*Article*

# Intelligent System for Monitoring Water Content and Solute Concentrations in Soil Cultivated with Fertigated Lisianthus

**Osvaldo Nogueira de Sousa Neto[1], Paulo Hercilio Viegas Rodrigues[2], Nildo da Silva Dias[1], Pedro Ramualyson Fernandes Sampaio[1], Ana Luiza Ferreira[1], Hans Raj Gheyi[3] and Sergio Nascimento Duarte[2*]**

[1] Rural Federal University of Semi-arid, Mossoró, Brazil; osvaldo.neto@ufersa,edu.br; nildo@ufersa,edu.br; ramualyson@hotmail.com; ferreira.analuizal@gmail.com
[2] College of Agriculture "Luiz de Queiroz", University of São Paulo, Piracicaba, Brazil; phrviegas@usp.br; snduarte@usp.br
[3] Federal University of Campina Grande, Campina Grande, Brasil; hgheyi@gmail.com
* Correspondence: snduarte@usp.br; Tel.: +55(19)3447-8543

**Abstract:** In precision agriculture in fertigated crops it is necessary to optimize the use of water and chemicals, and enable efficient application of fertilizers in order to ensure the best yield and avoid risks of soil salinization and contamination. In this study, an intelligent system was developed with the objective of monitoring, in real-time, moisture and solute concentrations in soil cultivated with lisianthus (*Eustoma grandiflorum*, var. Casablanca) fertigated under a protected environment. During one crop cycle, moisture was monitored in soil solution using TDR100 reflectometer and solute concentrations were monitored with ceramic cup extractors. Plants were fertigated with a solution containing five potassium concentrations (50, 100, 150, 200, and 250 mg dm$^{-3}$) applied when the soil reached moisture limits of 0.20, 0.15, 0.13, 0.11, and 0.09 cm$^3$ cm$^{-3}$. Experimental plots were arranged in a randomized block design in a 5 x 5 factorial scheme (moisture limits x potassium concentrations in soil solution), with four replicates. The proposed intelligent system enabled precise monitoring of moisture and electrical conductivity by TDR, and potassium, and other solute concentrations with extractors, being indicated for the management of lisianthus fertigation under greenhouse conditions with greater environmental safety and reduction of water consumption and risk of salinization.

**Keywords:** irrigation management, fertigation, TDR probe, ceramic extractors, salinity.

## 1. Introduction

Worldwide, irrigated agriculture is facing serious problems with water scarcity [1,2], forcing many farmers to deal with biosaline agriculture, using unconventional such as saline/brackish or recycled water sources for crop production [3] and also to develop more precise methods of irrigation and water and fertilizer management systems [4-8]. Consequently, there is increasing pressure to optimize the management of the water used in irrigation and ensure optimal production and economic returns to avoid salinity and other environmental damages [9,10].

 doi:10.20944/preprints202212.0035.v1

In modern cultivation under protected conditions, plants are supplied with nutrient solutions rather than simply irrigation water. However, the excess nutrient solution draining below the root zone contains considerable levels of nutrients that may be considered to be pollutants [4,11] as well as a waste of financial resources.

In the specific case of the lisianthus crop, a new and promising cut flower that has recently started to be produced in Brazil, both irrigation and fertigation practices have a major impact on the production and quality of stems and flower buds. However, many producers of this species of flowers produced in Southeastern Brazil have relied on empiricism or fertilizer recommendations of other countries, resulting in the application of insufficient or excessive amounts of water and fertilizers [12,13]. These actions have resulted in low crop yield, due to either deficit or excess moisture in the soil, contamination of the soil by the accumulation of excess nutrients, and soil salinization [14].

Intelligent systems for properly managing fertilizers and water in soil solution can be used in protected environments to minimize environmental contamination from fertigation leaching and, consequently, considerable savings of water and fertilizers are conciliated with high yields and greater water use efficiency [15,16,4,17] besides prevention and control of soil salinization in the intensively irrigated areas [3]. In these systems, the use of Time Domain Reflectometry and solution extractors associated with a mass balance equation of the applied solution [18,19] is a key tool that assists in monitoring and estimation of moisture content, controlling salinity, and nutrient application [20].

In this study, an intelligent system was developed with the objective of monitoring, in real-time, moisture and solute concentrations in fertigated soil cultivated with lisianthus (*Eustoma grandiflorum*, var. Casablanca) in greenhouses.

We conclude that intelligent systems for determining soil water content are needed to increase water use efficiency in fertigated crops. Also, real-time monitoring solute concentrations helps in the efficiency of fertilizer use and prevents contamination of fertigated soils. Finally, automatic systems to monitor solute concentrations in real-time can also prevent the accumulation of salts in soils cultivated under protected conditions.

## 2. Materials and Methods

The study was conducted in two greenhouses at the Department of Biosystems Engineering of the "Luiz de Queiroz" College of Agriculture, University of São Paulo (ESALQ/USP), in the municipality of Piracicaba, SP, Brazil (22º 42′ South latitude and 47º 38′ West longitude, at an altitude of 546 m).

Experimental plots were constructed in two arched greenhouses (6.40 m wide x 17.5 m long) with polyethylene cover (0.15 mm thick), both having front and side protections covered by 50% shade net. The experimental unit was composed of an excavated bed + drainage system + intelligent system for monitoring water and nutrients of the soil solution (TDR probe and solution extractors) (Figure 1).


**Figure 1.** Schematic design of an experimental plot (bed + drainage system).

Beds were excavated with dimensions of 0.7 x 15 x 0.50 m and then filled with soil material (EC = 0.38 dS $m^{-1}$), totaling 5 longitudinal beds per greenhouse spaced apart by 0.40 m. These beds were coated with waterproof plastic canvas and received a corrugated drain tube with a 0.065 m internal diameter and a 0.10-m-thick layer of gravel + geotextile to avoid losses of soil particles and clogging of the drainage system. The drains were connected to a reservoir that served to store and monitor the leached nutrient solution of excessive fertigation.

The soil used was collected at 0.50 m from the arable layer of a profile classified as*Red Yellow Latosol* (Oxisol) [21]. After filling the beds, the soil remained at rest for 20 days, being irrigated daily with supply water for particle stabilization and, subsequently, soil samples were collected for physical-hydraulic (Table 1) and chemical (Table 2) characterization in the layers of 0-15 and 15-30 cm.

