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Effects of different irrigation scheduling methods on physiology, yield, and irrigation water productivity of soybean varieties

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ABSTRACT

An adequate irrigation schedule can result in significant water savings and improved crop yields, especially in large areas such as commodity crops. However, insufficient information is available regarding soybean crops in terms of irrigation scheduling methods and their interaction with irrigation water productivity (IWP) for different soybean varieties. The objective of this study was to quantify the effect of climate-, soil-, and plant-based irrigation scheduling methods on the physiology, yield, and IWP of three soybean varieties. A shelter experiment was conducted using a randomized design with split plots of two factors and five replications. Five irrigation methods and three soybean varieties (TMG 7067, 58i60RSF IPRO, and NA 5909) were tested. In CB (climate-based method) the evapotranspiration-water balance was used; in SB1 and SB2 (soil-based methods), irrigation at field capacity was applied when the soil matric potential reach − 20 kPa at depths of 0.1 m and 0.3 m, respectively; while In PB1 and PB2 (plant-based methods), canopy temperature depressions (CTD) of ~2 °C and ~4 °C, respectively, were employed to trigger irrigation. The amount of irrigation water applied under all irrigation scheduling methods ranged from 310 (PB1 and PB2) to 786 mm (V1 under SB1). The net photosynthetic rate (A), stomatal conductance (gs), transpiration (E), and leaf water potential (LWP) were higher under SB1 and SB2 than under other irrigation methods. On average, grain yield (GY) was significantly higher in SB1 (3.5 Mg ha^{-1}), than in SB2 (3.0 Mg ha^{-1}), CB (2.5 Mg ha^{-1}), PB1 (2.4 Mg ha^{-1}) and PB2 (2.0 Mg ha^{-1}). However, it was also found that PB1 treatment resulted in significantly increased IWP (0.84 kg m^{-3}) compared to the other irrigation treatments. Overall, the choice of irrigation scheduling methods for soybean crops under tropical conditions should be based on the technology level, water resource availability, and individual farmer goals to maximize GY per unit area (SB1 and SB2) or optimize IWP (PB1). In addition, despite the ease of use of climate- and plant-based methods, all of these methods should be calibrated against soil-based methods under different climatic conditions and for a large number of genotypes.

1. Introduction

The percentage of soybean yield gaps caused by water deficit in the United States (Grassini et al., 2015), Brazil (Sentelhas et al., 2015), and China (Wang et al., 2022) is around 30%, 42%, and 50%, respectively. These percentages are expected to expand as the global climate becomes warmer, increasing the demand for new irrigated soybean fields. A recent study showed that irrigation of soybean reduces the land area required to produce an equivalent amount of biofuel crop yield by two-four times compared with rainfed management (Rodriguez et al., 2018). However, there is insufficient information available regarding soybean varieties in terms of irrigation scheduling methods.

The purpose of irrigation scheduling is to determine the exact amount and timing of water application to crops (Sałata et al., 2022), and it is based on at least one variable of the soil-plant-atmosphere system (Kang et al., 2021). The adoption of an adequate irrigation scheduling method is essential to secure the physiological processes of crops and, hence, yield (Kumar Jha et al., 2019). Moreover, efficient irrigation scheduling reduces water use and energy consumption (Souza and Rodrigues, 2022). In contrast, over- and under-irrigation associated with inadequate or poorly designed irrigation scheduling has resulted mainly in low grain yield and irrigation water productivity (IWP),

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waterlogging, soil salinization, and rises in water table levels (Yohannes et al., 2019; de Almeida et al., 2022; Quiloango-Chimarro et al., 2022).

Irrigation scheduling methods can be classified as climate-, soil-, or plant-based (Steele et al., 1994). Climate-based methods for irrigation scheduling typically use climatological parameters to estimate potential evapotranspiration (ET), crop coefficient curves to refine crop water use estimates, and soil water storage capacity (SWSC) data (Pereira et al., 2020). Soil-based methods for irrigation scheduling are based on soil moisture sensors that are used to monitor either the soil water potential or soil water content (Bwambale et al., 2022). Plant-based methods for irrigation scheduling use crop water status measurements such as canopy temperature (Veysi et al., 2017), leaf water potential (Costa et al., 2020), sap flow rates (Conejero et al., 2007), stomatal resistance (Cannavo et al., 2016), and turgor pressure (Zimmermann et al., 2013). To date, no studies have simultaneously compared the effectiveness of these three methods in soybean production.

Scientific and field extension efforts to enhance irrigation scheduling in soybeans have concentrated on climate-based methods rather than on soil- or plant-based methods. For example, recent studies have focused on the accuracy of crop coefficient values in southern Brazil (da Silva et al., 2019) and the quantification of crop evapotranspiration using the eddy covariance technique in the USA (Anapalli et al., 2022). However, difficulties in matching an adequate irrigation scheduling method in soybean are related to larger differences in amount of irrigation water applied and IWP among genotypes, depending on the maturing group. For example, Garcia et al. (2010) reported differences between maturing varieties V and VI in amount of irrigation water applied and IWP of 65 mm and 0.6 kg m^{-3}, respectively. In addition, in other legumes, responses to irrigation scheduling were associated with differences in growth habits (Rowland et al., 2010) and genetic differences in water use strategies (Farooq et al., 2019). In this context, it is necessary to conduct trials dealing with different irrigation scheduling methods in accordance with the characteristics of different soybean cultivars.

The objective of this study was to quantify the effects of different irrigation scheduling methods (soil-, climate-, and plant-based methods) used by agricultural producers on the physiology, yield, and IWP of three soybean varieties under tropical conditions.

2. Materials and methods

2.1. Characterization of the experimental area, planting and crop management

A rain-out shelter experiment was carried out at the Biosystems Engineering Department, University of São Paulo (USP/ESALQ), Piracicaba, São Paulo, Brazil (22°46'39" S, 47°17'45" W) from October 2020 to February 2021. The cover structure consisted of a ceiling height of 5.2 m, a transparent plastic cover (diffuser film), and a black screen on the sides that intercepted 30% of the incident radiation. Waterproofed concrete containers of 0.33 m^3 (1.0 m length, 0.4 m width and 0.8 m depth) were filled with sandy-loam soil (Oxisol Typic Ustox).

