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ORIGINAL PAPER

Productivity and quality of beet (*Beta vulgaris L.*) under different drip irrigation management methodologies

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Abstract

This study investigated the effects of different drip irrigation management techniques on beetroot (Beta vulgaris L.) productivity and quality in a controlled greenhouse environment. Climate-based methods (weather station, evaporation pan), soil-based methods (capacitive moisture sensors, tensiometry), and a commercial method (FieldNET by Lindsay) were compared. The evaluation considered applied water volume, yield, water use efficiency, root diameter, and dry mass of root and shoot. Soil-based methods, particularly the SoilWatch sensor, resulted in the highest productivity (88 tons ha^{-1}), representing a 62% increase compared to the lowest yield, and quality (30.2 mm root diameter), a 19% improvement. However, tensiometry demonstrated superior water use efficiency (45.2 kg m^{-3}), with the lowest applied water volume (132 mm), reflecting a 37% reduction in applied water compared to the highest. Climate-based methods showed potential but required precise parameter calibration. The commercial method, while productive, exhibited lower water use efficiency with its default settings. The study underscores the importance of integrating real-time soil moisture monitoring for optimal irrigation management in beetroot cultivation, emphasizing the need to tailor strategies based on specific crop and environmental conditions.

Introduction

Sustainable agricultural production faces increasing challenges due to climate change and the need to optimize water use in irrigated agriculture, especially in crops like beetroot (Beta vulgaris L.), where irrigation management efficiency plays a crucial role in achieving high yields and high quality of the final product (Guno and Agaton 2022; Mu et al. 2023).

The cultivation of beetroots is directly affected by soil water availability, making it vital to understand and control irrigation management practices to maximize yield and root quality. In many agricultural ecosystems, water is a limited resource, and therefore, efficient irrigation use is important to ensure the sustainability and profitability of crops (Rolbiecki et al. 2019; Babichev et al. 2021).

Beetroot, cultivated on approximately 10,000 hectares in Brazil, plays a crucial role in the country's economy and food security. With an annual production of 170,000 tons, the crop generates approximately R$ 700 million, creating jobs and income. The state of São Paulo, the largest national producer, supplies the domestic market with this nutrient-rich vegetable. Optimizing irrigation management and increasing beetroot productivity are strategic to ensure food security for the population, boost producers' income, and strengthen Brazil's position in the global food market (IBGE 2017).

Water use efficiency is crucial to ensure the sustainability and profitability of crops, especially in regions with limited water resources. In this context, precision agriculture has driven the development of advanced irrigation management strategies, with a focus on optimizing water use and improving water efficiency. These strategies include the

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use of mathematical models to estimate evapotranspiration (ET) and soil moisture sensors to monitor crop water requirements. The integration of technologies such as soil moisture sensors, mathematical models, and automated and instrumented irrigation systems enables a more precise and efficient approach to water management in agricultural production. These innovations have the potential to increase productivity and environmental sustainability by reducing water waste and minimizing negative impacts on water resources (El-Naggar et al. 2020; Navinkumar et al. 2021; Guntur et al. 2022; Vianny et al. 2022).

This study aims to analyze the impact of different irrigation management techniques on beetroot cultivation by comparing approaches based on climate data, which estimate crop water requirements using weather stations and evaporation pans, with methods that directly measure soil moisture in the plant's root zone. For this direct measurement, capacitive sensors and tensiometers are used, providing instantaneous readings of soil moisture. The comparison between these methodologies will allow us to identify which irrigation strategies are most efficient in optimizing water use, increasing productivity, and improving the quality of beetroot, thus contributing to the sustainability of the crop in a context of increasing demand for water resources (Carvalho et al. 2012; Eisenhauer et al. 2021).

In this context, the present study proposes a comprehensive analysis of the effects of different irrigation management techniques. These techniques are based on climate methodologies, represented by two evapotranspiration estimation methods using data from two meteorological station models and a reduced class A evaporation pan. Additionally, soil methodologies are employed, utilizing two capacitive sensor models and tensiometry, compared with the use of a commercial irrigation management system provided by a partner company. The aim is to evaluate the impact of these management techniques on three fronts: the sustainability of the activity, final productivity, and quality of beetroots irrigated by drip irrigation systems and grown in a protected environment.

Materials and methods

Characterization of the experimental environment

The study was conducted in a controlled environment inside a greenhouse (Fig. 1A) comprising 3 interconnected bays with a total area of approximately 400 m^2 and a height of 5.2 m, featuring a transparent plastic roof diffusing radiation and black shade screens covering the sides, intercepting 50% of global radiation. The greenhouse was located in Piracicaba – SP (Fig. 1B), which has an Aw tropical climate according to the Köppen scale, characterized by summer rainfall and dry winters (Dias et al. 2017).

The experimental unit consisted of 396 independent plots (Fig. 1C), each containing 330 L of Xanthic Ferralsol (Red-Yellow Latosol, Brazilian classification), with sandy loam texture from the Sertãozinho series, containing 24% clay, 5% silt and 71% sand, irrigated via a surface drip system with an average flow rate of 3.6 L per hour. The irrigation was individually operated through manual valves to control water application.

For this experiment, the beetroot crop (Beta vulgaris L.), cultivar "Ferry Morse - Early Wonder Tall Top," belonging to the Chenopodiaceae family, was selected. This tuber develops through the swelling of the hypocotyl, exhibiting characteristics of large, erect foliage, smooth roots, and intense red coloration (Tivelli et al. 2011).

In the southeastern region of Brazil, its planting window extends throughout the year, with a preference for periods of milder temperatures. It has an average cycle of 75 days after sowing, with spacing of 10 × 18 cm and a density of up to 350,000 plants per hectare, resulting in an average yield of 20 to 35 tons per hectare (Tivelli et al. 2011; Sousa et al. 2020).

The irrigation management control techniques were initially divided into two groups: the first based on climatological data and the second on soil data, both compared with a commercial management system, as presented in Table 1.