**Table 1.** Physical-hydraulic characterization of the *Red Yellow Latosolo* (Oxisol) used in the experiment

| **Layer** | **Particle size (%)** | | | **Density (kg dm$^{-3}$)** | | **Porosity (%)** | | | **Textural Class** |
|---|---|---|---|---|---|---|---|---|---|
| **(m)** | **Sand** | **Silt** | **Clay** | **Bulk** | **Particle** | **Micro** | **Macro** | **Total** | |
| 0 – 0.15 m | 73.0 | 8.0 | 19.0 | 1.29 | 2.66 | 27.51 | 22.59 | 0.501 | Sandy Loam |
| 0.15–0.30 m | 74.4 | 8.6 | 17.0 | 1.32 | 2.60 | 29.43 | 19.87 | 0.493 | Sandy Loam |

 doi:10.20944/preprints202212.0035.v1

**Table 2.** Chemical characterization of the *Red Yellow Latosol* (Oxisol) used in the experiment.

| Layers | pH | OM | P | K | Ca | Mg | H+Al | SB | CEC | V |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CaCl_2$ | g $dm^{-3}$ | mg $dm^{-3}$ | ---------------mmolc $dm^{-3}$------------ | | | | | | % |
| 0 - 0.15 m | 5.6 | 14 | 6 | 0.8 | 17 | 9 | 20 | 26.8 | 46.8 | 57 |
| 0.15 - 0.30 m | 5.6 | 15 | 6 | 0.9 | 16 | 9 | 20 | 25.9 | 45.9 | 56 |

| Layers | B | Cu | Fe | Mn | Zn | Na | Si |
|---|---|---|---|---|---|---|---|
| | …………---------------------------mg $dm^{-3}$------------------------------ | | | | | | mg $kg^{-1}$ |
| 0-0.15 m | 0.18 | 0.6 | 19 | 26.5 | 0.8 | 8 | 8 |
| 0.15 - 0.30 m | 0.17 | 0.8 | 18 | 26.7 | 0.9 | 8 | 8 |

pH = Hydrogen potential; OM = Organic matter; P = Phosphorus; K = Potassium; Ca = Calcium; Mg = Magnesium; H+Al = Potential acidity; SB = Sum of bases; CEC = Cation exchange capacity; V = Bases saturation;

After 20 days of frequent irrigations, undisturbed soil samples were collected in the layers of 0-0.15 and 0.15-0.30 m from the experimental units to construct the soil water retention curve fitted by the model of [22], later used in crop irrigation management.

In this study, an intelligent system was developed with the objective of monitoring, in real-time, moisture, electrical conductivity, and solute concentrations in soil. Plants were fertigated with solutions containing five potassium concentrations (50, 100, 150, 200, and 250 mg $dm^{-3}$) applied when the soil reached the moisture limits of 0.20, 0.15, 0.13, 0.11, and 0.09 $cm^3$ $cm^{-3}$. Experimental plots were arranged in a randomized block design in a 5 x 5 factorial scheme (moisture limits x potassium concentrations in soil solution), with four replicates, totaling 100 plots (50 plots for each one of the two greenhouses).

Transplanting of lisianthus seedlings to the beds was performed at a population density of 64 plants per $m^2$ (0.125 x 0.125 m), which resulted in 60 plants per plot.

Probe-TDR system for real-time monitoring of soil water content and electrical conductivity of soil solution was installed at 25 points. The system was composed of a TDR100 reflectometer (Campbell Scientific, Logan-Utah), with reading expanded by 4 multiplexers connected to 8 probes. The whole system was actuated by a Datalogger CR10X from Campbell Scientific, which also stored the data.

The probes were made with three rods by the method described by [23] using 3.3-m-long RFM-KMP RG-58 50 Ω coaxial cable; BNC screw connector; 3-mm-diameter AISI 304 stainless steel rod; Epoxiglass epoxy resin; and Epoxiglass catalyst. To identify possible manufacturing failures, each probe was individually tested using a multimeter to evaluate the occurrence of insulation between the central rod (steel core) and the lateral rods (mesh). Probes that showed defects were discarded and replaced.

To estimate the electrical conductivity of the soil, the probes were calibrated in the laboratory, and the probe-TDR-multiplexer system was managed by PCTDR software version 2.08, which made it possible to obtain important variables for programming the system, such as cable and probe lengths, probe offset, etc.

The probe constant (Kp) was determined using 11-L tanks containing 6 solutions with different potassium concentrations (0, 50, 100, 150, 200, and 250 mg $L^{-1}$) prepared with potassium chloride and distilled water. The electrical conductivity of the solutions was determined with a conductivity meter, and then Kp was obtained for the 25 probes, which were coupled to 4 multiplexers, arranged at two levels of multiplexing (Figure 2).

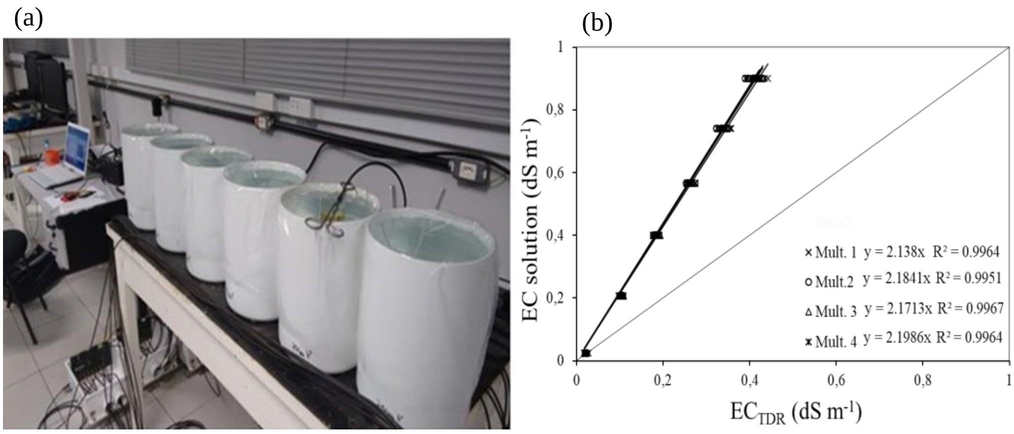


**Figure 2.** Details of the test for calibrating the probes (a) and obtaining the angular coefficient or constant of the probe (Kp) for a set of probes in each multiplexer – Mult. (b).

PCTDR software was configured by the average Kp for each multiplexer to enable the determination of the actual Kp, which consists of the angular coefficient (Kp = $\alpha$) of the line derived from a regression between values of EC in the solutions with increasing potassium concentrations and electrical conductivity (EC) estimated by the TDR. In each experimental unit, two TDR probes were installed at depths of 0.15 and 0.30 m in a horizontal position.

During one cycle of lisianthus, the soil solution was monitored with the probe-TDR system, measuring the electrical conductivity of the solution (ECs), and volumetric moisture ($\theta$) by using the model of [24].

Simultaneously with the installation of the TDR system, soil solution extractors were installed in the central part of the plot, allowing calibration by correlating the parameters obtained in the TDR system with those obtained by the solution extractors. Also, in four opportunities, soil samples were collected in the beds.

A drip irrigation system was installed with pressure-compensating emitter tubes spaced by 0.20 m, an internal diameter of 16 mm, and a nominal flow rate of 2.20 L $h^{-1}$ for an operating pressure of 250 kPa.

As lisianthus was cultivated at reduced spacing and the plant is sensitive to water deficit in the root system, at the establishment stage three drip tubes with a length of 1.4 m and spaced apart by 0.20 m were used to ensure complete wetting of the surface area in the plot. Drip tubes were fed by microtubes with a 5.0 mm internal diameter, which were connected to an individual panel for each protected environment, where the system of actuators (solenoid valves) was installed for automation.

Water and fertilizer application systems were composed of the following items: a reservoir tank of 5000 L for water supply; two reservoir tanks of 500 L each, one for the fertilizer solution A and the other for fertilizer solution B; five reservoir tanks for storing the solutions with the respective potassium concentrations; 200-mesh disc filter, set of valves, manometers and solenoid valves.

 doi:10.20944/preprints202212.0035.v1

Replacement of crop water demand was performed based on the average values of actual soil moisture estimated by the TDR probe readings collected by an automatic system (Figure 3). In this system, the apparent electrical conductivity ($EC_{TDR}$) was also monitored. The system was installed in one of the greenhouses and monitored all experimental units, making it possible to accurately indicate the time to irrigate each treatment studied.