Daily solar radiation, minimum and maximum air temperatures, relative humidity, and wind speed were recorded at 10-minute intervals using an automatic station installed inside the experimental area connected to a CR1000 data logger (Campbell Scientific, Logan, Utah, USA). For the estimation of reference evapotranspiration (ET_o), the method of Penman-Monteith was used (Allen et al., 1998). Daily weather parameters during the growing cycle are presented in Fig. 1.

Soybean was sown on October 24, 2020, in a single row per container with an intra-row spacing of 0.40 m and an inter-row spacing of 0.09 m (10 plants per container) (Fig. S1A). The sowing date was within the soybean planting window in Southeast Brazil. Certified seed of three commercial varieties that are suitable for irrigated conditions and present a super-early cycle (118–128 days) was sourced from Compass Minerals in São Paulo, Brazil, and used in this study: TMG 7067 (V1), which is in high demand, is distinguished by its semi-determinate growth habit and belongs to maturity group 6.5 (Zuffo et al., 2022); 58i60RSF IPRO (V2), which is distinguished by its indeterminate growth habit and resistance to lodging and belongs to maturity group 5.8 (Chechi et al., 2020); and NA 5909 (V3), which is distinguished by its indeterminate growth habit and stability under varying soil and climatic conditions and belongs to maturity group 6.2 (Durli et al., 2022).

Phosphate fertilizer was applied uniformly by hand at sowing in each container at a rate of 200 kg P_2O_5 ha^{-1}. Potassium fertilizer was top dressed on 20 and 40 days after sowing at a rate of 100 kg K_2O ha^{-1}, being the total equivalent to 200 kg K_2O ha^{-1}. Fertilization was based on guidelines for soybean provided by van Raij et al. (1997). The chemical soil parameters of 0–0.4 m soil layer before fertilizer application were as follows: pH, 5.2; soil organic matter content, 11.1 g kg^{-1}; available potassium content, 80.1 mg kg^{-1}; and available phosphorus content, 4.4 mg kg^{-1}. Pesticide applications were made when necessary and weed control was conducted manually throughout the growing season.

2.2. Experimental design and treatments

A random design with split plots of two factors, irrigation scheduling methods and soybean varieties, was used in the experiment. 15 combinations of irrigation scheduling methods and soybean varieties were used in this trial. Each treatment was performed in five replicates, for a total of 75 plots (Fig. S1B). All plants were irrigated based on daily evapotranspiration (K_c initial growing = 0.50) (Allen et al., 1998) during the first 20 days. Later, soybean varieties were subjected to five irrigation scheduling methods (M) as follows: soil-moisture-based through soil water potential (SB1 and SB2), climate-based through evapotranspiration-water balance (CB), and plant-based through canopy temperature depression (PB1 and PB2). Irrigation water was provided through a drip irrigation system. A drip line of 1 m length was installed in each plot with six emitters, each with a flow rate of 0.6 L h^{-1} and spaced at 0.15 m, resulting in a total flow rate of 3.6 L h^{-1} per container (plot). All plots were controlled individually through micro-registers installed on a control panel.

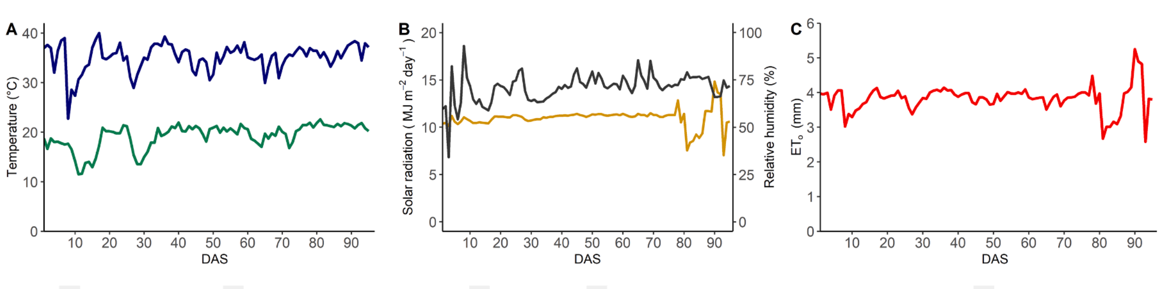

Fig. 1. A: Maximum and minimum air temperature, B: relative humidity and solar radiation, and C: reference evapotranspiration (ET_o) in the experimental area throughout the growing season.

2.2.1. Evapotranspiration and soil water balance–based irrigation scheduling

2.2.1.1. Crop evapotranspiration estimation. Soybean crop evapotranspiration was calculated according to Eq. 1 (Allen et al., 1998):

$$ET_c = K_c\ ET_o \tag{1}$$

where ET_c is the daily actual evapotranspiration of soybean (mm), K_c is the crop coefficient (dimensionless), and ET_o is the daily reference evapotranspiration (Penman-Monteith method) (mm). The specific K_c values (Fig. S2) adopted during the crop development (II), mid-season (III), and end season (IV) were 0.80, 1.15 and 0.50, respectively (Allen et al., 1998; Payero and Irmak, 2013). The reference evapotranspiration (ET_o) was calculated on a daily step (Allen et al., 1998):

$$ETo = \frac{0.408\,\Delta\,(Rn - G) + \gamma\,\frac{900}{T+273}\,u2\,(es - ea)}{\Delta + \gamma\,(1 + 0.34\,u2)} \tag{2}$$

where R_n is the surface radiation balance (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the partial vapour pressure (kPa), Δ is the slope of the saturation vapour pressure curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$).

