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ORIGINAL PAPER

# Single and dual crop coefficients and their impact on the irrigation management of sugarcane cycles in the Brazilian savanna

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**Abstract**
Brazil is the world's leading producer of sugarcane, with a substantial portion of its production (87.5%) located within the Brazilian savanna biome, a region characterized by severe water deficit from May to September, which limits crop yield. Therefore, accurate and up-to-date information on key variables for optimizing irrigated sugarcane cultivation in this area is essential. This study aimed to determine the crop water requirement, the single (Kc) and dual ($Kc_{dual}$) crop coefficients for sugarcane (plant cane and ratoon) cycles in the Brazilian savanna, using a multi-method approach that integrates lysimetry and FAO-56–based modeling. The water requirement was determined through lysimetry ($ETc_L$), and the values of Kc and $Kc_{dual}$, including tabulated, experimental, and estimated coefficients, were compared and utilized in irrigation simulations. Total $ETc_L$ was 1756.5 mm in the first cycle (plant cane) and 1201.4 mm in the first ratoon cycle. For plant cane, lysimeter-derived Kc values were more consistent with values from the literature than those observed for ratoon; however, the dual Kc values were similar in both cycles. In the plant cane cycle, irrigation depth increased when the lysimetric Kc ($Kc_L$ = +10.3%) and the experimental dual Kc ($Kc_{dual\ E}$ = +6.6%) were applied. In contrast, water savings were achieved using the estimated single ($Kc_{SE}$ = −11.2%) and estimated dual ($Kc_{dual\ e}$ = −0.8%) coefficients compared to the tabulated Kc. In the ratoon cycle, all coefficients indicated lower irrigation depths ($Kc_L$ = −27.1%; $Kc_{SE}$ = −3.6%; $Kc_{dual\ E}$ = −20.1%; $Kc_{dual\ e}$ = −21.1%). Furthermore, factors such as the limited experimental area, potential border effects, local microclimatic disturbances, and constraints related to root system dynamics in lysimeter-based experiments should be considered. The integration of lysimetric measurements with FAO-56 estimates provides practical crop coefficients, enabling more precise irrigation scheduling and optimized water use in the Brazilian savanna.

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## Introduction

Sugarcane is one of the most economically important cultivated crops worldwide, playing a strategic role in agro-industrial and bioenergy systems through the production of ethanol, sugar, molasses, traditional solid sugar products (e.g., rapadura), and distilled spirits, among others (Emídio et al. 2019; Azlan et al. 2020; Tischler et al. 2021; Gomes et al. 2021; Baqueta et al. 2022). In 2022, Brazil (782.59 million Mg), India (490.53 million Mg), and China (104.99 million Mg) ranked among the largest producers. Nevertheless, the highest yields were reported in Peru (121.5 Mg ha$^{-1}$), Guatemala (116.2 Mg ha$^{-1}$), and Senegal (113.9 Mg ha$^{-1}$) (FAO 2025).

In Brazil, São Paulo is the largest producer (353.5 million Mg), followed by Minas Gerais (81.7 million Mg) and Goiás (78.6 million Mg), with average yields in the 2024/25 growing season of 80.1, 82.8, and 81.0 Mg ha$^{-1}$, respectively (Conab 2025).

Sugarcane holds great importance for the state of Goiás; however, its relatively low yield compared to the top-ranking states highlights the need to investigate factors limiting crop growth, development, and yield within this biome, the Cerrado (Brazilian savanna).

Among Brazil's sugarcane-producing regions, the Cerrado biome predominates. In this region, the water deficit characteristic of its climate (Alvares et al. 2013) is considered one of the main constraints on yield. At specific phenological stages of sugarcane development (Marchiori et al. 2017), such as sprouting and tillering, water restriction can negatively impact crop development, yield, and quality (Marchiori et al. 2017; Dias et al. 2023). Dingre and Gorantiwar (2021) reported a 25.3% reduction in sugarcane yield due to water stress, accompanied by significant decreases in plant height, leaf area, number of tillers, and dry matter. On the other hand, it is worth noting that some genetically improved varieties exhibit greater tolerance to water deficit (Ferreira et al. 2017). However, even for improved varieties, accurate quantification of crop water use remains essential to support irrigation management under Cerrado conditions.