(a) (b) (c)

**Figure 3**. Detail of the automatic system for monitoring soil moisture and electrical conductivity using the probe-TDR system. (a) Initial stage. (b) TDR reading. (c) Cutting stage.

In each experimental unit, irrigation depths were calculated using the readings obtained from the TDR probe through the equation of [25]. Irrigations were initiated whenever the soil reached its previously established lower moisture limit ($\theta_{low}$), and the volume of water applied was sufficient for the soil to reach its upper moisture limit ($\theta_{upp}$), equivalent to field capacity ($\theta_{CC}$) at the effective depth of the root system of 0.30 m and surface area of the plot equal to 0.94 m$^2$. Thus, the irrigation time of each plot was calculated by Equation 1:

$$t = \frac{(\theta_{sup} - \theta_{inf}).Z.A}{N.q.E_a}, \tag{1}$$

where:
$t$ - Irrigation time, h;
$\theta_{sup}$- Upper soil water content, volume basis, m$^3$ m$^{-3}$;
$\theta_{inf}$ - Lower soil water content, volume basis, m$^3$ m$^{-3}$;
$Z$ - Effective depth of the root system, mm;
$A$ - Surface area of the plot, m$^2$;
$q$ - Average flow rate of each emitter, L h$^{-1}$;
$E_a$- Application efficiency, decimal.
$N$ – Number of hours of irrigation.

Soil moisture and $EC_{TDR}$ data were collected daily and processed in an electronic spreadsheet and, when necessary, irrigations were performed. Irrigations were controlled by a system called Module for Control of Actuators (MCA), which was used in the automation of the control of solenoid valves and motor pump set, coupled to a central computer containing an application that automatically determines the times corresponding to the application of irrigation depths in each plot.

As only potassium doses were variable, the other nutrients were applied using a fertigation solution containing 25% of the original nutrient concentration suggested by [26]. Irrigation was also performed with fertigation, maintaining the concentrations of the other macro and micro elements common to all treatments, except potassium.

The electrical conductivity of the soil solution was monitored by a TDR probe. However, potassium concentration in the composition of the fertigation solution was obtained using values of potassium concentrations from the solution extractors.

For the collection of soil solution, a vacuum pump was used in the solution extractors with internal suction of approximately 76 kPa; after 24 h, the solution was collected with a syringe connected to a flexible silicone tube and then placed in hermetically sealed containers for analysis of potassium in the soil solution, determined by flame emission photometry. Soon after the collection of the soil solution, soil moisture was measured with the TDR probe.

Values of ionic concentrations obtained in the collections with solution extractors were corrected for the soil saturation moisture read by the TDR probe, according to Equation 2:

$$C_{estimated}\, pc = \frac{c_{pc}.U_{pc}}{Us} \tag{2}$$

where:

$C_{estimated}\ pc$ - electrical conductivity or ion concentration in saturation extract, estimated from the values measured in the soil solution, obtained with porous cup extractor, dS $m^{-1}$;

$C_{pc}$ - electrical conductivity or ion concentration in soil solution, obtained with porous cup extractor, dS $m^{-1}$;

$U_{pc}$ - soil moisture at the time when vacuum is applied in the porous cup extractor, g $g^{-1}$;

$U_s$ - soil moisture in the saturated paste, g $g^{-1}$.

The amounts of potassium chloride applied were calculated for the soil solution to recover potassium concentrations initially established in the treatments ($K_1$ = 50, $K_2$ = 100, $K_3$ = 150, $K_4$ = 200, and $K_5$ = 250 mg $dm^{-3}$), according to Equation 3.

$$K_A = \frac{K_F.VP.\theta_{CC} - K_{EE}.VP.\theta_A}{V_{CC}} \tag{3}$$

where:

$K_A$ - Potassium concentration of fertigation solution to be applied, mg $L^{-1}$;

$K_F$ - Final potassium concentration at field capacity, mg $L^{-1}$;

$K_{EE}$ - Actual potassium concentration in soil solution, mg $L^{-1}$;

$VP$ - Volume of soil contained in the plot, L;

$\theta_{CC}$ - Soil moisture at maximum retention capacity, L $L^{-1}$;

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$\theta_A$ - Actual soil moisture, L L$^{-1}$;
$V_{CC}$ - Volume required for the soil to reach maximum retention capacity, L.

For the balancing of the nutrient solution and supply of macronutrients of the fertigation solution, simple fertilizer salts of high solubility and low impurity content were used. KCl was used as a source of potassium ($K^+$), with approximately 49.8% of $K^+$. A stock solution of micronutrients was composed of products with a high purity index, recommended for laboratory use. Concentrations of fertilizer salts, potassium ($K^+$), and sodium ($Na^+$), and the values of electrical conductivity (EC) and pH of the fertigation solution can be observed in Table 3.

The electrical conductivity of the solution ranged from 1.09 to 1.64 dS m$^{-1}$, and a linear increase was observed as a function of the increase in potassium concentration supplied by KCl in the solution. The pH values of the solutions with different potassium concentrations were little influenced by increased KCl concentrations and were close to neutrality, showing that the solution used by [26] maintained balanced relationships between cations and anions.

**Table 3 -** Average concentration of fertilizers and fertigation solution characteristics.

| **Fertilizer** | **$K_1$** | **$K_2$** | **$K_3$** | **$K_4$** | **$K_5$** |
|---|---|---|---|---|---|
| | | | **mg L$^{-1}$** | | |
| KCl | 100.40 | 200.80 | 301.20 | 401.61 | 502.00 |
| $NH_4NO_3$ | 58.92 | 58.92 | 58.92 | 58.92 | 58.92 |
| $Ca(NO_3)_2.4H_2O$ | 210.52 | 210.52 | 210.52 | 210.52 | 210.52 |
| $NH_4H_2PO_4$ | 29.58 | 29.58 | 29.58 | 29.58 | 29.58 |
| $MgSO_4.7H_2O$ | 139.41 | 139.41 | 139.41 | 139.41 | 139.41 |
| FeEDTA 13% | 1.92 | 1.92 | 1.92 | 1.925 | 1.92 |
| $H_3BO_3$ | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 |
| $CuSO_4.5H_2O$ | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 |
| $(NH_4)_6Mo_7O_{24}$ | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| $MnSO_4$ | 0.40 | 0.403 | 0.403 | 0.403 | 0.40 |
| $ZnSO_4 \cdot 7H_2O$ | 0.06 | 0.063 | 0.063 | 0.063 | 0.06 |
| Solution | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ |
| $K^+$ (unidade??) | 62.45 | 115.17 | 168.375 | 218.750 | 268.500 |
| $Na^+$ (mg L$^{-1}$) | 84.65 | 88.77 | 90.575 | 90.400 | 85.950 |
| EC (dS m$^{-1}$) | 1.09 | 1.26 | 1.404 | 1.529 | 1.641 |
| pH | 7.06 | 7.26 | 7.1125 | 7.09 | 7.1875 |

Potassium concentrations in soil were established with the application of two pore volumes of the corresponding solutions in each experimental plot, applied for seven hours of drip fertigation. During the fertigation cycles to establish potassium concentrations in soil solution, samples of drained solutions were collected at different application times,

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precisely to record the evolution of electrical conductivity and potassium concentration in the drained solution as a function of an increase in the volume of solution applied.