2.2.1.2. Water balance model. Water balance model represents the balance of input, output and change of soil water storage (ΔS) in the effective root zone as showed in Eq. 3 (Hillel, 2003):

$$ET = I - P + U - R - D + W_0 - W_e \tag{3}$$

where I is the irrigation amount (mm), P is the effective rainfall (mm), U is the water table recharge (mm), R is the surface runoff (mm), D is the deep percolation (mm), W_0 is the initial soil water storage (mm) and W_e is the end soil water storage (mm). Eq. 4 was simplified since the experiment was carried out in containers under rain-out shelter conditions and then used to estimate irrigation amount (mm):

$$I = ET + (W_e - W_0) \tag{4}$$

2.2.1.3. Irrigation shift. The irrigation shift considers different data regarding soil water content. Total available water (TAW, mm) and readily available water (RAW, mm) in the top 0.40 m of the root zone were calculated as (Allen et al., 1998):

$$TAW = (\theta_{FC} - \theta_{PWP}) \times Z_r \tag{5}$$

$$RAW = p \times TAW \tag{6}$$

where θ_{FC} is the volumetric soil water content at field capacity (m^3 m^{-3}), θ_{PWP} is the volumetric soil water content at permanent wilting point (m^3 m^{-3}), Z_r = root system depth (mm), and p is the average fraction of the total available water (TAW) that can be depleted from the root zone before water stress occurs (ranging between 0 and 1). In the case of soybean, p is equal to 0.50 (Allen et al., 1998). On a daily basis, Eq. 4 was employed to estimate the amount of irrigation. When the calculated value was close to the threshold represented by RAW, irrigation was initiated to return to θ_{FC}.

2.2.2. Soil-moisture-based irrigation scheduling

Irrigation scheduling based on soil moisture was managed according to the average soil matric potential measured through tensiometry in all five plot replications of each soybean variety. In each plot, a battery of two tensiometers installed at 0.1 and 0.3 m depths provided measurements of 0–0.2 and 0.2–0.4 m soil layers, respectively. Soil matric potential was monitored daily, and irrigation was carried out to increase the soil water to field capacity for each soil layer according to the following criteria: a) SB1, when the soil matric potential reached around − 20 kPa at 0.1 m depth and b) SB2, when the soil matric potential reached around − 20 kPa at 0.3 m depth.

The amount of irrigation was estimated from the soil matric potential using the van Genuchten approach (van Genuchten, 1980), according to Eq. 7:

$$\theta\ (\Psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha \times \Psi_m)^n\right)^m} \tag{7}$$

where θ (ψm) is the soil volumetric water content (cm^3 cm^{-3}), θ_r is the soil residual volumetric water content (cm^3 cm^{-3}), θ_s is the volumetric water content of the saturated soil (cm^3 cm^{-3}), m and n are the regression parameters of equation (dimensionless), α is the parameter with dimension equal to the inverse of the tension (kPa^{-1}) and ψ_m is the function of the matric potential (kPa). The fitting parameters for the van Genuchten model and the physical water-retention parameters of the soil (Table 1) were estimated using non-deformed soil samples collected prior to the beginning of the trial at two depths, 0.1 and 0.3 m.

2.2.3. Plant-based irrigation scheduling

The canopy temperature (Tc) was measured using a portable infrared sensor TIV 6500 (Vonder, Curitiba, Brazil) with the emissivity adjustment set at 0.95. The device has a minimum measurement diameter of 6 mm and a distance to spot size of 10:1.

The canopy temperature data collection was conducted from 21 DAS until the end of the growing season. Measurements were continuously replicated for five readings of each plot at the top of the canopy, focusing on sampling leaves that were fully exposed to the sunlight from 10:30 to 11:30 AM, and then averaged. Canopy temperature depression (CTD) was calculated for each soybean variety, according to Eq. 8:

$$CTD = T_c - T_{air} \tag{8}$$

where T_c is the canopy temperature and T_{air} is the air temperature readings during the measurement period. Irrigation was triggered according to the following criteria: a) PB1, when the average CTD was ~2 °C and b) PB2, when the average CTD was ~4 °C. These CTD thresholds were developed based on preliminary data collected by our team (Almeida, 2021).

The amount of irrigation was calculated according to evapotranspiration and soil water balance methodology. However, only steps corresponding to items 2.2.1.1 (crop evapotranspiration estimation) and 2.2.1.2 (soil water balance) were conducted because under these plant-based methods, irrigation started when CTD reached the corresponding threshold for PB1 and PB2.

2.3. Physiological measurements

Physiological measurements were conducted at 37 DAS (end of the vegetative stage) and 52 DAS (floral initiation of soybean). The gas exchange parameters: net photosynthesis (A), stomatal conductance (gs), and transpiration (E); and predawn leaf water potential (LWP) were measured on fully expanded leaves from the top of the plant. Gas exchange parameters were measured in three replications per plot with a portable gas exchange system Li-6400 XT (IRGA/LiCOR-Inc, Lincoln, Nebraska, USA) from 9:00 to 11:00 h. The equipment was set to use concentrations of 400 μmol CO2 mol^{-1} in the leaf chamber, and the photon flux density photosynthetic active used was 1000 μmol [quanta] m^{-2} s^{-1}.

Predawn LWP of soybean was measured with a pressure chamber model 3005 (Soil Moisture, Santa Barbara, California, USA). One leaf of each plot was sampled between 3:00 and 5:00 AM and processed in the pressure chamber, which was slowly pressurized until a droplet of liquid appeared on the cut surface. In order to reveal integrated treatment effects, pooled data of physiological parameters (average values for the

Table 1
Empiric parameters (α, m e n), soil residual and saturation water content (θ_r, θ_s) of the Van Genutchen model (1980), moisture at field capacity (θ_{fc}), moisture at the permanent wilting point (θ_{pwp}) and available water capacity (AWC).

Layers (m)	Θ_s (cm^3 cm^{-3})	Θ_r (cm^3 cm^{-3})	α (kPa^{-1})	m	n	θfc	θpwp	AWC
0–0.2	0.421	0.098	1.3464	0.1799	2.7175	0.227	0.106	24.2
0.2–0.4	0.412	0.085	1.5708	0.1648	2.5028	0.226	0.098	25.6

two measurement dates) were used to perform the analysis of variance.