Fig. 1 **A** - Location map of Piracicaba city - SP, Brazil; **B** - Interior of the greenhouse; **C** - Experimental plot, composted of a concrete box, subdivided into 3 plots of 330 liters of soil each

Table 1 Presentation of the methodologies employed in irrigation management, Ψ - soil water retention tension, cc - field capacity, f - water availability factor, Kc - crop coefficient, ETo - reference evapotranspiration, kp - tank coefficient, VCS - capacitive sensor model 2

Treatment	Methodology	Equipment	Description
1	Soil	Tensiometer*	Manual read; installed a 15 cm Ψcc = -5 kPa; Ψlimit = -15 kPa
2		SoilWatch Capacitive sensor	Manual read; installed a 15 cm Ψcc = -5 kPa; Ψlimit = -15 kPa
3		VCS Capacitive sensor	Manual read; installed a 15 cm Ψcc = -5 kPa; Ψlimit = -15 kPa
4	Weather	Standard station	Daily ETo por Penman-Monteith kc Embrapa. f = 0,6
5			Daily ETo por Hargreaves e Samani kc Embrapa. f = 0,6
6		Azevedo station Do Yourself Movement	ETo diário por Penman Monteith kc Embrapa. f = 0,6
7			Daily ETo por Hargreaves e Samani kc Embrapa. f = 0,6
8		Class A pan	ETo Pan x kp kc Embrapa. f = 0,6
9	Commercial irrigation management system		

*Reference technique

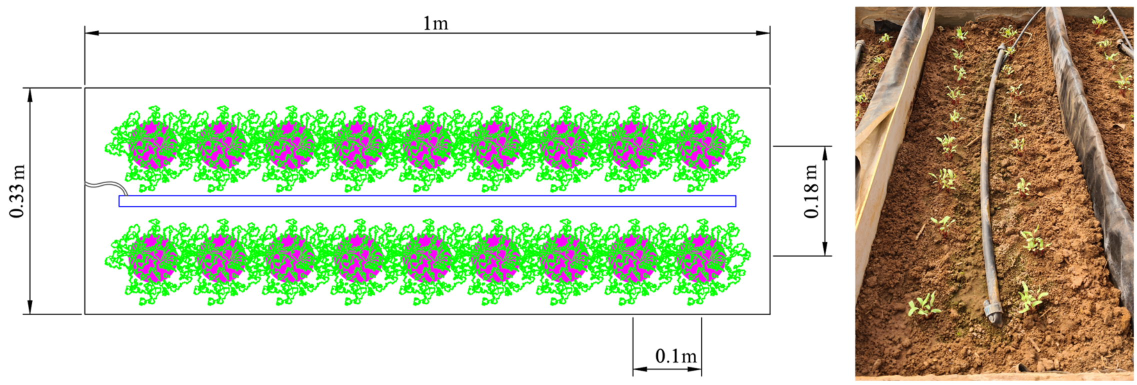

Fig. 2 **A** - Beetroot planting layout (with units in meters), with spacing of 0.1 m between plants and 0.18 m between rows, featuring the placement of a drip tube in the central corridor of the plot fed by a network of microtubes; **B** - Spatial distribution of plants in the experimental plot

It is noteworthy that in all employed methodologies, a variable irrigation schedule was utilized.

For the management based on climatological methodology, two weather stations were installed inside the greenhouse, positioned at a height of two meters above the ground, with sensors accommodated on a specific bar for this purpose. Additionally, the Class A evaporation pan was placed on a wooden platform, isolating it directly from the surrounding soil.

Thus, the study comprises 9 treatments with 6 replications each, forming a randomized complete block design (RCBD 9 × 6), aiming to reduce experimental variability and increase the precision of comparisons between treatments. Each experimental unit consisted of 18 plants, with a planting layout depicted in Fig. 2. Planting was conducted on July 27th, with harvest on October 10th, encompassing a period of 75 days.

Soil-based irrigation management

For the tensiometry technique, a sensor element with a ceramic porous capsule was selected, with a diameter of 21.5 mm and a length of 60 mm, connected to a PVC tube with a length of 220 mm. The PVC tube had an acrylic tube attached to its upper part, measuring 100 mm in length and 15 mm in diameter, which was sealed with the aid of a cork for puncture tensiometers.

For reading the sensor element, a digital tensiometer from the brand Tensimeter was used, which displays the water retention tension in the soil in units of mbar or kPa, as shown in Fig. 3A. It is noteworthy that the center of the ceramic porous capsule was installed at a depth of 15 cm (thus in contact with the layers of 12–18 cm), estimating the average moisture of the 0–20 cm layer through its reading, as schematically presented in Fig. 3B.

Nonetheless, the SoilWatch (Pino Tech) and VCS (Tinovi) soil sensors (Fig. 4) have dimensions of 19 × 84 mm and 19 × 53 mm, respectively. These dimensions represent the

Fig. 3 **A** - Digital tensimeter used for reading the tensiometer; **B** - Moisture sensor elements installed next to beet, being VCS, SoilWatch and tensiometer (left to right)

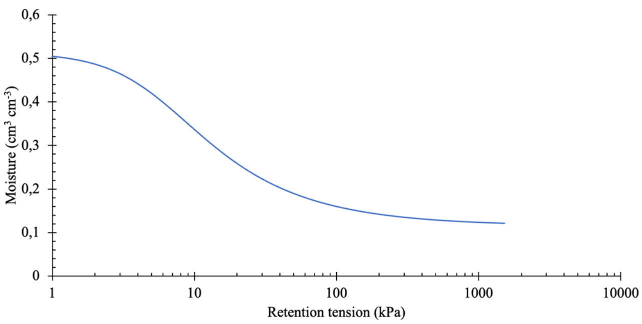

Fig. 4 Soil water retention curve for the soil used in the experimental plots of the greenhouse

Table 2 Adjustment parameters for the red-yellow latosol for the van Genuchten equation

Parameter	Value
θr	0.1549
θs	0.4629
α	0,6352
M	0.4550
N	1,8347

width and length of the sensor element. The center of the sensor element is installed at a depth of 15 cm, vertically fixed within the soil, in contact with the soil layer ranging from 10.8 to 19.2 cm for SoilWatch and 12.35 to 17.65 cm for VCS.

It is noteworthy that for the soil sensors, a depth of installation of 15 cm was considered. Although there is no limitation on the installation depth for capacitive sensors, the same proposal was followed for tensiometry. This decision was made because installation in a very shallow zone may result in the tipping over of the tensiometer, rendering it unusable (Jiao et al. 2021).

To obtain the actual soil moisture through the soil water retention curve (Fig. 4), five soil samples were collected and analyzed at the Soil and Water Quality Laboratory of the Escola Superior de Agricultura Luiz de Queiroz - USP. The soil water retention curve was generated using these samples, and the adjustment parameters (Table 2), the van Genuchten model, were extracted for moisture estimation (van Genuchten 1980).