After fertigation cycles were completed, total doses of fertilizers applied varied with KCl doses and, consequently, $K^+$ contents applied depending on concentrations of the fertigation solution (Table 4).

**Table 4.** Fertilizer doses applied to establish potassium concentrations in soil solution.

| **Fertilizer** | **$K_1$** | **$K_2$** | **$K_3$** | **$K_4$** | **$K_5$** |
|---|---|---|---|---|---|
| | | | **kg $ha^{-1}$** | | |
| KCl | 357.427 | 714.854 | 1072.281 | 1429.708 | 1787.135 |
| $NH_4NO_3$ | 210.587 | 210.587 | 210.587 | 210.587 | 210.587 |
| $Ca(NO_3)_2.4H_2O$ | 752.473 | 752.473 | 752.473 | 752.473 | 752.473 |
| $NH_4H_2PO_4$ | 105.736 | 105.736 | 105.736 | 105.736 | 105.736 |
| $MgSO_4.7H_2O$ | 498.298 | 498.298 | 498.298 | 498.298 | 498.298 |
| FeEDTA 13% | 6.880 | 6.880 | 6.880 | 6.880 | 6.880 |
| $H_3BO_3$ | 2.109 | 2.109 | 2.109 | 2.109 | 2.109 |
| $CuSO_4.5H_2O$ | 0.063 | 0.063 | 0.063 | 0.063 | 0.063 |
| $(NH_4)_6Mo_7O_{24}$ | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 |
| $MnSO_4$ | 1.439 | 1.439 | 1.439 | 1.439 | 1.439 |
| $ZnSO_4{\cdot}7H_2O$ | 0.223 | 0.223 | 0.223 | 0.223 | 0.223 |
| **Dose of Potassium** | **$K_1$** | **$K_2$** | **$K_3$** | **$K_4$** | **$K_5$** |
| g $parcela^{-1}$ | 16.774 | 33.547 | 50.321 | 67.095 | 83.868 |
| g $plant^{-1}$ | 0.280 | 0.559 | 0.839 | 1.118 | 1.398 |

## 3. Results

### *3.1. Soil leaching with potassium solutions*

Potassium concentrations in the soil were established with the application of two pore volumes of the corresponding solutions in each experimental plot, applied during seven hours of fertigation. Figure 4 shows the moisture and electrical conductivity profiles of the soil solution recorded with a TDR at the time of fertigation.

It can be seen that for all treatments the final moisture measured was around 0.23 $cm^3$ $cm^{-3}$. The final electrical conductivity measured was 1.27, 1.43, 1.56, and 1.69 dS $m^{-1}$ for potassium solutions of 100, 150, 200, and 250 mg $L^{-1}$, respectively.

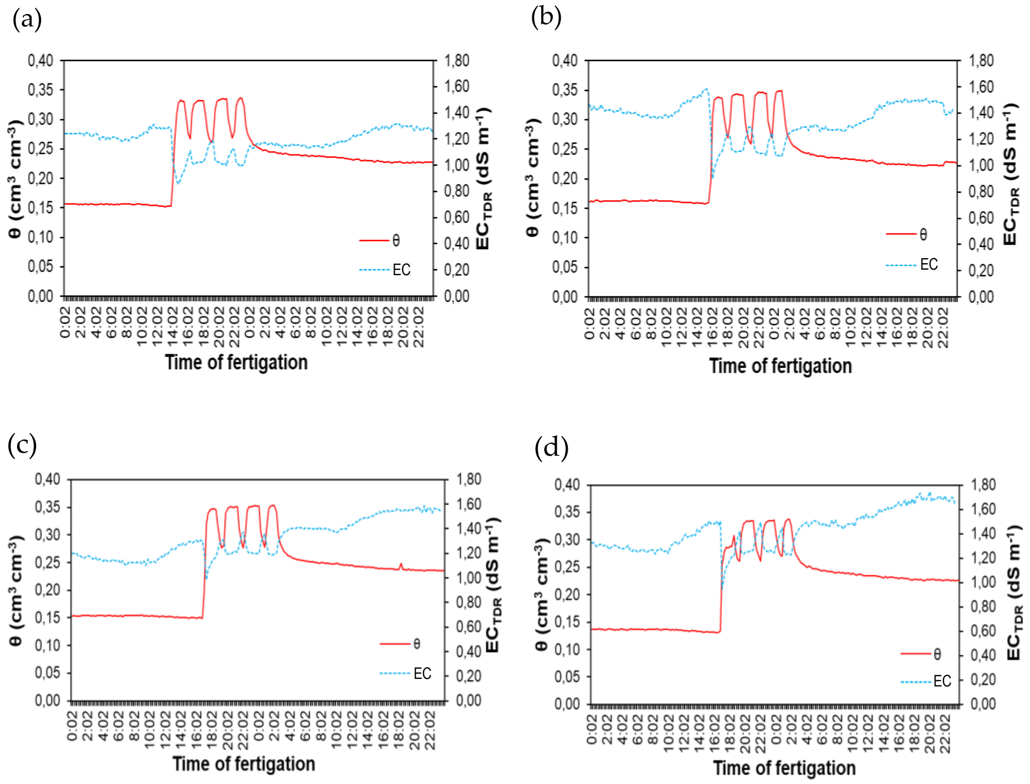


**Figure 4.** Profiles of soil volumetric moisture (θ) and electrical conductivity (EC) measured by TDR during the application of two pore volumes of the solutions of potassium concentrations of 100 (a), 150 (b), 200 (c), and 250 (d) mg $L^{-1}$ measured at 30 cm depth.

*3.2. Soil water content and depth of water applied*

Figure 5 shows the average profiles of volumetric soil water content recorded throughout the crop cycle, for each moisture limit studied; it was observed that potassium concentrations did not affect irrigation frequency.

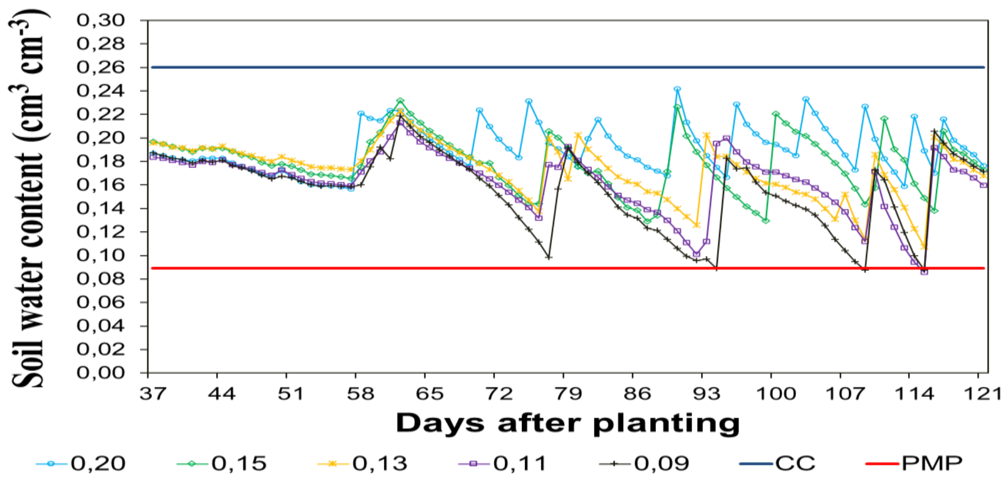


**Figure 5** - Average profiles of volumetric content of water in the soil for the different moisture limits applied during the lisianthus crop cycle

During the cycle, irrigations were performed every 6, 10, 12, 12, and 12 days on average, when the humidity limits of 0.20, 0.15, 0.13, 0.11, and 0.09 $cm^3.cm^{-3}$ were adopted, respectively. The treatments with soil moisture limits of 0.11 and 0.09 $cm^3.cm^{-3}$ did not show differences in irrigation frequency in relation to the treatment with a moisture limit of 0.13 $cm^3.cm^{-3}$, showing that below this last value of moisture the amount of water actually available is very small in the studied soil.