The Cerrado region of Goiás is characterized by a distinct dry season (May to September) and a rainy season (October to April) (Alvares et al. 2013). Under these climatic conditions, sugarcane producers routinely anticipate yield losses associated with seasonal water scarcity, which has driven research efforts and the adoption of irrigation-based management strategies (Dias and Sentelhas 2018). In response, several studies have been conducted in this field, leading to the development of new technologies tailored to sugarcane management (Campos et al. 2014; Scudeletti et al. 2021; Liu et al. 2021; Dao et al. 2023; Teixeira et al. 2022a; Kumar et al. 2023; Xavier et al. 2024).

Sugarcane exhibits marked variability in water demand across its phenological stages, which directly influences crop growth, yield, and irrigation requirements (Segato et al. 2006; Surendran et al. 2016; Cardozo et al. 2018; Casaroli et al. 2023). For the RB92579 variety, water demand is estimated at 2.60 mm day$^{-1}$ during the initial stage, 3.33 mm day$^{-1}$ during the development stage, 6.38 mm day$^{-1}$ at full development, and 4.89 mm day$^{-1}$ during the final (maturation) stage (Silva et al. 2014). According to previous findings, two phenological stages are particularly sensitive to water deficit: the sprouting phase (Segato et al. 2006; Teixeira et al. 2022b) and the phase of rapid crop growth (Dingre et al. 2021), during which the plant's leaf area expands and water demand increases for gas exchange (Pires et al. 2008). Over its growth cycle, the RB92579 variety requires approximately 1,686.75 mm of water (Silva et al. 2014).

Timely irrigation prevents losses in yield, biomass production, and sucrose accumulation (Costa et al. 2023; Mehdi et al. 2024), as both water scarcity and excess can cause damage that is sometimes irreversible. This is because each developmental stage requires specific water replenishment, depending on intrinsic and extrinsic factors (Carvalho et al. 2013).

The volume of water required for irrigation is calculated based on water inputs, such effective precipitation, and outputs, including soil water evaporation, plant transpiration, and other losses (Tfwala et al. 2021). Water losses as vapor from a surface covered with the crop under non-limiting water conditions are referred to as crop evapotranspiration (ETc). ETc can be determined through agrometeorological and plant-based monitoring and is estimated as the product of reference evapotranspiration (ETo) and the crop coefficient (Kc) (Allen et al. 1998).

Thus, greater accuracy in estimating ETo and Kc leads to more reliable irrigation scheduling for replenishing plant water (Gonçalves et al. 2024; Veysi et al. 2024). ETo is commonly determined using the Penman–Monteith equation, as recommended by the FAO (Bulletin 56). Kc, in turn, can be determined using either the single or dual approach. The dual approach divides Kc into two components: the basal crop coefficient (Kcb), which represents plant transpiration, and the soil evaporation coefficient (Ke), both of which are influenced by atmospheric demand (Allen et al. 1998). Managing irrigation to supply the optimal amount of water is more critical than often perceived, as water deficit and excess impact production costs, product quality, and yield (Dias and Sentelhas 2018; Xiao et al. 2022). In this context, several studies have focused on determining local Kc values using various techniques, including lysimetry (Antunes Júnior et al. 2021a), the energy balance method (Martins et al. 2022), and the soil water balance method (Dingre and Gorantiwar 2020).

The weighing lysimeter technique is the standard for determining crop and reference evapotranspiration (Moorhead et al. 2017). A weighing lysimeter consists of a sealed, impermeable container that measures evapotranspiration based on changes in mass due to water inflow or outflow, directly measuring water dynamics in cultivated or bare soil (Lyles et al. 2024). Its use in agricultural research is necessary for obtaining direct measurements of ETo and ETc and for calibrating models that estimate these variables (Moorhead et al. 2017; Liu et al. 2017). Microlysimetry, on the other hand, determines direct soil water evaporation by measuring changes in mass caused by water entering or leaving the microlysimeter. This technique is especially valuable because it isolates soil evaporation from plant transpiration (Facchi et al. 2017).