2.4. Shoot growth parameters, yield and irrigation water productivity

Plants were harvested from a subsample of each plot (plants from the central part of the row) at physiological maturity and divided into vegetative and reproductive components. To measure plant height and stem diameter, a flexible measuring tape and a digital pachymeter were used, respectively. Leaf area was determined with a leaf area meter LI-3000 C (LiCOR-Inc, Lincoln, Nebraska, USA). The leaf area index (LAI) was calculated by dividing measured leaf area by sampling area. Additionally, the number of nodes per plant was recorded. The aboveground components were then dried at 60 °C in an oven with forced air circulation for 72 h. Then, vegetative and reproductive components were weighed on a precision scale to obtain the aboveground biomass, yield and yield components (pods per plant and 100-grain weight). The grain yield was adjusted for 130 g kg^{-1} moisture and scaled to Mg ha^{-1}. Irrigation water productivity (kg m^{-3}) was calculated as the ratio of grain yield to the total amount of water applied.

2.5. Statistical analysis

All the statistical analyses were performed with R Studio (R Project for Statistical Computing, version 4.1.2). Shapiro-Wilk and Levene tests were used for the estimation of normality and homogeneity of variance. The effects of irrigation scheduling and variety were evaluated at the 0.05 and 0.01 probability levels using the F-test. The means of variables with a significant F-test value were compared using the Fisher's least significant difference test (LSD) at 0.05 probability level. Principal Component Analysis (PCA) was used to generate the bi-plots to show the relationship between the varieties and the assessed variables under the different irrigation scheduling methods. To assess the suitability of the data for PCA, Bartlett's test of sphericity was performed to check for multicollinearity among the variables (Rojas-Valverde et al., 2020).

3. Results

3.1. Irrigation water applied

This study revealed significant variations in the amount of water applied using various irrigation methods. On average, the amount of irrigation water applied was significantly higher in SB1 (614 mm), than in SB2 (522 mm), CB (358 mm), PB2 (310 mm) and PB1 (309 mm). The total amount of irrigation water applied ranged from 309 mm for PB1 in varieties V1, V2 and V3 to 786 mm for SB1 in V1 (Table 2). Moreover, the irrigation water applied in SB1 was higher than that applied in SB2 for the three varieties V1, V3, and V2 in that order. In the CB and PB methods (PB1 and PB2), the amount of water applied varied depending on the phenological stage but not on the crop variety, as the crop coefficient (Kc) varied only by phenological stage.

This study revealed a significant result, demonstrating that approximately 85% of the water was applied during the crop development (II) and mid-season (III) stages, regardless of the irrigation scheduling approach or soybean variety. The number of irrigation events varied among the methods, with SB1 having the highest number of events (on average, 43 events), and CB and PB2 having the lowest number of events (on average, 36 events).

3.2. Physiological responses

The irrigation scheduling method had a significant impact on the photosynthetic rate (A), stomatal conductance (gs), transpiration (E), and leaf water potential (LWP). In contrast, the effect of soybean variety was only significant on gs and E. Furthermore, the interaction between irrigation scheduling method and soybean variety was significant for gs and LWP (Table 3).

The two soil-based irrigation methods (SB1 and SB2) resulted in higher A and gs values compared to the two plant-based methods (PB1 and PB2) and the climate-based method (CB) (Table 3). Specifically, the A values were reduced by 11.5%, 19.3%, and 27.8% for CB, PB1, and PB2, respectively, compared to SB1, which had the highest A values.

Table 2
Amount of irrigation water applied and number of irrigation events for each stage of development of three soybean varieties subjected to different irrigation scheduling methods.

	Stage of development	Irrigation scheduling methods														
		CB			SB1			SB2			PB1			PB2		
		V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3
Irrigation water applied (mm)	I	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	II	90	90	90	166	60	131	86	53	80	78	78	78	65	65	65
	III	213	213	213	563	378	373	497	323	402	181	181	186	186	186	186
	IV	25	25	25	57	57	54	60	24	41	20	20	15	29	29	29
	Total	358	358	358	786	496	559	643	400	523	309	309	309	310	310	310
Number of irrigation events	I	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	II	5	5	5	7	5	6	7	5	6	4	4	4	3	3	3
	III	10	10	10	19	14	13	12	10	11	11	10	13	14	11	12
	IV	1	1	1	2	2	2	2	2	2	2	2	2	1	1	2
	Total	36	36	36	48	41	41	44	37	39	37	36	39	35	35	37

CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety; I: initial growing (0 to 20 days after sowing - DAS), II: crop development (21 to 55 DAS); III: mid-season (56 to 90 DAS); IV: end-season (91 to 100 DAS).

Table 3
Average values of photosynthesis, stomatal conductance, transpiration, and leaf water potential of three soybean varieties submitted to different irrigation scheduling methods.

	Photosynthesis (μmol m^{-2} s^{-1})				Stomatal conductance (mol m^{-2} s^{-1})			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	19.02	21.08	17.58	19.23 bc	0.51 ABb	0.65 Aa	0.38 Bb	0.51
SB1	23.21	21.52	20.46	21.73 ab	0.86 Aa	0.63 ABa	0.55 Bab	0.68
SB2	23.02	21.17	21.99	22.06 a	0.94 Aa	0.67 Ba	0.67 Ba	0.76
PB1	18.40	16.72	17.47	17.53 cd	0.51 Ab	0.40 Ab	0.35 Ab	0.42
PB2	16.53	16.04	14.54	15.70 d	0.52 Ab	0.43 Ab	0.34 Ab	0.43
Mean	20.04 A	19.31 A	18.41 A		0.67	0.56	0.46	
M				* *				* *
V				ns				* *
MxV				ns				*
	Transpiration (mmol m^{-2} s^{-1})				Leaf water potential (MPa)			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	9.26	10.67	7.13	9.02 ab	-3.13 Aa	-2.00 Bab	-2.13 Bb	-2.42
SB1	11.89	10.60	9.76	10.75 a	-2.27 Aab	-2.33 Aab	-2.10 Ab	-2.23
SB2	11.72	10.65	9.85	10.74 a	-1.83 Ab	-1.47 Ab	-1.93 Ab	-1.74
PB1	8.12	7.43	6.78	7.44 b	-2.00 Ab	-2.57 Aa	-2.47 Ab	-2.35
PB2	7.24	6.99	6.12	6.78 b	-2.65 ABab	-2.40 Aa	-3.35 Aa	-2.80
Mean	9.65 A	9.27 A	7.93 B		-2.38	-2.15	-2.40	
M				* *				* *
V				*				ns
MxV				ns				* *

CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety; M: irrigation scheduling method; V: variety; * : significant differences at the 0.05; * * significant differences at the 0.01; ns: not significant; Means followed by distinct lowercase letters within a column and distinct capital letters within a row are different by the LSD test at 0.05 significance.

