMc) in LVA and NR.

Soil type		**Variables**							
LVA	NR	LVA	NR	LVA	NR	LVA	NR	LVA	NR
PMc	PMc	NF		DC (mm)		AC (mm)		DP (cm)	
-15	-10	9 aA	12 bB	7.7 aA	9.8 aB	38.9 aA	59.6 aB	26.4 aA	32.4 bB
-20	-15	9 aA	9 aA	8.1 aA	7.9 aA	42.3 aA	42.3 bA	27.3 aA	26.3 aA
-25	-20	9 aA	9 aA	7.3 aA	8.5 aA	45.3 aA	50.2 aB	26.1 aA	27.1 aA
-30	-25	9 aA	8 aA	7.6 aA	7.7 aA	38.4 aA	36.9 bA	25.2 aA	22.3 aA
CV (%)		16.63		18.99		18.16		14.34	
		MFPA (g)		MFR (g)		MSPA (g)		MSR (g)	
-15	-10	37.7 aA	79.7 bB	6.1 aA	7.8 aA	3.4 aA	5.0 aA	1.3 aA	1.0 aA
-20	-15	42.9 aA	37.7 aA	2.7 bA	2.7 bA	3.7 aA	3.6 abA	0.4 bA	0.4 aA
-25	-20	38.2 aA	41.1 aA	3.9 abA	2.8 bA	3.2 aA	3.3 abA	0.6 abA	0.3 bA
-30	-25	36.9 aA	26.1 aB	5.3 abA	1.2 bB	3.3 aA	2.7 bA	1.0 abA	0.2 bA
CV (%)		54.24		31.78		18:00		21.04	

Different lowercase letters in a column and uppercase letters in a row differ from each other according to Tukey's test ($p < 0.05$). **Source**: Authors (2020)

5.3 Water Use Efficiency (USA)

At LVA/-25 kPa, a total irrigation depth of 40.7 mm was applied from transplanting to 33 DAT, resulting in an EUA of 1.06 g mm $^{-1}$ (Table 7). At LVA/-15 kPa, 28.8 mm was applied, resulting in an EUA of 1.31 g mm $^{-1}$. In turn, at LVA/-30 kPa, 47.1 mm was applied in 5 irrigation events during the lettuce cycle, equivalent to an EUA of 1.27 g mm $^{-1}$. Although the irrigation frequency in LVA/-15 kPa was slightly greater than that in LVA/-30 kPa, the total depth applied was 38.8% lower. This occurred because the moisture content in the PMc LVA/-15 kPa was 52.8%, and in the LVA/-30, it was 47%, which corresponds to depths of 2.9 mm and 7.8 mm per irrigation event, respectively. In general, the total irrigation depth and number of irrigations were greater in the NR than in the LVA for all the PMcs evaluated (Table 7).

The greatest total water depth (177.5 mm) was applied at NR/-10 kPa (Table 7), which resulted in the highest MFPA production among the evaluated PMcs (Table 6). Valeriano *et al*. (2016) reported the highest commercial weight of lettuce plants from water depths between 116 and 118 mm cycle $^{-1}$ in sandy loam soil; above this water depth, no significant gains in fresh matter production could be observed. In turn, Cardoso and Klar (2011) reported greater accumulation of fresh matter in the aerial part with the application of a water depth of 114 mm cycle $^{-1}$ at a PMc of -20 kPa in sandy soil.

The total number of irrigations in NR was dependent on the PMc, in which the reduction from -10 to -15 kPa significantly reduced the irrigation frequency in NR. The greater water depth applied in the PMcs in NR mainly influenced the EUA, with values below 1.0 g mm $^{-1}$ for all the PMcs evaluated. The PMc in NR/-10 kPa resulted in the highest EUA in NR, with the application of a total water depth of 177.5 mm distributed in 15 irrigation events, whereas NR/-25 kPa resulted in the lowest EUA in NR, with the application of a total water depth of 140.0 mm (Table 7). Bandeira *et al* . (2011) reported that water distribution and maintenance of optimal soil moisture levels throughout the crop cycle reduce drainage losses and periods of water stress, thus increasing the EUA.

Although the EUA in NR was lower than the LVA, the MFPA in NR/-10 kPa was higher among all the PMCs evaluated, with an average value of 79.7 g plant $^{-1}$ (Table 7). A higher EUA does not necessarily represent an increase in fresh mass production, as observed by Valeriano *et al*. (2016), where the application of 60% crop evapotranspiration (ETc) in American lettuce grown in a protected environment resulted in an EUA of 1.8 g mm $^{-1}$ and a commercial head weight of 120 g plant -1. On the other hand, the application of 95.73% ETc resulted in an EUA of 1.2 g mm -1 and a commercial head weight of 175.4 g plant -1.