Thus, separating water losses within the soil–plant system can be addressed through techniques (e.g., soil mulching) and/or technologies (e.g., subsurface irrigation) that minimize water waste in irrigated areas, thereby contributing to environmental sustainability (Sharma et al. 2018; Wang et al. 2018; Khawla et al. 2019).

Despite advances in irrigation management and the availability of literature crop coefficients, uncertainties remain regarding the adequacy of Kc values for a commercially important sugarcane variety commonly cultivated under the edaphoclimatic conditions of the Goiás Cerrado. Most existing coefficients are derived from generalized conditions or single methodological approaches (Antunes Junior et al. 2021a; Anjos et al. 2023), which may not fully capture local soil and climate interactions, or the water use dynamics of sugarcane varieties widely cultivated in this region. Consequently, refining Kc determination through a multi-method approach that integrates lysimetry, microlysimetry, and FAO-56–based modeling is essential to improve the accuracy of evapotranspiration estimates and irrigation planning for sugarcane production systems in the Brazilian savanna.

Therefore, this study aimed to determine the water requirement of sugarcane, including the single (Kc) and dual (Ke + Kcb) crop coefficients, as well as the irrigation depths, based on measurements obtained through lysimetry and microlysimetry.

## Materials and methods

### Experimental area

The experiment was conducted at the School of Agronomy experimental station (Federal University of Goiás), located in Goiás State, within the Brazilian savanna (Cerrado) biome (16°35’55.1"S; 49°16’40.5"W; 730 m). According to the Köppen classification, the climate is classified as Aw (tropical savanna), characterized by two distinct seasons: a dry season (May to September) and a rainy season (October to April). The average temperature ranges between 19 °C and 20 °C, and the annual rainfall ranges from 1600 to 1900 mm (Alvares et al. 2013).

Planting was carried out on July 22, 2018, using presprouted seedlings (PSS) of the RB92579 variety. Spacing was set at 0.5 × 1.5 m between plants and rows, respectively, totaling a cultivated area of 360 m². The area comprised 10 rows, each 24 m long, and the effective experimental area was 162 m² (6 rows × 18 m long). The entire cultivation area was fully irrigated using a surface drip irrigation system. Evaluations were conducted for the plant cane cycle (14 months; 2018/2019) and the first ratoon crop cycle (12 months; 2019/2020).

The soil in the experimental area was classified as a Latossolo Vermelho distrófico with a medium texture (Embrapa 2018) or as a Ferralsol according to the WRB system (WRB 2022). Before planting, soil samples were collected for chemical analysis (Table S1; supplementary material) and for determining soil physical–hydraulic properties (water retention curve). Conventional tillage was then performed, including plowing, harrowing, and furrowing.

A systemic insecticide (Thiamethoxam and Lambda-cyhalothrin) was applied to control the root spittlebug (*Mahanarva fimbriolata*) during the stalk growth.

### Soil chemical and physical-hydraulic properties

Fertilization was based on the results of the soil chemical analysis (Table S1; Supplementary material). No lime was applied for soil correction because base saturation was above 70% (Table S1; Supplementary material). In the planting furrow (plant cane cycle), 60 kg ha$^{-1}$ of nitrogen (urea), 120 kg ha$^{-1}$ of $P_2O_5$ (single superphosphate), and 140 kg ha$^{-1}$ of $K_2O$ (potassium chloride) were applied. In the ratoon cycle, fertilization was applied along the regrowth rows immediately after harvest, using 120 kg ha$^{-1}$ of nitrogen and 120 kg ha$^{-1}$ of $K_2O$ from the same sources. Topdressing fertilization was performed 45 days after planting, using a 20-00-20 formulation at a rate of 300 kg ha$^{-1}$.

Approximately 30 days after planting, undisturbed soil samples were collected using volumetric rings to construct the soil water retention curve (moisture vs. tension). The data were fitted to the van Genuchten (1980) equation (Fig. S1; Supplementary material). This fitting enabled the determination of saturated volumetric water content ($\theta_s$: 0.450 m³ m$^{-3}$), residual water content ($\theta r$: 0.2012 m³ m$^{-3}$), and permanent wilting point moisture ($\theta_{PWP}$: 0.2212 m³ m$^{-3}$). Additionally, based on these values, the water content at field capacity ($\theta_{FC}$: 0.3722 m³ m⁻³) and the limiting water content ($\theta_l$: 0.2967 m³ m⁻³) were determined using equations [S1] and [S2] (Supplementary material).