Still in relation to Figure 5, when analyzing, in particular, the treatment corresponding to the humidity limit of 0.20 $cm^3.cm^{-3}$, from 70 DAT, it is observed that the irrigation frequency increases and the interval between irrigations fall for three days as a result of the greater water demand of the crop, which was in an accelerated growth phase.

Analyzing the irrigation depths accumulated for the treatments, according to the moisture limits studied, it was found that the different concentrations of potassium in the soil solution also did not provide significant differences with regard to the water consumption of the lisianthus crop. There was a higher total water consumption, that is, 354.20 mm for the entire cycle (120 days) or 2.95 mm $d^{-1}$ on average for treatments with moisture limits of 0.20 $cm^3.cm^{-3}$ (Figure 6). On the other hand, treatments with lower limit humidity showed the lowest consumption, that is, 280.06 mm for the total cycle or 2.33 mm $d^{-1}$ on average.

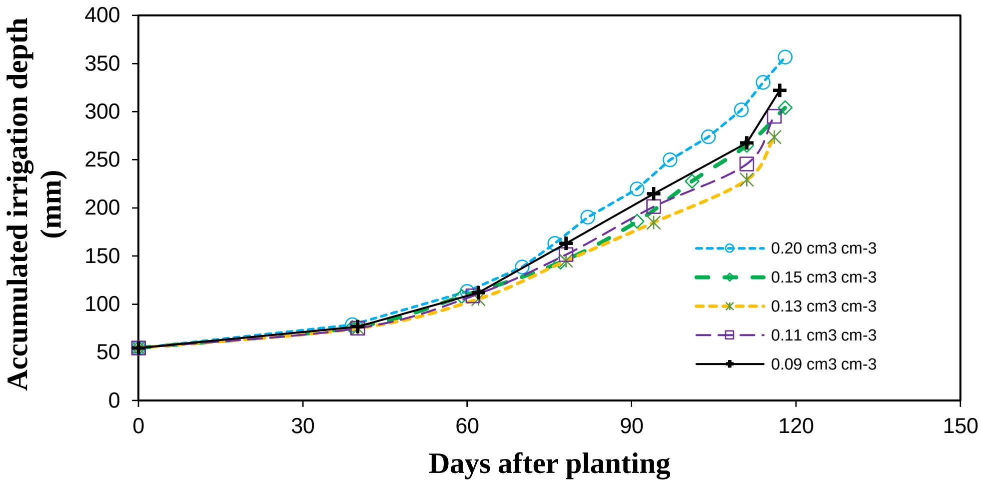


**Figure 6**. Average water consumption by lisianthus for the soil moisture limits

Regarding the comparison of water consumption of lisianthus plants subjected to moisture limits, the higher water consumption (highest total irrigation depth applied) for treatments with moisture limits of 0.20 $cm^3$ $cm^{-3}$, were 9.70, 14.73, 17.20, and 23.33% higher than those found with the other moisture limits studied.

*3.3. Doses of nutrients applied*

Concerning fertilizer masses applied for supplying macro and micronutrients to lisianthus plants fertigated under the different potassium concentrations in solution and soil moisture limits, it was observed that potassium doses get greater when plants were cultivated under a potassium concentration of 250 mg $L^{-1}$.

Despite increasing, the profiles remained relatively parallel until 120 DAT (end of cycle), and the highest total dose applied was 1272.61 kg ha$^{-1}$ at the potassium concentration of 250 mg L$^{-1}$, being 66.57, 61.53, 45.91, and 29.46% higher than the potassium concentrations of 50, 100, 150, and 200 mg L$^{-1}$, respectively (Figure 7). The other macro and micro nutrients applied were the same for the five potassium doses (Figure 8)

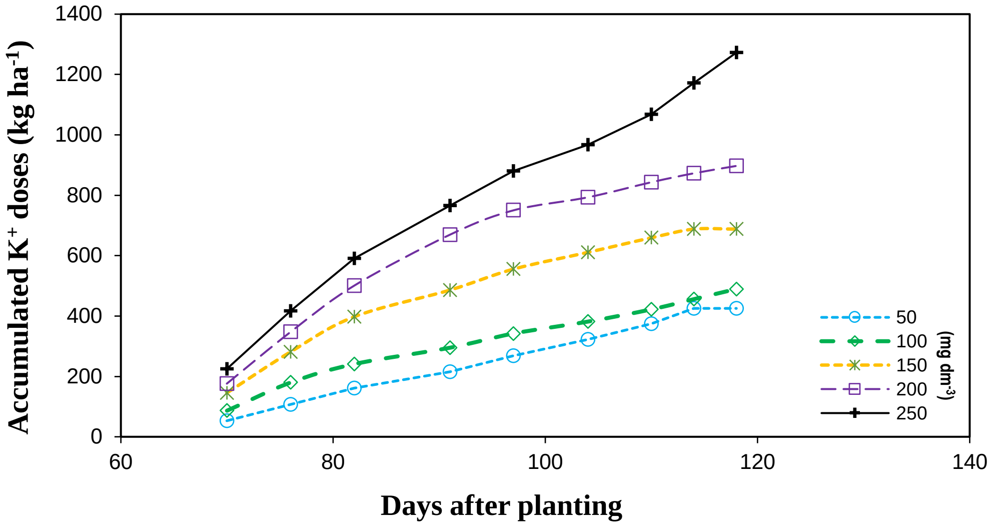


**Figure 7.** Accumulated potassium doses applied via fertigation for correcting potassium concentration in the soil solution at the moisture limit of 0.20 cm$^3$ cm$^{-3}$.

Considering that the moisture content of 0.20 cm$^3$.cm$^{-3}$ was the one that provided the highest final yields for the lisianthus crop and that for this moisture content a greater number of sampling points was available, we decided to present the evolution of the fertilizer consumption for this wetter condition (Figure 8).