Notably, V2 under the CB method exhibited gs values similar to those of SB1 and SB2, whereas for V3, PB1, and PB2 resulted in a greater reduction in gs values compared to SB2. The results also showed that transpiration (E) values were similar for SB1, SB2, and CB, but significantly decreased by 30.8% and 36.9% for PB1 and PB2, respectively, compared to SB1. Furthermore, the E values for V1 and V2 were higher than those for V3 by 17.8% and 14.5%, respectively.

Regarding leaf water potential, all soybean varieties exhibited a distinct behavior, with higher values obtained using the SB methods and lower values obtained using the PB methods (Table 3). Notably, the CB method achieved LWP values similar to those obtained using the SB method (SB1 and SB2), except for V1. In contrast, PB2 consistently exhibited the lowest LWP values for all soybean varieties examined. Overall, the results indicated that soil moisture-based methods favored

Table 4
Average values of plant height, leaf area index, stem diameter and number of nodes per plant of three soybean varieties subjected to different irrigation scheduling methods.

	Plant height (cm)				Leaf area index			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	128.1	88.6	111.1	109.3 ab	3.3 Bb	4.1 ABab	5.0 Ab	4.2
SB1	143.8	95.9	110.9	116.8 a	7.1 Aa	4.8 Bab	7.1 Aa	6.3
SB2	127.6	84.1	115.7	109.1 ab	6.6 ABa	5.7 Ba	7.3 Aa	6.6
PB1	105.1	70.0	103.6	92.9 b	4.5 Ab	2.4 Bc	4.1 Ab	3.7
PB2	118.5	72.3	102.2	97.6 b	3.0 Bb	2.9 Bbc	5.4 Ab	3.8
Mean	124.6 A	82.2 C	108.7 B		4.9	4.3	5.8	
M				*				* *
V				* *				* *
MxV				ns				* *
	Stem diameter (mm)				Number of nodes per plant			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	6.1 bc	5.4 ab	6.0 ab	5.8	21.2	18.7	16.7	18.9 a
SB1	7.7 a	5.6 a	5.4 ab	6.2	22.9	17.8	15.6	18.7 a
SB2	7.1 ab	5.4 ab	6.4 a	6.3	22.1	18.2	17.2	19.1 a
PB1	5.7c	4.3 b	5.1 b	5.0	20.1	15.9	15.6	17.2 a
PB2	5.9 bc	5.2 ab	5.5 ab	5.5	21.7	16.3	16.2	18.1 a
Mean	6.5	5.2	5.7		21.6 A	17.4 B	16.2 C	
M				* *				ns
V				* *				* *
MxV				*				ns

CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety; M: irrigation scheduling method; V: variety; * : significant differences at the 0.05; * * significant differences at the 0.01; ns: not significant; Means followed by distinct lowercase letters within a column and distinct capital letters within a row are different by the LSD test at 0.05 significance.

higher values of A, gs, E, and LWP than the other methods evaluated.

3.3. Morphological, yield and irrigation water productivity responses

The interaction between irrigation scheduling and variety was significant for leaf area index (LAI) and stem diameter (SD). The individual effects of irrigation scheduling and variety were significant for plant height (PH), leaf area index (LAI), stem diameter (SD) and number of nodes per plant (NNP), except irrigation scheduling for NNP (Table 4).

The highest average plant height was observed in SB1, followed by that in CB and SB2. PB1 and PB2 had the lowest average plant height. In addition, it was notable that the semi-determinate growth variety (V1) was tallest compared with the indeterminate growth varieties (V2 and V3). Under SB1 and SB2, the LAI was similar, indicating consistent performance and the highest average values among the irrigation treatments. In contrast, under the PB1 and PB2 treatments, all soybean varieties exhibited reduced LAI compared with SB methods. Notably, when comparing V2 under CB, the LAI values were comparable to those of SB1 and SB2. However, under PB1 and PB2, V2 displayed the largest reductions in LAI compared with the other varieties. Stem diameter followed a similar trend as LAI, showing the highest values for the SB methods. However, V1 exhibited reduced SD values for the CB and PB methods when compared to the SB methods, and V2 showed similar SD values among irrigation treatments, except for PB1.

Irrigation scheduling was significant for grain yield (GY), aboveground biomass (AB), and pods per plant (PP), whereas variety was significant for all these traits and for 100-grain weight (HGW). The interaction between irrigation scheduling and variety was significant for AB and PP (Table 5).

Among the irrigation scheduling methods studied, SB1 achieved the highest grain yield (3.5 Mg ha^{-1}). It was similar to the GY under SB2 but differed from the GY achieved in CB, PB1, and PB2. Notably, under SB2, GY was comparable to that observed in the CB and PB1 treatments, with an average of 2.6 Mg ha^{-1}. The lowest GY was observed in PB2, with a reduction of 43% compared to that observed in SB1. Irrigation scheduling methods PB1 and PB2 achieved the highest values for AB (12 Mg ha^{-1}) and PP (51 pods per plant) for all the soybean varieties. Reductions in AB and PP were observed under CB, PB1, and PB2 for V1 and V3, whereas for V2, only AB under PB2 was different from that achieved under the other irrigation scheduling methods. Overall, the results showed that under soil-based irrigation scheduling, grain yield and grain yield components tended to be higher than those under the other treatments.