Similarly, the capacitive soil moisture sensors were calibrated for the specific soil in question. Figure 5 illustrates the sensor responses to variations in volumetric moisture. Equations 1 and 2 for the VCS sensor, and Eqs. 3 and 4 for the SoilWatch sensor, estimate moisture retention tension. These equations correlate sensor readings with both soil water retention tension and volumetric water content, aiding in the irrigation management process using capacitive sensors.

$$\theta = -0.32181 \cdot P^3 + 90.5035 \cdot P^2 - 8477.79 \cdot P + 264553 \quad (1)$$

$$\Psi = -1.65409 \cdot P^3 + 476.56 \cdot P^2 - 45766.4 \cdot P + 1465080 \quad (2)$$

$$\theta = 0.0000575486 \cdot V^2 - 0.245001 \cdot V + 287.383 \quad (3)$$

$$\Psi = 0.000461047 \cdot V^2 - 2.53516 \cdot P + 3531.09 \quad (4)$$

Where:

θ - volumetric moisture (%);

Ψ - retention tension (kPa);

P - dielectric permittivity measured by the sensor (F m^{-1}); and.

V - voltage in millivolts at the sensor output (mV).

In order to reduce the coefficient of variability of soil sensor

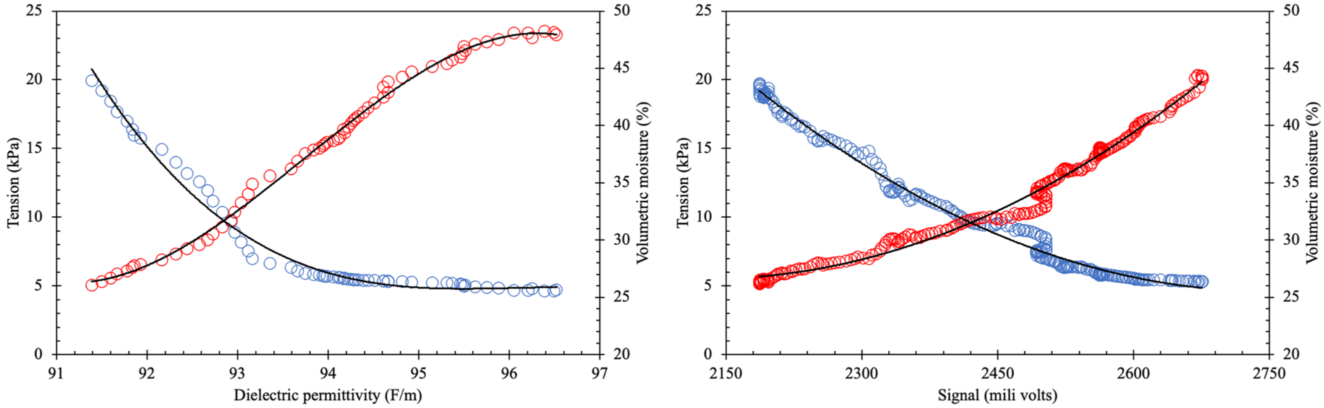

Fig. 5 Response of capacitive sensors to variations in volumetric moisture and soil water retention tension, for the red-yellow latosol. **A** – Sensor VCS; **B** – Sensor SoilWatch

Fig. 6 Sensor elements of the commercial Campbell weather station, including sensors for: pyranometer, barometer, combined temperature and relative humidity, anemometer and wind, connected to the CR1000 datalogger (left to right from top to bottom)

readings, readings are taken at 60-second intervals, followed by averaging to carry out irrigation management. This process homogenizes the readings and creates an estimate of the real trend in soil water behavior (Cardenas-Lailhacar and Dukes 2010; Domínguez-Niño et al. 2020).

Climate-based irrigation management

For climate-based management, the weather station models used included a complete professional station, commercially available from Campbell, equipped with a CR1000 datalogger, silicon photodiode LI200x, anemometer 03002, air temperature and relative humidity sensor model HMP45, and a Vaisala CS 106 barometer, as shown in Fig. 6. Additionally, a second model developed by the author (Azevedo 2021; Azevedo et al. 2024) was employed, as depicted in Fig. 7.

This model offers the same functionalities as the previous one, with the added capability to calculate evapotranspiration using the Penman-Monteith methodology (Eq. 5) and Hargreaves and Samani method (Eq. 6). It provides real-time data to the user through an online database and a bot on the Telegram application, utilizing a central controller model ESP8266 (Hargreaves and Samani 1985; Allen et al. 2006).

$$ETo = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \quad (5)$$

Where:

ETo - Reference Evapotranspiration (mm day^{-1});

Δ - Slope of the saturation vapor pressure curve (kPa ºC^{-1});

Fig. 7 Developed weather station IoT, including: datalogger mounting box, sensor bar on the station tripod and uses sensor elements (left to right)

γ - Psychrometric coefficient (kPa ºC^{-1});
T - Air temperature at 2 m height (ºC);
u2 - Wind speed at 2 m height (m s^{-1});
Rn - Net radiation (MJ m^{-2} day^{-1});
G - Soil heat flux density (MJ m^{-2} day^{-1});
es - Saturation vapor pressure (kPa); and.
ea - Partial vapor pressure (kPa).

$$ETo = a \cdot \left(\frac{R_a}{2{,}45}\right) \cdot (T_{max} - T_{min})^b \cdot (T_{med} + c) \quad (6)$$

Where:

ETo - Reference Evapotranspiration (mm day^{-1});
a, b, and c - Adjustment parameters;
Ra - Extraterrestrial solar radiation (MJ m^2 day^{-1});
Tmax - Maximum temperature in the period (ºC);
Tmin - Minimum temperature in the period (ºC); and.
Tmed - Average temperature in the period (ºC).

Still, evapotranspiration is also calculated using a Class A pan, which had its readings taken every day around 8:00 AM, with evapotranspiration calculated using Eq. 7 (Doorenbos and Pruitt 1977).

$$ETo = ECA \cdot kp \quad (7)$$

Where:

ETo - Reference Evapotranspiration (mm day^{-1});
ECA - Pan evaporation (mm day^{-1});
Kp - Pan coefficient.