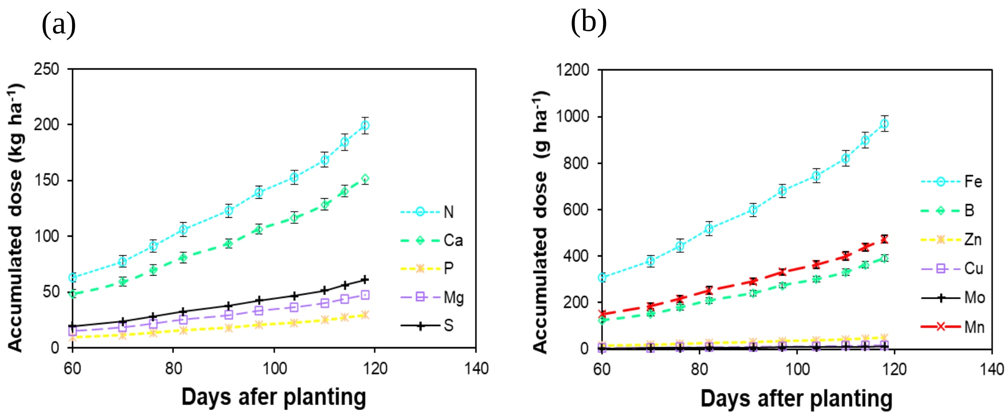


**Figure 8**- Accumulated doses of macro (a) and micronutrients (b) applied via fertigation at the moisture limit of 0.20 cm$^3$ cm$^{-3}$.

Accumulated doses of N, Ca, Mg, S, and P were incremental as the crop cycle progressed and dependent on the applied irrigation depths, which resulted in the application

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of 199.12, 151.68, 60.79, 47.58, and 29.38 kg ha$^{-1}$, respectively, for the density of 640,000 plants ha$^{-1}$.

The most significant microelements in the fertigation solution were Fe, Mn, and B, which resulted in total doses equivalent to 970.88, 473.94, and 391.09 g ha$^{-1}$, respectively. For the other micronutrients, at the end of the cycle, the amounts applied were 49.77, 16.95, and 10.94 g ha$^{-1}$ of Zn, Cu, and Mo, respectively.

*3.4. Nutrients in the soil*

It is observed from the profiles that the management of potassium concentration in the soil solution, as desired, affected the contents of exchangeable potassium in the soil throughout the lisianthus crop cycle. In soil samples collected at 0.15 m, the profiles representing the variation of potassium concentration during the crop cycle remained parallel, showing good performance of the mass balance equation, and also a slight increase in potassium concentration in the samples collected at 50 DAT. At the depth of 0.30 m, the profiles showed similar behaviors; however, a slight crossing of the profiles was observed around 50 DAT (Figura 9).

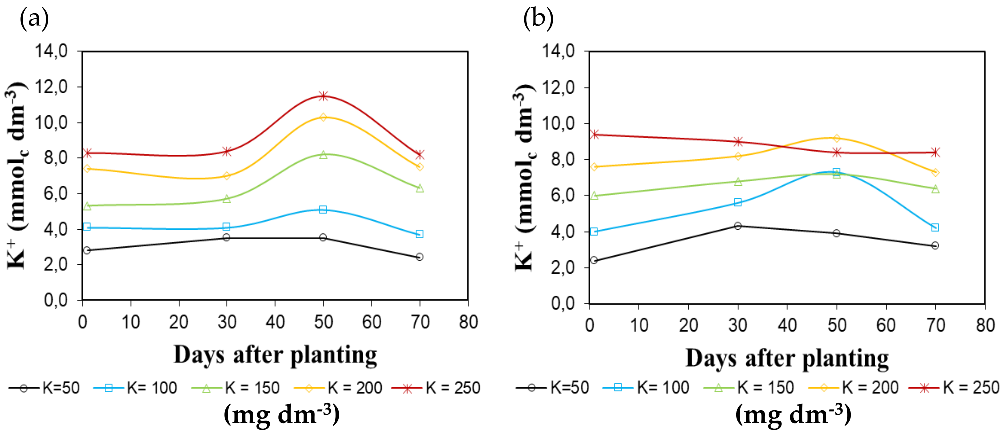


**Figure 9**. Contents of exchangeable K ($K^+$) in the soil throughout the first 70 days of the lisianthus cycle at 15 (a) and 30 (b) cm depths under the moisture limit of 0.20 cm$^3$ cm$^{-3}$.

With regard to the other elements in the soil, there are similarities in behavior during the cycle for the applied treatments (Figure 10), evidencing the efficiency of fertigation management, which allowed maintaining ionic relationships favorable to the development of the crop. It is worth pointing out the variation in the concentration of $Ca^{2+}$, $Mg^{2+}$, P, S, and Na, in the samples collected at 50 DAT. This sudden variation, observed in all profiles of the respective elements, occurred because the soil sample was collected immediately after fertigation, with not enough time for complete redistribution of the solution in the soil profile until the condition of equilibrium with the solid phase of the soil was achieved.