The individual effects of irrigation scheduling and variety were significant for irrigation water productivity (IWP) (Fig. 2). Irrigation scheduling methods CB and PB1 achieved the highest IWP values among all treatments, averaging 0.78 kg m^{-3} (Fig. 2A). These treatments (CB and PB1) were different from SB1, SB2, and PB2, which achieved an average IWP value of 0.61 kg m^{-3}. Moreover, among the varieties, V2 achieved the highest IWP, with an average value of 0.84 kg m^{-3} (Fig. 2B).

3.4. Principal component biplot analysis for assessed agronomic and physiological variables

The first two principal components (PCs) explained 79.6% of the total variance, with PC1 and PC2 accounting for 53.4% and 26.2%, respectively (Fig. 3). Variety V2 under CB, SB1, and SB2 exhibited a higher GY. Additionally, V3 under SB1 and SB2 demonstrated higher AB, LAI, NPP, A, E, and gs values. Furthermore, V2 and V3 exhibited higher IWP values under CB conditions. In contrast, V1 and V3 under PB1, as well as all varieties under PB2, were associated with lower values of leaf water potential (LWP), indicating higher water stress. In contrast, V1 under SB1 and SB2 demonstrated higher vegetative growth (SD, PH, and NNP), but lower GY (90º angle with the vector GY).

4. Discussion

The purpose of irrigation scheduling is to provide an optimal water supply as well as to adjust the appropriate frequency to minimize water use and ensure crop productivity. Although research has been conducted on irrigation scheduling improvement with numerous plant species

Table 5
Average values of grain yield, aboveground biomass, pods per plant and 100-grain weight of three soybean varieties subjected to different irrigation scheduling methods.

	Grain yield (Mg ha^{-1})				Aboveground biomass (Mg ha^{-1})			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	1.5	3.4	2.6	2.5 bc	8.4 Bb	10.0 ABa	11.2 Aab	9.9
SB1	2.9	4.2	3.4	3.5 a	12.8 Aa	11.5 Aa	12.1 Aa	12.1
SB2	2.3	3.4	3.3	3.0 ab	11.8 ABa	11.0 Ba	13.0 Aa	11.9
PB1	1.8	2.9	2.6	2.4 bc	8.8 Ab	9.4 Aa	10.1 Ab	9.4
PB2	1.6	2.2	2.2	2.0c	8.4 ABb	7.2 Bb	10.3 Ab	8.6
Mean	2.0 C	3.2 A	2.8 B		10.0	9.8	11.3	
M				* *				* *
V				* *				* *
MxV				ns				*
	Number of pods per plant				100-grain weight (g)			
	V1	V2	V3	Mean	V1	V2	V3	Mean
CB	35.8 ABb	43.8 Aab	29.9 Bb	36.5	11.1	14.1	10.8	12.0 a
SB1	65.8 Aa	49.3 Ba	41.5 Ba	52.2	9.6	13.0	11.1	11.3 a
SB2	62.1 Aa	41.8 Bab	44.0 Ba	49.3	9.8	13.4	10.4	11.2 a
PB1	43.3 Ab	39.6ABab	27.8 Bb	33.6	10.2	13.2	11.6	11.6 a
PB2	46.4 Ab	30.3 Bb	31.0 Bb	39.0	9.9	13.4	10.9	11.3 a
Mean	50.7	40.8	34.9		10.1 B	13.4 A	10.9 B	
M				* *				ns
V				* *				* *
MxV				*				ns

CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety; M: irrigation scheduling method; V: variety; * : significant differences at the 0.05; * * significant differences at the 0.01; ns: not significant; Means followed by distinct lowercase letters within a column and distinct capital letters within a row are different by the LSD test at 0.05 significance.

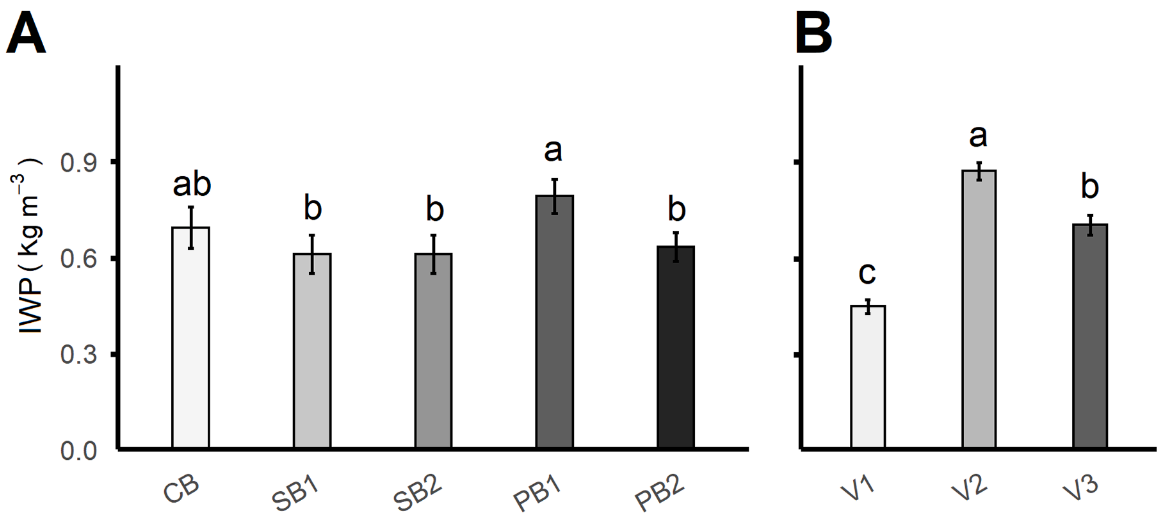

Fig. 2. Effect of irrigation scheduling methods on irrigation water productivity (IWP) of three soybean varieties. Distinct lowercase letters are different by the LSD test at 0.05 significance. CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety.