It is worth noting that for the estimation of crop evapotranspiration, the reference evapotranspiration was multiplied by the crop coefficient (Kc), derived from calibration performed for the southeastern region for cultivation without mulch cover. Therefore, the initial Kc was 1.02, the average Kc was 1.18, and the final Kc was 0.84 for periods of 30, 24, and 21 days, respectively (Carvalho et al. 2011b).

Additionally, it was considered for both methodologies a daily average root growth of 0.5 cm, reaching a total depth of 20 cm, which altered the actual water availability (AWA) daily until the 40th day (Guerra and Machado 2022).

It is important to highlight that for each of the methodologies, a calculation spreadsheet was created, where the depletion of actual water availability in the soil was performed daily, irrigating only when the AWA fell below zero (θ < 23.84%), restoring the moisture to field capacity (θ = 33.62%).

Lastly, the commercial system employed is called FieldNET (Fig. 8) from the company Lindsay. This is a telemetry solution for real-time online irrigation control and management, configured for the local condition with sandy loam soil with an available water capacity of 79 mm m^{-1}, classified as hydrological group C, with maximum crop growth and root depth of 40 and 20 cm, using rainfall-free meteorological data and the same Kc values (0.5; 1.05; and 0.95), practicing conventional cultivation and using 1100 degree days for crop maturity.

Biometric and physiological analyses

The chlorophyll a, b, and total (ICF) indices were determined using an electronic chlorophyll meter (Chlorolog CFL1030, Falker), taking three readings in each plot. Leaves from the middle third of the plant were selected to obtain an average corresponding to the respective treatment. Leaf temperature

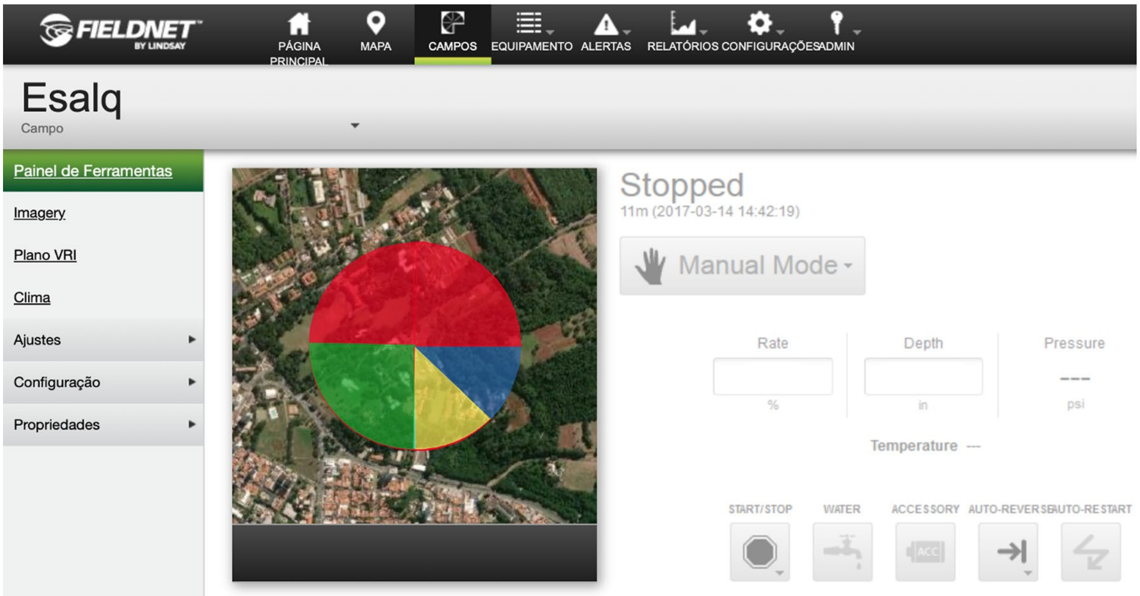

Fig. 8 Image of the commercial irrigation management software

was also evaluated using an infrared thermometer to calculate the Crop Water Stress Index (CWSI), as follows in Eq. 8, complemented with leaf water content (LWC [%]) in Eq. 9 (Turner 1981; Martínez et al. 2017).

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LBI}}{(T_c - T_a)_{LBS} - (T_c - T_a)_{LBI}} \quad (8)$$

Where:

CWSI - Crop Water Stress Index, dimensionless;
T_c - Crop temperature (°C);
T_a - Air temperature (°C);

$(T_c - T_a)_{LBI}$ - Lower base temperature line, which corresponds to the difference in temperature between the environment and the surface of a leaf without water restrictions in °C. It represents the smallest difference between air and leaf temperature among all evaluated measurements;

$(T_c - T_a)_{LBS}$ - Upper base temperature line, which corresponds to the difference in temperature between the ambient air and a leaf surface with water deficit in °C. It represents the largest difference between air and leaf temperature among the evaluated measurements.

$$LWC = \frac{MU - MS}{MU} \cdot 100 \quad (10)$$

Where:

LWC - Leaf Water Content (%);
MU - Leaf Moisture Mass (g);
MS - Leaf Dry Mass (g).

To determine the Crop Water Stress Index (CWSI), baselines were established using data from experimental plots with different irrigation management. The lower baseline was defined from plots with full irrigation, representing minimal water stress, while the upper baseline was defined from plots with total irrigation suspension, representing maximum water stress. Canopy and air temperatures were measured in both plots to construct the baselines and calculate the CWSI for each treatment.

In addition, gas exchange analysis and carbon assimilation by leaf surface were conducted at 55 days after sowing (DAS) using a portable photosynthesis analyzer - IRGA (LI-COR model LI-6400XT). The analysis utilized a CO_2 concentration of 400 ppm, an air flow rate of 300 mL min^{-1}, and a light source coupled with 1200 µmol m^2 s^{-1}. The evaluation included measurements of net CO_2 assimilation rate, intercellular CO_2 concentration, stomatal conductance, transpiration rate, and stomatal resistance, with readings taken in the morning (Gondim et al. 2015; Gonçalves and Dias 2021).

For the description of leaf geometry, a benchtop leaf area meter, LI-3100 C model from Li-Cor, was used to estimate measurements of width, length, and unit leaf area, with the estimation of leaf area index (LAI) through Eq. 10 (Favarin et al. 2002).

$$LAI = \frac{\sum ULA}{Cs} \quad (10)$$

Where:

LAI - Leaf Area Index;

ULA - Unit Leaf Area (m^2);

Cs - Crop spacing (m^2).