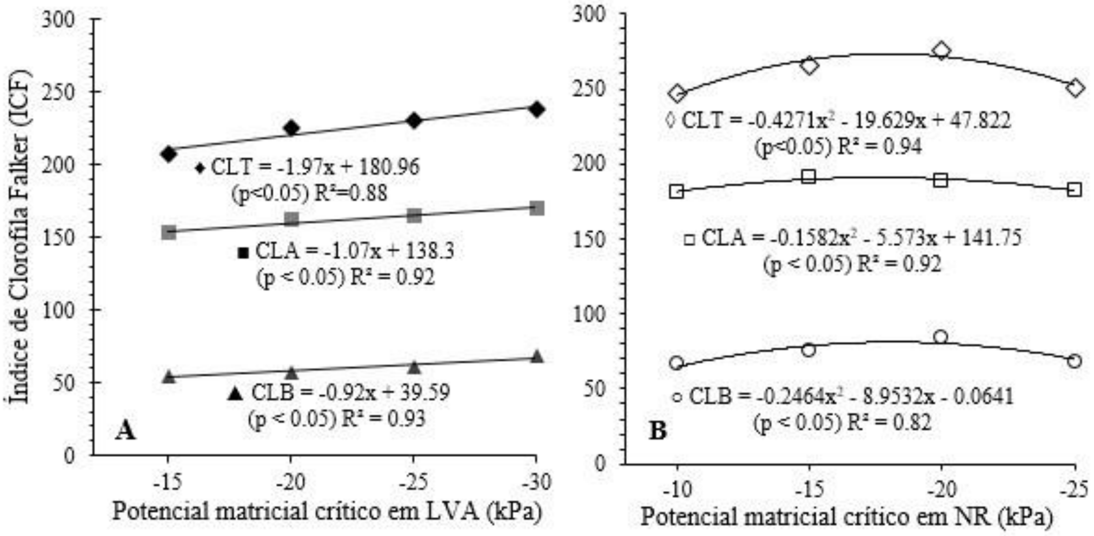
Table 7. Critical water replacement potential (PMc), moisture at field capacity (Θ_{cc}), moisture at critical potential (Θ_{pc}), water depth applied per irrigation event (LI), irrigation depth applied before (Initial) and after treatment differentiation (Irrigation), total water depth applied (Total), total number of irrigations (NI) and water use efficiency (EUA) in lettuce grown in packages filled with LVA and NR in a protected environment.

Soil type	PMc (kPa)	Θ_{cc} (%)	Θ_{pc} (%)	LI (mm)	Blades (mm)		Total	NI	USA (g mm $^{-1}$)
					Home	Irrigation			
LVA	-15	55.6	52.8	2.9	8	20.8	28.8	7	1.31
	-20	55.6	50.7	4.9	8	29.7	37.7	6	1.13
	-25	55.6	49.0	6.5	8	32.7	40.7	5	1.06
	-30	55.6	47.0	7.8	8	39.1	47.1	5	1.27
NR	-10	40.4	29.8	10.8	15	162.5	177.5	15	0.44
	-15	40.4	24.7	16.0	15	128.2	143.2	8	0.26
	-20	40.4	21.8	18.9	15	170.6	185.6	9	0.22
	-25	40.4	20.0	20.8	15	125.0	140.0	6	0.18

5.4 Chlorophyll index

The Falker chlorophyll indices showed a linear increase as a function of the critical potentials used in LVA (Figure 4A), whereas in NR (Figure 4B), the indices showed quadratic responses, indicating a point of maximization of chlorophyll contents in NR. Valença *et al*. (2018) reported a linear increase in total chlorophyll with a reduction in the water volume applied to lettuce grown in pots, which occurred because of the increase in chlorophyll concentration due to the smaller amount of leaves observed in the treatments with lower water replacement. A similar behavior was observed for the PMc in NR (Table 6), in which the NF decreased significantly with increasing PMc from -10 to -15 kPa. For LVA, the linear increase in chlorophyll content did not significantly alter the NF, since the NF values remained constant between the PMc values of -15 and -30 kPa (Table 6).

Figure 4. Falker indices of chlorophyll a (CLA), chlorophyll b (CLB) and total chlorophyll (CLT) for LVA (A) and NR (B) as a function of the critical water replacement potential in lettuce grown in a protected environment.



Source: Authors (2020)

5.5 Principal component analysis (PCA)

PCA is a statistical multivariate analysis technique that linearly transforms an original set of variables, initially correlated with each other, into a substantially smaller set of uncorrelated variables that contain most of the information of the original dataset (HONGYU, 2015).

In the principal component analysis, the first three components accounted for more than 80% of the accumulated variance (Table 8), with the first two components accounting for 72.81% of the explained variance. The variables with the largest contributions to the first component, which accounted for 55.69% of the total variance, were MFPA, MSPA, and NF. For the second principal component, which accounted for 17.11% of the total variance, the variables with the greatest weights were MSR and MFR.