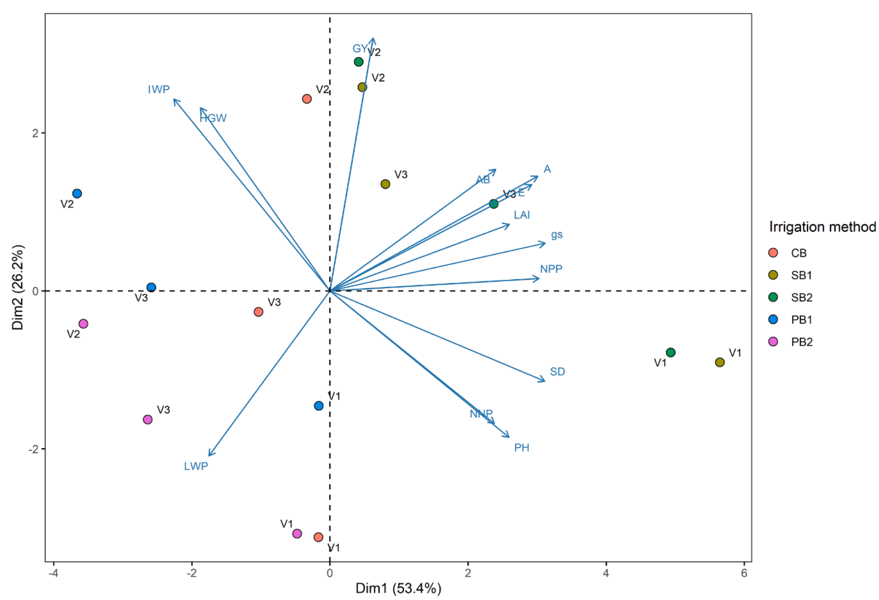

Fig. 3. PCA-Biplot of studied variables and irrigation scheduling methods. The angles between the vectors derived from the middle point of biplots exhibit positive or negative interactions of studied traits. Net photosynthesis rate (A); stomatal conductance (gs); transpiration (E); leaf water potential (LWP); plant height (PH); leaf area index (LAI); stem diameter (SD); number of nodes per plant (NNP); grain yield (GY); aboveground biomass (AB); number of pods per plant (NPP); 100-grain weight (HGW); CB: climate-based through evapotranspiration-water balance; SB1: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.1 m soil depth); SB2: soil-moisture-based through soil water potential (irrigation initialization based on −20 kPa threshold at 0.3 m soil depth); PB1: plant-based through canopy temperature depression (Tc-Tair = 2 °C); PB2: plant-based through canopy temperature depression (Tc-Tair = 4 °C); V1: TMG 7067 variety; V2: 58i60RSF IPRO variety; V3: NA 5909 variety.

(Garcia et al., 2010; Sharma et al., 2017; Hou et al., 2021; Bwambale et al., 2022), only Sui and Vories (2020) used different irrigation scheduling methods in soybean simultaneously, evaluating only the number of irrigation events. Our findings indicate that irrigation scheduling methods based on soil, evapotranspiration, and plant measurements have distinct effects on the physiology, yield, and irrigation water productivity of different soybean varieties.

4.1. Amount and frequency of irrigation under different scheduling methods

The amount of irrigation water applied in the CB irrigation scheduling method was lower than that applied in the SB irrigation scheduling method for all soybean varieties. This could be because in CB there were prolonged irrigation intervals (Table 2), which may inhibit normal plant growth in terms of leaf area (Farg et al., 2012). In addition, the soybean crop coefficient used in this experiment was adapted from the FAO K_c approach (Allen et al., 1998). Previous researches demonstrate that adopting universal K_c values may lead to less effective irrigation management (Marin and Angelocci, 2011; Segovia-Cardozo et al., 2019; Gundim et al., 2023). For example, Hou et al. (2022) reported that a K_c for cotton obtained locally in the south of China was 10% higher than the FAO K_c during the flowering stage. In our experiment, it was possible that the FAO K_c adopted in the CB method was lower than required due to higher differences in irrigation water applied, especially in phase III (reproductive stage).

The soil-based irrigation scheduling methods showed significant differences in irrigation water applied among the three soybean varieties (496–786 mm), despite the use of similar MG groups in this experiment (5.8 to 6.5). Crop water use can be reduced by decreasing transpiration (He et al., 2017) and the leaf area index (Pinnamaneni et al., 2022; Petry et al., 2023). In this study, variety V2 showed lower values of transpiration, leaf area, and stomatal conductance, and also showed low water demand under SB1 and SB2. The variety V2 also showed lower plant height and number of nodes per plant, which is consistent with the study of He et al. (2017), who reported that a low leaf area is associated with a reduction in other morphological variables (branch number and leaf number), but not in grain yield.

There was a difference in the amount of irrigation water applied between SB1 and SB2. This could be because the soil at a depth of 0.10 m dried rapidly, and irrigation in SB1 was conducted when the soil matric potential at 0.10 m depth reached − 20 kPa. Consequently, the irrigation events in SB1 were more frequent than those in SB2 (Table 2). Research conducted by Soulis et al. (2015) used simulations to indicate that the optimal sensor position for effective irrigation scheduling was approximately 0.10 m below the soil surface. Considering these findings, SB1 could be the most favorable option as its positioning aligns with the recommended depth. This is supported by the morphological and physiological responses under SB1, as discussed below.