Still, at the end of the cycle, the estimation of productivity for each plot was carried out, complemented by qualitative analyses, including average root diameter, fresh and dry shoot mass, fresh and dry root mass, leaf number, and leaf area index. This was followed by root juice extraction to obtain soluble solids measurement expressed in degrees Brix using a portable refractometer.

Interpolating productivity data with management metrics allows for the estimation of crop water efficiency indices such as Water Use Efficiency (WUE) (Eq. 11), as well as the average irrigation depth and average irrigation interval used (Eqs. 12 and 13) (Stanhill 1986).

$$WUE = \frac{\left(\frac{Productivity}{Depth}\right)}{10} \tag{11}$$

$$D_m = \frac{Depth}{N_i} \tag{12}$$

$$II_m = \frac{Cycle}{N_i} \tag{13}$$

Where:

Productivity (kg ha^{-1});

WUE - Water Use Efficiency (kg m^{-3});

Depth - Volume of water applied (mm);

D_m - Average irrigation depth (mm);

N_i - Number of irrigations;

II_m - Average irrigation interval (days); and.

Cycle - Crop cycle duration (days).

To provide a comprehensive evaluation of irrigation management techniques, a ranking system was developed incorporating qualitative and quantitative parameters. This system considers three key aspects: (1) quality of the final product, assessed by equatorial tuber diameter (larger diameters indicating higher quality); (2) sustainability of the activity, measured by water use efficiency (WUE, kg m^{-3}), with higher values indicating more efficient water use; and (3) productive potential, determined by total productivity (tons ha^{-1}). For each aspect, techniques are ranked based on their performance, with the highest receiving 9 points and decreasing by 1 point for each subsequent position. Points are summed across aspects to obtain a final score for each technique, enabling a comprehensive ranking that balances quality, sustainability, and productivity. For instance, if technique A ranks 1st in quality, 3rd in sustainability, and 2nd in productivity, its final score would be 9+7+8=24. This ranking system facilitates a holistic assessment of irrigation management techniques, considering their impact on various aspects of beetroot production.

Additionally, it is evident from the analysis of climatological norms of the locality that there is low variability in monthly average temperature (Fig. 9 - A), as well as incident radiation (Fig. 9 - B). This, combined with cultivation in a protected environment, suggests that the cultivation may be influenced solely by the management practices employed. Therefore, a single cultivation cycle is implemented as an experimental strategy.

Data analysis was performed using R software in conjunction with the ExpDes.pt package, applying Tukey's test ($p<0.05$) for mean comparison among treatments. Additionally, Shapiro-Wilk and Bartlett's tests were conducted to verify the assumptions of normality and homogeneity of variances, respectively. Exploratory data analysis, such as scatter plots and boxplots, complemented the interpretation of results.

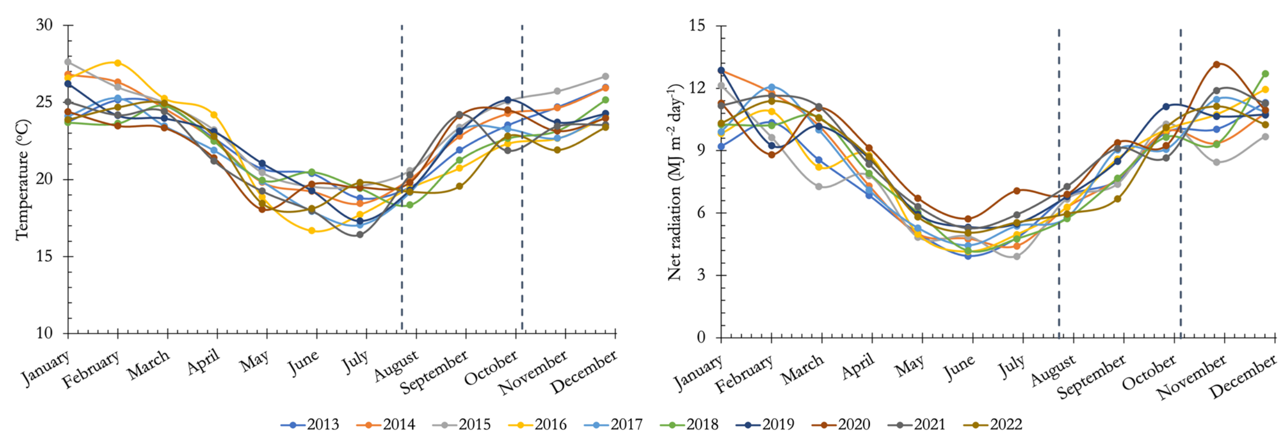

Fig. 9 Climatological norms of the locality with marking of the cultivation cycle period. **A** - Temperature; **B** - Net radiation

Table 3 Water consumption data and spatialization of irrigation for each of the employed management practices, with average irrigation interval (TRm) and average applied depth (Lm)

Treatment	Depth (mm)	Irrigation *N.*	TRm (days)	Lm (mm)
Tensiometer	132,84	37	2,03	3.59
SoilWatch	233,29	46	1.63	5.07
VCS	210.06	52	1.44	4.04
PM - Campbell	195,65	42	1.79	4.66
HS - Campbell	351,99	52	1.44	6.77
PM - Azevedo	189,48	50	1.50	3.79
HS - Azevedo	355,12	65	1.15	5.46
Pan	199.67	43	1.74	4.64
Commercial system	408,48	52	1.44	7.86

Table 4 Productivity data and qualitative analysis of water resource use. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	Productivity (tons ha^{-1})	WUE (kg m^{-3})
Tensiometry	60.06 cd	45.21 a
SoilWatch	86.42 ab	37.04 b
VCS	68.81 bcd	32.76 bc
PM – Campbell	73.14 abc	37.38 b
HS – Campbell	77.41 abc	21.99 d
PM – Azevedo	73.72 abc	38.91 ab
HS – Azevedo	72.60 abc	20.44 d
Pan	53.62 d	26.85 cd
Commercial system	88.38 a	21.64 d

The biometric and physiological analyses were conducted 55 days after sowing (DAS). This timing corresponds to a crucial stage in beetroot development, where the plant is undergoing rapid root tuber formation and vegetative growth. This specific time point was chosen to assess the plant's response to the different irrigation methods during this critical growth stage, allowing for comparisons between treatments and identification of potential impacts on beetroot yield and quality.