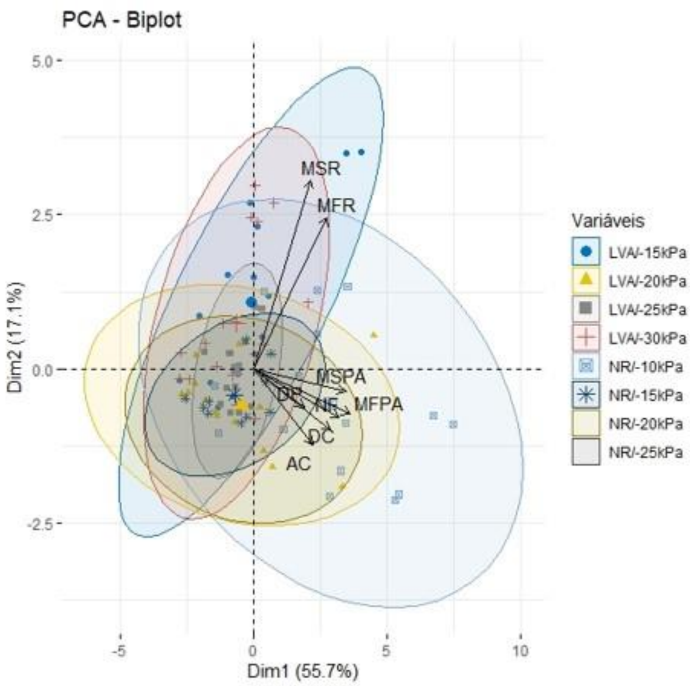
In the graphical representation of the PCA (Figure 5), practically all the variables are responsible for the discrimination of the NR/-10 kPa group, whereas the MSR and MFR variables are more responsible for the discrimination of the LVA/-15 and LVA/-30 kPa groups. Thus, the three groups are similar in terms of root production; however, the NR/-10 kPa group is characterized by plants with greater shoot development, with greater production of MFPA, MSPA, and NF and higher values of AC, DC, AP and DP, whereas the LVA/-15 and LVA/-30 kPa groups are characterized by smaller plants but greater root development due to greater production of MFR and MSR. Soundy *et al.* (2005) evaluated the effects of deficit irrigation with replacement on field capacity in lettuce. The authors reported that root mass accumulation was similar between treatments and that the application of deficit irrigation more effectively affected weight accumulation in the shoot system than in the root system. The authors state that under moderate water deficit conditions, roots are likely to exhibit greater lateral and in-depth development to access water at depth in response to drying in the uppermost part of the soil.

Table 8. Principal component analysis of lettuce phenometric parameters in all PMCs evaluated in LVA and NR.

Variance components	**Main components**				
	1	2	3	4	5
Eigenvalues	4.45	1.36	0.81	0.69	0.38
Total variance explained (%)	55.69	17.11	10.16	8.72	4.80
Cumulative variance (%)	55.69	72.81	82.98	91.70	96.51
Variables	Correlation with principal components				
NF	**0.84**	-0.20	-0.18	-0.14	-0.34
MFR	0.72	**0.64**	0.08	0.14	0.06
A.D	0.75	-0.26	-0.27	-0.17	0.48
B.C	0.58	-0.32	0.22	0.69	0.03
MFPA	**0.95**	-0.19	-0.05	0.03	-0.03
MSR	0.56	**0.81**	0.01	-0.01	0.01
MSPA	**0.91**	-0.09	-0.17	-0.12	-0.15
DP	0.49	-0.16	0.78	-0.34	0.03

Source: Authors (2020)

Figure 5. Dispersion (b *biplot graph*) of PMCs in LVA and NR. MSPA: Dry mass of aerial parts; MFPA: Fresh mass of aerial parts; DP: Plant diameter; NF: Number of leaves; DC: Stem diameter; AC: Stem height; MSR: Dry mass of roots; MFR: Fresh mass of roots.



Source: Authors (2020)

6 CONCLUSIONS

The use of electronic tensiometers integrated with an Arduino microcontroller board was able to monitor, store matric potential data, and trigger and interrupt irrigation at all critical matric potentials evaluated in Red–Yellow Latosol and

Regolithic Neosol. The irrigation frequency at the critical matric potential of -10 kPa in the Regolithic Neosol resulted in the greatest variation in matric potential at the end of each irrigation event.

For critical matric potentials below -15 kPa in the Neosol Regolithic period, the irrigation frequency was substantially reduced. Under these conditions, water deficit hampered the growth of the lettuce plants in the pots. The highest water use efficiency for lettuce occurred in Red–Yellow Latosol at a critical matric potential of -15 kPa. However, despite having a lower WUE, the highest shoot fresh weight production occurred in the Neosol Regolithic period at a critical matric potential of -10 kPa. Furthermore, the results demonstrated that shoot production was favored at the critical potential of NR/-10 kPa. However, the critical potentials of -15 and -30 kPa favored root development in LVA but did not achieve the productive performance observed at NR/-10 kPa.

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