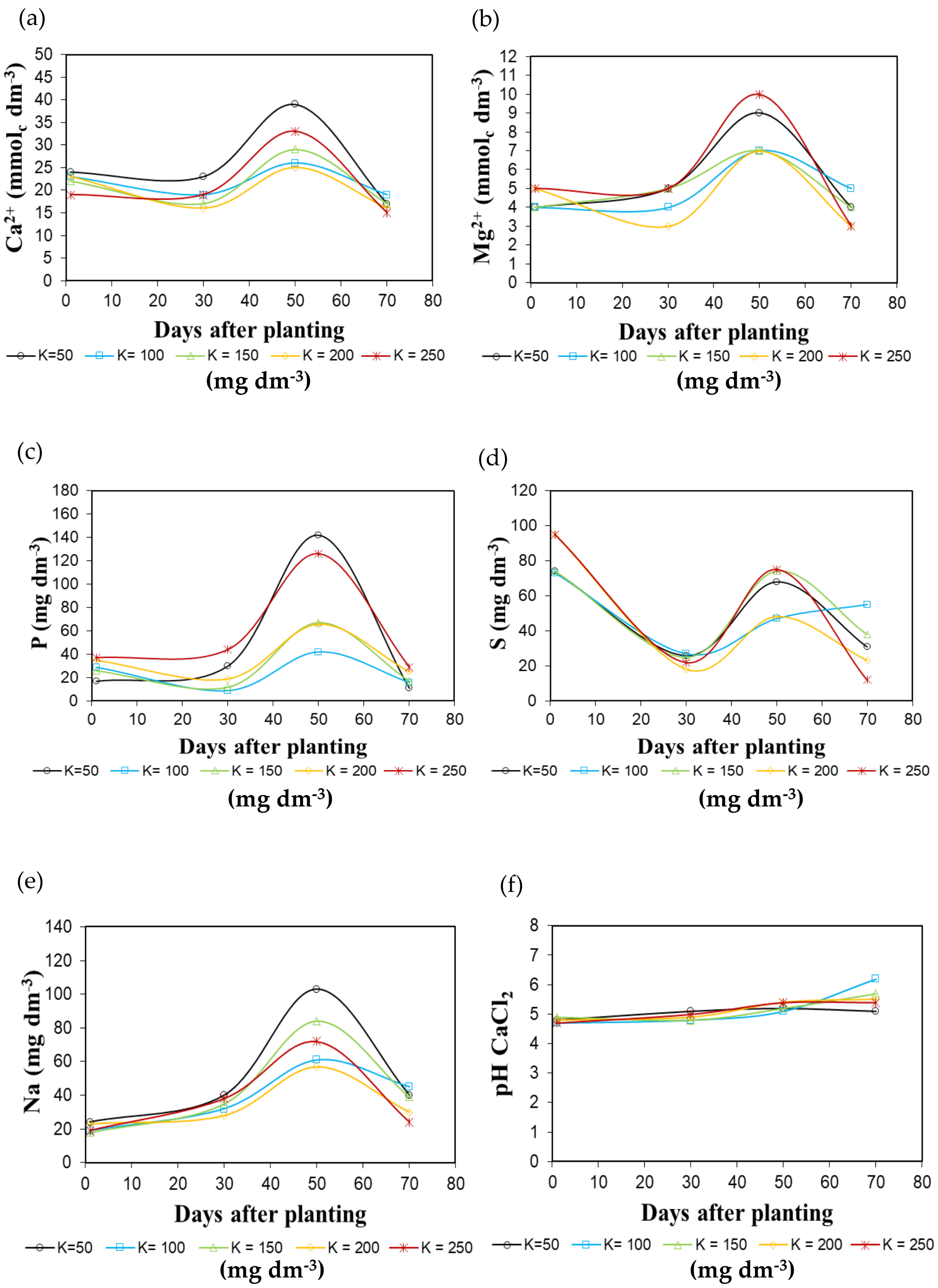


**Figure 10** - Contents of Calcium (a), Magnesium (b), Phosphorus (c), Sulfur (d), and Sodium (e) and pH in calcium chloride (f) in the soil throughout the first 70 days of the cycle of lisianthus crop grown under the moisture limit of 0.20 $cm^3$ $cm^{-3}$.

*3.5. Nutrients in soil solution*

It can be verified that the average values for macro and micronutrients are similar between plants of the applied treatments, which is considered satisfactory since the purpose of the present study was to vary only the potassium concentrations in the soil solution (Figure 11). On average, calcium concentrations in soil solution ranged from 93.41 to

153.19 mg $L^{-1}$, with the lowest value found at 45 DAT (accelerated growth stage and beginning of the formation of the first buds). It is also possible to observe in Figure 11 that, except for potassium, the order of predominance of macronutrients in the soil solution under the studied conditions was Ca > S > Mg > P.

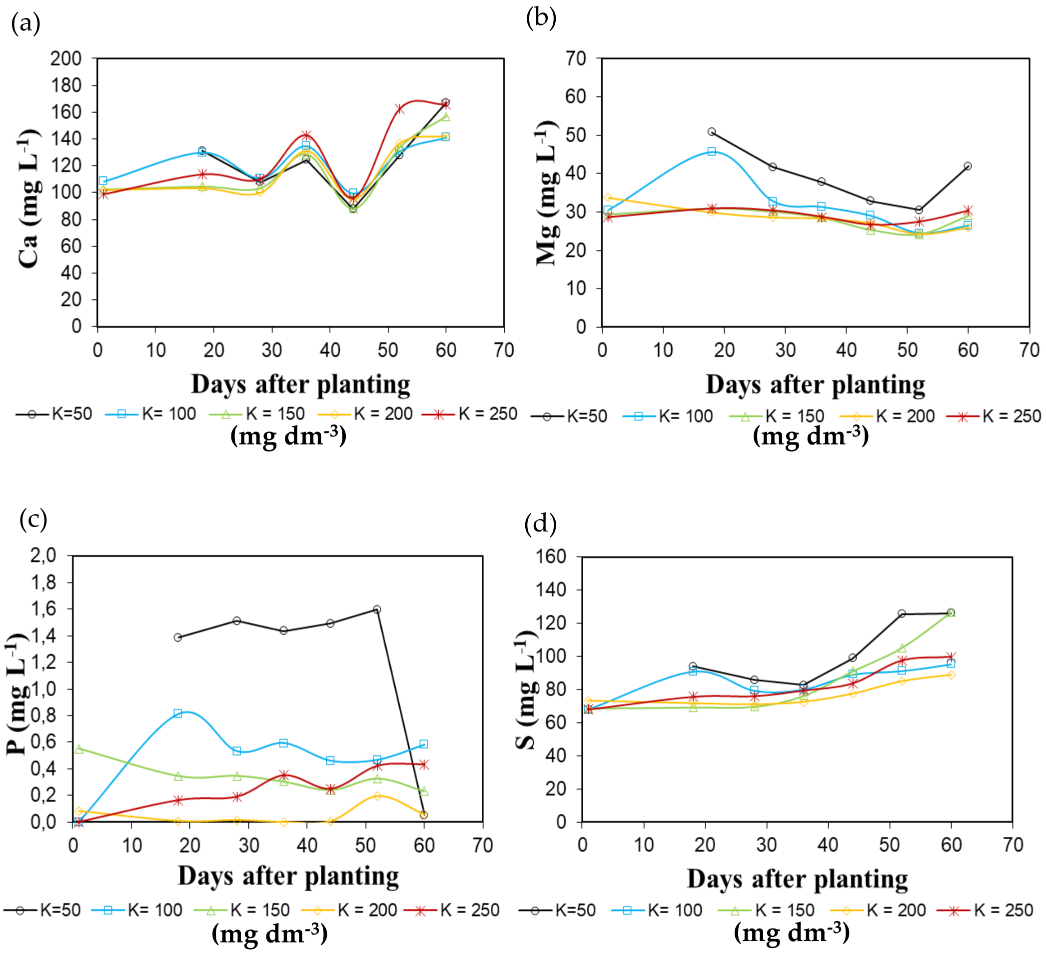


**Figure 11** - Concentrations of macronutrients in soil solution throughout the first 70 days of the cycle of lisianthus crop grown at the moisture limit of 0.20 $cm^3$ $cm^{-3}$.

Similar behaviors were observed between treatments (potassium concentrations in soil solution) regarding the effect on the concentrations of micronutrients. It can be verified in Figure 12 that the relationship between the concentrations of micronutrients in the soil solution follows the following order of magnitude: Fe > B > Zn > Mn > Cu > Mo.