Results and discussion

Crop response to water use

Table 3 shows the considerable disparity in applied irrigation depths for each of the treatments. It can be observed that climatological management methodologies based on evapotranspiration calculation using the HS model and the commercial methodology resulted in water consumption close to double that of methodologies based on soil sensors, as well as the Penman-Monteith method for both stations.

It is also worth noting that the tensiometry technique resulted in the lowest total water consumption during the study period, as well as the lowest number of irrigations and average depth. This technique consistently averaged around 2 days for all treatments studied, consistent with average data observed in the literature (Carvalho et al. 2011a; Melo Filho et al. 2020; Oliveira et al. 2022).

Additionally, complementing the management data, Table 4 presents the productivity data and qualitative analysis of water resources applied. It is noteworthy that both the commercial technique and the soil sensor method achieved high productivity, with a slight variation in water use efficiency. Tensiometry stands out for its superior performance, requiring less water volume for beet production.

At this point, it becomes evident that almost all management techniques have a high capacity to reduce water consumption in beet irrigation management. All obtained values are better than the national average (around 20 kg m^{-3}), resulting in a water use efficiency upper than almost all data observed in the literature.

This section presents the findings of the study evaluating the effects of different irrigation management techniques on beetroot production, focusing on yield, quality parameters, and water use efficiency. The results reveal distinct responses in beetroot growth and water use across the irrigation management strategies. Soil-based methods, particularly those utilizing soil moisture sensors, generally resulted in higher yields and improved quality attributes compared to climate-based approaches. Additionally, significant differences in water use efficiency were observed among the treatments, highlighting the potential for optimizing irrigation and resource management in beetroot cultivation. The following sections will detail these findings and discuss their implications for sustainable and efficient beetroot production.

Biometric and physiological analyses

During the biometric measurements, carried out on the 55th day after sowing (DAS) of the crop, leaf temperature readings were obtained as shown in Table 5, supplemented by the estimation of CWSI and measurements of total chlorophyll index. It is noteworthy that at the time of reading, the air temperature was 23.1 °C.

While leaf temperatures were generally lower than air temperature, suggesting ample water availability, variations in CWSI values indicated differences in plant water status among irrigation treatments. However, significant variation was observed only between the tensiometry methodologies and those using the Hargreaves and Samani method for estimating evapotranspiration, as corroborated by CWSI values exceeding 0.4, along with leaf water content exceeding 50%, consistent with other findings in the literature (Stagnari et al. 2014b; Hosseini et al. 2019).

Table 5 Leaf temperature measurements for the 55th DAS, with CWSI estimation and total chlorophyll measurement. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	Leaf T. (oC)	Tair - TLeaf	CWSI	LWC (%)	Chlorophyll
Tensiometer	19.85 a	3.25	0.59 a	66.93 a	34.15 a
SoilWatch	19.13 ab	3.97	0.47 ab	58.88 ab	31.31 a
VCS	19.22 ab	3.88	0.49 ab	62.37 a	33.33 a
PM - Campbell	19.62 ab	3.48	0.55 ab	62.45 a	33.27 a
HS - Campbell	18.71 b	4.39	0.40 b	46.31 b	33.21 a
PM - Azevedo	19.01 ab	4.09	0.45 ab	56.84 ab	31.15 a
HS - Azevedo	18.67 b	4.43	0.40 b	62.17 a	31.86 a
Pan	19.49 ab	3.61	0.53 ab	55.94 ab	32.00 a
Commercial system	18.83 ab	4.27	0.42 ab	54.73 ab	31.82 a

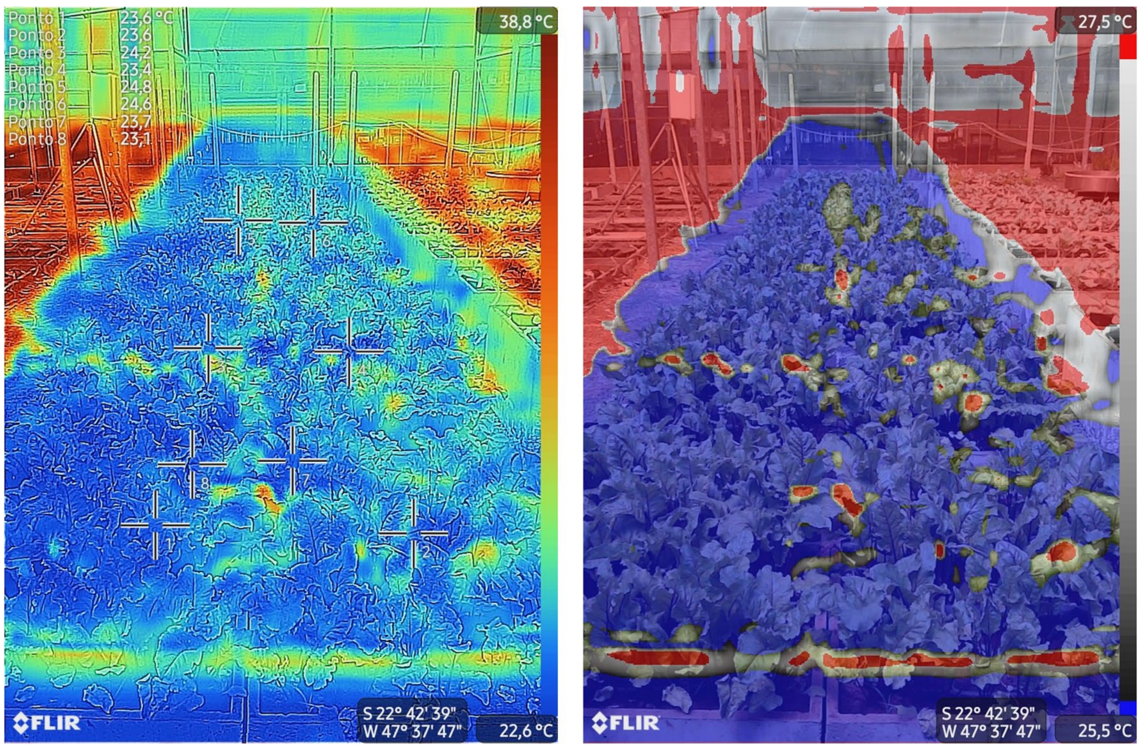

Fig. 10 Thermal image of the experimental area. (**A**) Canopy temperature variation (23.4 °C a 24.8 °C) across treatments (indicated by markers) with an air temperature of 28.1 °C. (**B**) Spatial distribution of temperatures above and below 25.5 °C, highlighting that canopy temperatures remained below this threshold while some structural components of the experimental setup exceeded it

Through the analysis of Fig. 10, the spatial variability of canopy temperatures throughout the greenhouse can be observed, indicating homogeneity of temperatures below 25 °C across the canopy area (with air temperature around 28.1 °C). Furthermore, Fig. 11 depicts the average temperature throughout the cultivation cycle, with a general mean of 21.9 °C.