4.2. Soil-based irrigation scheduling methods improving physiological, morphological and yield responses

In general, the soil-based irrigation scheduling (SB1 and SB2) achieved the highest values of A, gs, E, and LWP for all soybean varieties. This could be because, in SB, each variety received a different amount of irrigation water to meet the full water demand during the growing cycle (Koester et al., 2016), and the irrigation frequency was higher than that in the other treatments (Puértolas et al., 2020). These favorable physiological responses under SB1 and SB2 resulted also in higher grain yield and grain yield components compared to the other treatments. Previous research shows that full irrigation under soil-based irrigation scheduling methods is optimal for yield and yield components in genotypes of rice (Kumar et al., 2017; Quiloango-Chimarro et al., 2022) and sugarcane (Santos et al., 2019). In contrast, reductions in A, gs, E, and LWP were observed under the CB and PB methods. It is possible that the CB and PB irrigation methods resulted in water stress, leading to reductions in physiological parameters. According to Vijayaraghavareddy et al. (2020), decreases on physiological parameters during the growing cycle cause mainly LAI reductions, leading to yield penalties. The yield reduction was even higher in PB compared to CB, which was combined with reductions of PH, LAI, SD, and NNP in the three varieties to a larger extent in V2. This could be because less water availability is related to diminished shoot and root growth (Mak et al., 2014). It is remarkable that V1 under all the soil-based irrigation scheduling methods was associated with higher PH and SD (Fig. 3) but lower GY, which will be considered by farmers for adequate variety selection.

4.3. Enhancing irrigation water productivity via plant-based irrigation scheduling

Canopy temperature depression (CTD) has been used as an indicator for irrigation scheduling but not to calculate the irrigation amount (Irmak et al., 2000; Khorsand et al., 2019). Irrigation amounts for plant-based methods can be calculated according to climate-based (Veysi et al., 2017) or soil-based methods (Osroosh et al., 2015). In this study, the amount of irrigation for PB1 and PB2 was based on evapotranspiration and soil water balance. However, this method likely underestimated the amount of water needed for soybean varieties. In addition, the CTD threshold selected in this experiment may have emphasized a certain level of water stress since Idso et al. (1980) demonstrated in wheat, barley, and sorghum that positive values of CTD are associated with deficit irrigation. This was clearly shown in the PCA, where lower values of leaf water potential were associated with PB1 and PB2, suggesting that these treatments were under water stress. Hou et al. (2019) reported that irrigation scheduling strategies in soybean with similar CTD thresholds maximize IWP rather than yield. However, only PB1 showed higher IWP values when compared to PB2 because a CTD of 4 °C (PB2) contributed to a greater yield penalty for all soybean varieties. On the other hand, under SB, previous research demonstrates that IWP for soybean is lower since it is focused to match grain yield potential (Gajić et al., 2018). Therefore, CTD could be a feasible option for irrigation scheduling where water is scarce, but further research should be conducted to determine the adequate CTD for soybeans in tropical conditions.

4.4. Implications for selecting an irrigation scheduling method

The findings of this study imply that although optimum values of IWP were obtained with lesser amounts of irrigation water applied, such conditions did not result in higher GY per unit area, as observed in the CB and PB1 methods. This is consistent with the general trend observed by Cetin and Akinci (2022), where the IWP tends to increase with a decrease in the amount of irrigation water applied. However, the same methods could led to over-irrigation as mentioned by Sobenko et al. (2019). Thus, plant- and climate-based methods require careful consideration of local factors, appropriate K_c values, and the efficiency of the irrigation system. Moreover, the implementation of PB methods is often hindered by the need to combine them with additional irrigation scheduling approaches (Jones, 2004), which may complicate their application.

In certain instances, farmers may not always assign the highest priority to IWP when a sufficient supply of irrigation water is available (Jovanovic et al., 2020). Instead, they may concentrate on enhancing yields per unit area. However, this approach can reduce financial returns. For example, soil-based methods require extensive soil sampling and testing (Sui and Vories, 2020) as well as the cost of sensors. Therefore, researchers are focusing on developing cost-effective soil moisture sensors, such as Abdelmoneim et al. (2023) who created a soil moisture monitoring system (USD 82.20) for drip-irrigated lettuce.

It is important to note that any irrigation scheduling method can improve the IWP compared with inefficient irrigation practices (Chen et al., 2023). For example, Byrareddy et al. (2020) mentioned that the irrigation amount for coffee production in Vietnam is often twice the recommended application amount, with an average of 510 m^3 ha^{-1} of overirrigation per year. Another important factor is the cost of energy, in the sense that reducing the amount of irrigation water applied can reduce pumping hours (Souza and Rodrigues, 2022).

5. Conclusions

This study showed that different irrigation scheduling methods based on soil, weather, and plant variables significantly influenced the physiology, yield, and yield of soybean varieties. On an average, the amount of irrigation water applied was significantly higher in SB1 (614 mm) than in SB2 (522 mm), CB (358 mm), PB2 (310 mm), and PB1 (309 mm). During the reproductive stage (phase III), these differences were more pronounced and exhibited notable variation between varieties.

Irrigation methods that received higher irrigation amounts (SB1 and SB2) also showed the highest values for net photosynthetic rate (A), stomatal conductance (gs), transpiration (E), and leaf water potential (LWP). Consequently, under these methods, grain yield was also higher (1.25 Mg ha^{-1}); however, irrigation water productivity (IWP) was lower (0.61 kg m^{-3}). It is remarkable that grain yield and irrigation water productivity followed opposite trends when the SB methods were compared with the CB and PB methods.

The results suggest that climate- and plant-based irrigation scheduling techniques should be calibrated against a soil moisture sensor method to guarantee that the water or grain productivity potential of each crop variety can be attained under diverse soil and climatic conditions. It is remarkable that when properly calibrated, all these methods can be adapted to attain higher grain yields per unit area or increased irrigation water productivity (deficit irrigation, adjusting planting dates, and new cultivars) depending on the objectives of individual farmers.

Nevertheless, it is important to explore economic investment opportunities to implement an efficient irrigation scheduling approach. For instance, soil-based methods are labor-intensive and costly compared with climate-based methods. It is important to note that each method has its advantages and disadvantages. Therefore, future research should focus on assessing its impact on economic income and expenditure. Moreover, affordable technologies to enhance all tested methods should be developed to ensure accessibility for small farmers.

CRediT authorship contribution statement

França Ana Carolina Ferreira: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gundim Alice da Silva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Coelho Rubens Duarte:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Quiloango-Chimarro Carlos Alberto:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Costa Jéfferson de Oliveira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108709.

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