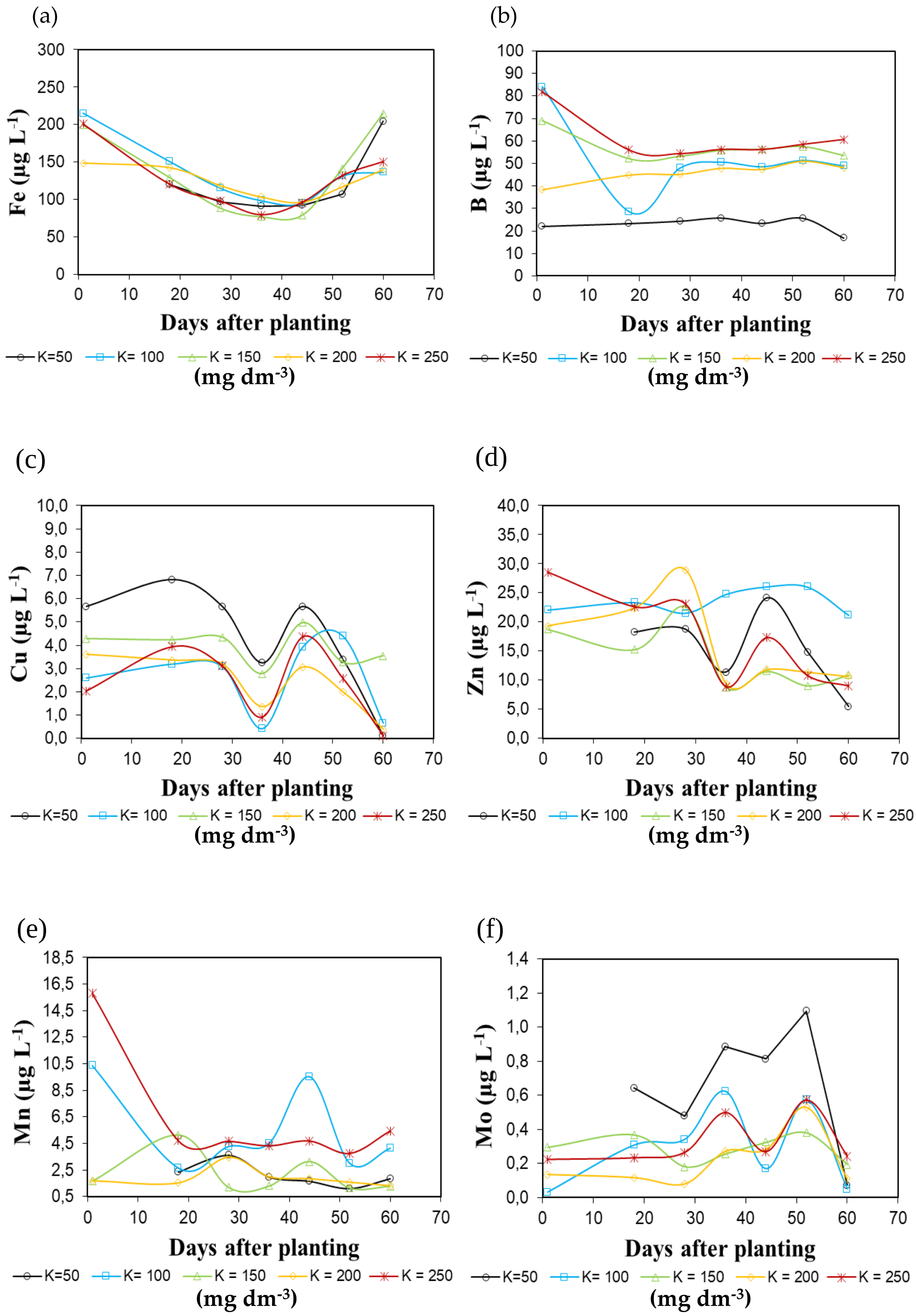


**Figure 12** - Concentrations of micronutrients in the soil solution during the first 60 days of the cycle of lisianthus crop cultivated under the moisture limit of 0.20 cm³ cm⁻³.

Iron concentration in the solution showed a decreasing behavior until 40 DAT, reached the lowest concentration, and then increased after that date (Figure 12 a). Minimum iron concentration in the soil solution coincides exactly with the beginning of the most active growth stage and with the transition to the reproductive stage, that is, with the period of the greatest nutritional requirement of the crop. On the other hand, boron concentrations in the soil solution remained virtually stable throughout the cycle (Figure 12b); however, a significant difference was observed in the treatment with the lowest potassium concentration in the soil solution (50 mg $L^{-1}$) in comparison to the other treatments, which seems to highlight a possible interaction between the variation of boron concentration as a result of potassium variation in the soil solution.

## 4. Discussion

Different potassium concentrations managed in the soil solution did not provide significant differences corncerning the water consumption of the lisianthus crop. The profiles that relate the variation of the volumetric water content with time (Figure 2) clearly show the rhythm of water consumption by the crop according to the stages of development; in addition, they allow the identification of the exact moment when irrigation was performed, as well as quantification of the applied depth [13]. It is verified, therefore, that the use of the TDR technique coupled to the data acquisition system (data logger), in addition to making it possible to obtain data related to the exposure of lisianthus crop to critical levels of moisture in the soil, which would not be possible with the use of tensiometers due to the high tensions of the drier treatments, allowed the recording of instantaneous variations in soil moisture. Mounzer et al. [27] reinforce that accurate and continuous monitoring of variations in soil water content in the laboratory, in a greenhouse or, in the field are important means to investigate water consumption by plants and provide an efficient basis for irrigation management.

Through the applied nutrient accumulation curves (Figures 4 and 5) it is possible to know the nutritional demand at each growth stage. Thus, the risk of applying excessive doses of fertilizers can be reduced, as well as reducing the risk of providing doses below the minimum required by the plant to achieve productivity goals [28].

To obtain high yields from crops under greenhouses, excessive doses of fertilizers are usually applied, which can result in an accumulation of fertilizer residues and, consequently, in an increase in soil salinity [29]. Fertigation management is a tool that allows plants to obtain the amount of nutrients required at each phenological stage, resulting in greater efficiency and savings in the use of fertilizers [30].

Comparing the original soil analysis before fertigation (Table 2) with the results sampled during the experiment (Figures 6 and 7), it is verified that the contents of all nutrients increased, with the exception of Mg and pH, which remained approximately constant. During the cultivation cycle, no symptoms of nutritional deficiency or signs of toxicity were verified in lisianthus plants. This fact reinforces the statement that the management of fertigation allows the maintainence of ionic relationships favorable for the development of the crop, both in the solution and in the solid phase of the soil [14,28].

Comparing the average values of Ca, Mg, S, and P obtained in the extractors (Figure 8) with the levels suggested in the solution by [26], it is verified that there was a concentration of these elements in the soil solution, with the exception of phosphorus. Possibly in the case of phosphorus, there were problems in the extraction since [31] points out that the correlation between the phosphorus extracted in saturated paste and phosphorus obtained with porous capsule extractors is not good.

Similar behaviors can be observed between treatments (potassium concentrations in soil solution) regarding the effect on the concentrations of the micronutrients iron (Fe) and boron (B) in the soil solution over the cultivation period, highlighting the variation in the concentration of these two micronutrients most required by lisianthus plants, according to [12].

Lao et al. [32] report that nutrient levels in the soil solution should be known in order to establish appropriate approximation for nutrient management in high-frequency fertigation. It can be inferred that the management of ions in soil solution with extractors capsules is a tool for great protection for the nutritional supply of fertigated environment.

Silva et al. [17], studying fertigated crops in a substrate composed of coconut fiber, found the feasibility of using solution extractors to monitor the concentration of nutrients in the soil solution. [33] and [29] also came to the conclusion that the use of soil solution extractors is a viable alternative for ionic monitoring during the cycle of crops fertigated with high frequency.

Once periodic monitoring has been established, the concentration of fertilizers applied via irrigation water, usually daily or every few days can be controlled to keep the concentration of the soil solution fluctuating within an adequate range [30], ensuring good nutrient availability without osmotic problems.

Considering that fertilizer application is monitored regularly, there is generally no need for intentional applications of leaching fractions, avoiding possible waste of water, energy, and fertilizers, in addition to subsoil contamination [28].

## 5. Conclusions

- Continuous monitoring of soil water content with TDR enabled the calculation of the irrigation depth precisely and in the determination of the right time for starting the irrigation of lisianthus in a protected environment;
- Ceramic cup extractors were able to maintain the different proposed potassium concentrations and approximately similar concentrations of other nutrients in the soil solution, as desired.

**6. Patents:** Not applicable

**Acknowledgments:** The authors thank Fundação de Apoio à Pesquisa do Estado do São Paulo - FAPESP for funding the research.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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