Nonetheless, no significant variations were observed in chlorophyll index among the treatments, as well as for total chlorophyll, demonstrating uniform growth across the management methods employed.

Table 6 presents the results of the crop's gas exchange analysis, with emphasis on photosynthesis. The treatments managed via the commercial station showed no significant variation and were the highest scoring, followed by the SoilWatch soil sensor. Negative highlights were observed for both the class A tank and the commercial system, which exhibited the lowest photosynthesis rates.

It is noteworthy that although there is a significant difference in almost all photosynthesis rate values, they are slightly higher than the data found in the literature for the same period, ranging from 10 to 20 µmol m^{-2} s^{-1}, corroborating the possibility that all management practices had a positive impact on the employed production system (Melo Filho et al. 2020; Oliveira et al. 2022).

For stomatal conductance data, once again, the Penman-Monteith methodology with data from the commercial station along with the SoilWatch soil sensor showed the best evaluations, indicating the greatest possibility of gas exchange with the environment. Conversely, this was not

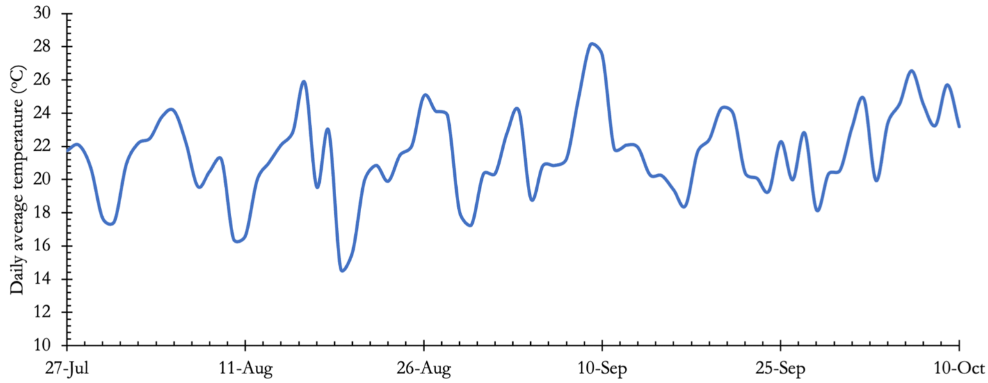

Fig. 11 Temporal distribution of temperatures throughout the cultivation cycle, with a global average temperature of 21.98 °C over the period

Table 6 Gas exchange analysis results, measurement for the 55th DAS. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	Photosynthesis (umol m^{-2} s^{-1})	Stomatal (mol m^{-2} s^{-1})	Transpiration (mmol m^{-2} s^{-1})
Tensiometer	24.67 e	0.63 f	8.24 g
SoilWatch	26.59 b	0.77 b	9.06 b
VCS	24.98 d	0.57 g	7.59 horas
PM - Campbell	26.87 a	0.82 a	9.12 a
HS - Campbell	26.91 a	0.66 e	8.45 e
PM - Azevedo	26.30 c	0.63 f	8.40 f
HS - Azevedo	24.28 f	0.67 d	8.53 d
Pan	21.92 g	0.46 h	7.23 i
Commercial system	21.47 h	0.70 c	8.79 c

Table 7 Qualitative data of harvested tubers. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	Diameter (mm)	°Brix	Root FM (g)	Root DM (g)
Tensiometer	61.44 ab	10.34 a	110.11 cd	70.11 ab
SoilWatch	66.99 a	8.27 d	158.43 ab	88.29 a
VCS	63.36 ab	8.80 abcd	126.16 bcd	73.22 ab
PM - Campbell	63.47 ab	9.00 abcd	134.09 abc	78.55 ab
HS - Campbell	63.78 ab	10.17 ab	141.91 abc	91.45 a
PM - Azevedo	64.28 ab	9.57 abcd	135.16 abc	81.30 ab
HS - Azevedo	64.83 ab	8.42 cd	133.10 abc	75.62 ab
Pan	59.01 d	9.94 abc	98.30 d	61.01 b
Commercial system	67.74 a	8.54 bcd	162.04 a	90.83 a

the case for the VCS soil sensor and the tank methodology, which were above other data found in the literature (Yolcu et al. 2021; Khozaei et al. 2021).

Similarly, for transpiration rate, the same trend was followed, with positive extremes for the Penman-Monteith methodology with data from the commercial station along with the SoilWatch soil sensor. However, the values were below the averages found in the literature, which can be explained by the low temperature at the time of readings (Melo Filho et al. 2020).

Table 8 Qualitative data related to the aerial part of the crop. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	FM aerial (g)	DM aerial (g)	Leaf *N.*
Tensiometer	141.42 ab	46.19 de	11.83 ab
SoilWatch	140.13 ab	57.64 bcd	11.75 ab
VCS	117.84 ab	44.18 e	9.83 c
PM - Campbell	122.29 ab	45.94 de	10.50 bc
HS - Campbell	131.69 ab	70.39 a	11.33 ab
PM - Azevedo	115.21 ab	49.63 cde	11.08 abc
HS - Azevedo	158.12 a	58.71 abc	11.00 abc
Pan	105.67 b	46.56 cde	11.33 ab
Commercial system	145.71 ab	65.13 ab	12.33 a

Table 7 presents qualitative data related to each of the management practices for the crop. It can be observed that with the commercial system and the SoilWatch soil sensor, the largest equatorial root diameters, fresh and dry root masses were obtained, which also showed the lowest levels of soluble solids. However, these values were close to those found in the literature (Carvalho et al. 2011a; Stagnari et al. 2014a).

In Table 8, qualitative data regarding the aerial part of the crop are presented. Notably, the commercial system and the HS methodology with data from the developed station and commercial station stand out for the highest dry and fresh aerial masses, as well as for the number of leaves. These values are close to those found in the literature (Yasamin-shirazi et al. 2020).

In Table 9, data regarding leaf geometry, unit leaf area per plant, and leaf area index are presented. Notably, the HS methodologies with data from both stations stand out for having the widest and longest leaves. Additionally, the commercial methodology and the SoilWatch soil sensor methodology resulted in the highest total leaf areas per plant. Once again, these values are slightly higher than those found in the literature (Stagnari et al. 2014a; Melo Filho et al. 2020).

It is also observed that the values of leaf area index (LAI) showed small but significant variations, again falling within the range described in the literature, supporting the theory that none of the methodologies had a significantly negative

Table 9 Leaf geometry data and leaf area index. Means followed different letters are significantly different ($p < 0.05$) by Tukey's multiple range test

Treatment	Width (cm)	Length (cm)	Total leaf area (cm^2)	LAI
Tensiometer	6.44 bc	18.88 b	1497.25 a	3.74 a
SoilWatch	6.55 bc	19.43 ab	1526.47 a	3.82 a
VCS	6.58 abc	18.67 bc	1460.92 ab	3.65 ab
PM - Campbell	7.50 ab	18.89 b	1320.71 ab	3.30 ab
HS - Campbell	7.79 a	18.40 bc	1549.76 a	3.87 a
PM - Azevedo	6.46 bc	17.46 c	1389.97 ab	3.47 ab
HS - Azevedo	7.19 ab	20.16 a	1499.81 a	3.75 a
Pan	5.70 c	17.61 c	1249.73 b	3.12 b
Commercial system	6.72 abc	18.87 b	1530.86 a	3.83 a

impact on crop development throughout the cycle (Tullio et al. 2013).

Multi-criteria analysis of irrigation methods

Finally, Table 10 presents a synthesis of the analyses conducted, divided into sustainability, productivity, and quality aspects. It highlights the high performance of the management carried out by the SoilWatch soil sensor, achieving maximum scores in all categories, followed by the Penman-Monteith evapotranspiration estimation methodology with meteorological data from the commercial station.

While this study focused on a single installation depth for soil moisture sensors, it is important to acknowledge that installation depth can influence both productivity and water use efficiency. Further research investigating the effects of varying sensor depths on beetroot production under different irrigation management strategies is recommended (Marek et al. 2020; Yu et al. 2021).

Additionally, the selection of an appropriate soil water retention tension threshold for initiating irrigation is crucial for optimizing water use and achieving desired productivity levels. Higher tension thresholds may reduce water consumption but potentially decrease productivity, while lower thresholds may increase water consumption without guaranteeing an optimal economic outcome. Therefore, further studies are needed to determine the optimal soil water retention tension thresholds for beetroot irrigation under different environmental conditions and management practices (Silva et al. 2015; Miranda and Pereira 2019).

Conclusion

This study underscored the critical role of irrigation management in optimizing beetroot production. While soil-based methods generally outperformed climate-based approaches, the most notable finding was the superior performance of soil moisture sensor-based irrigation compared to the commercial method (FieldNET). Specifically, the SoilWatch sensor facilitated a 62% increase in yield and a 19% improvement in quality attributes (e.g., larger root diameter) compared to the commercial method. This highlights the potential of readily available soil moisture sensors to optimize water use and enhance beetroot production, surpassing the performance of commercial irrigation management systems.

The calibration of the SoilWatch sensor showed a slight overestimation of soil water retention tension in the target range, leading to increased water consumption compared to tensiometry. This, combined with the sensitivity of beetroot and water availability, resulted in increased productivity but penalized sustainability.

The methodologies based on climate showed low variability in response at the evaluated points, confirming their high potential for water management. However, it requires the selection of parameters with high accuracy, such as kc values, f factor, and parameters A, B, and C related to the Hargreaves and Samani methodology, which showed the highest variability.

The commercial irrigation management system (FieldNET) demonstrated high performance in terms of tuber productivity and quality, but exhibited lower water use efficiency with its default settings. Notably, water productivity was 37% lower compared to the SoilWatch sensor and 20% lower compared to tensiometry. While this commercial system offers flexibility in configuration parameters, recalibration based on real-time soil moisture data may be necessary

Table 10 Final ranking of methodologies based on scores (1–9) obtained in the analyzed aspects

Treatment	Quality	Productivity	Sustainable	Total	Ranking
Tensiometer	2	2	9	13	3º
SoilWatch	8	8	6	22	1º
VCS	3	3	5	11	4º
PM - Campbell	4	4	7	15	3º
HS - Campbell	5	7	3	15	3º
PM - Azevedo	6	6	8	20	2º
HS - Azevedo	7	5	1	13	3º
Pan	1	1	4	6	5º
Commercial system	9	9	2	20	2º

to achieve more sustainable water use and optimize its performance.

Nevertheless, the management via VCS soil sensor showed low potential in irrigation management, scoring poorly in the evaluated criteria, indicating that calibration within the agronomic interest range did not yield satisfactory performance.

The reduced class A pan management showed low predictive capacity for water balance in a protected environment, which, although not its standard operating condition, is commonly observed in small-scale production systems due to its simplicity and ease of daily operation.

Tensiometry, despite its lower productivity compared to the main studied systems, exhibited water use efficiency 20% higher than the second-place method, presenting itself as a viable alternative in agricultural production, especially in environments where water resources are costly.

However, it is important to acknowledge the limitations of this study, which was conducted under controlled greenhouse conditions using a single soil type and beetroot cultivar. Further research is necessary to evaluate the performance of these irrigation management techniques under varying environmental conditions and across a wider range of soil types and cultivars. Additionally, future studies should incorporate economic analyses to assess the cost-effectiveness of each irrigation strategy, considering factors such as sensor technology investment and potential yield gains. By addressing these limitations and expanding the scope of investigation, future research can contribute to the development of more robust and comprehensive irrigation management strategies for beetroot production in diverse agricultural contexts.

Author contributions A.T.A. e R.D.C. developed the methodology of the experiment, with A.T.A. led and supervised by R.D.C.; A.T.A., R.D.C. and T.H.S.B. wrote and revised the text of the paper; A.T.A. and T.H.S.B. prepares the data. All authors reviewed the manuscript.

Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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