The total available water in the soil (TAW = 1000 [$\theta_{FC}$ – $\theta_{PWP}$] Zr), for an effective root zone depth of Zr = 0.60 m (Costa Neto et al. 2021), was 90.6 mm; the readily available water (RAW = TAW • $_f$) was 45.3 mm.

Soil moisture was monitored using a capacitance probe (model Diviner 2000, Sentek Pty Ltd, Australia) at different depths (0.10 and 0.40 m). The probe was previously calibrated for the soil in the study area, resulting in separate calibration equations (Table S2; Supplementary material).

## Plant assessments

Biometric measurements were taken approximately every 45 days on ten randomly selected plants (clumps). For each plant, three stalks were measured at the main phenological stages of the crop (I: initial growth; II: rapid vegetative development; III: full vegetative growth; IV: maturation). Yield and technological analyses (Consecana 2006) were performed on the day of harvest (plant cane: 418 days after planting; ratoon: 349 days after cutting). In the lysimeter, biometric measurements of plant height and leaf area index were taken only twice to minimize plant handling. Measurements were performed during the plant cane (144 and 383 DAP) and ratoon (154 and 316 DAC) cycles.

Plant height (H, m) was measured with a measuring tape from the soil surface to the insertion of leaf + 1 (Silva et al. 2012a). The leaf area index (LAI, m² m⁻²) was calculated as the ratio between leaf area and ground area. Leaf blade length and width were measured at the middle portion of the leaf + 3 (Kuijper 1915) to estimate individual leaf area (Hermann and Câmara 1999). Ground area was determined by multiplying row spacing by 1.0 m of row length (1.5 m²). Total leaf area was extrapolated to the plot area based on the number of tillers/stalks per meter.

Yield (Y, Mg ha⁻¹) was estimated based on the fresh mass of 10 stalks collected at each of 20 sampling points within the experimental area, row spacing, and the number of stalks per linear meter. Additionally, on the day of harvest, ten representative stalks were randomly collected from ten points within the experimental area for technological analyses. The fresh bagasse was weighed and dried in a forced-air oven at 70 °C until constant weight was reached. The extracted juice was subjected to technological analyses, including °Brix (total soluble solids), POL (apparent sucrose content), RTS (recoverable total sugars), and juice purity, following the Consecana (2006) methodology using Octapol as the clarifying reagent.

## Weather measurements

Solar radiation, air temperature, rainfall, relative humidity, and wind speed were obtained from an automatic weather station approximately 300 m from the experimental area. These data were used to characterize the meteorological conditions during the cultivation period and to estimate reference evapotranspiration (ETo) using the Penman–Monteith equation (Allen et al. 1998). In addition, the same data were used to estimate the single (Kc) and dual (Ke + Kcb) crop coefficients (Allen et al. 1998).

## Lysimetry and microlysimetry

Crop potential evapotranspiration ($ETc_L$) was determined using a weighing lysimeter, while soil evaporation was obtained from microlysimeters ($Ev_{ML}$).

The lysimeter was constructed from a 1,500 L polyethylene tank (top diameter: 1.75 m; height: 0.9 m). A drainage system was installed at the bottom of the lysimeter, consisting of a 0.10 m gravel layer, a 0.05 m coarse sand layer, a geotextile fabric, and a perforated pipe connected to the outside. On top of the drainage layer, soil from the experimental area was placed in the same sequence of layers, air-dried, and compacted to achieve an average bulk density of 1,300 kg m⁻³ (approximately the local average). After filling, the soil in the lysimeter was saturated via capillary rise (water introduced through the drainage pipe) and then covered with a double-layer plastic sheet to minimize evaporation losses. The soil was allowed to drain until the moisture stabilized. At this point, the soil water content at pot capacity ($\theta_{Lpc}$ = 0.3942 m³ m⁻³), similar to field capacity, was recorded (Casaroli and van Lier 2008). Eight pre-sprouted seedlings were planted in the lysimeter and arranged in two centered rows (≈0.50 m apart). This configuration ensured approximately 30 tillers within the lysimeter area (2.4 m²), simulating the field plant density for this variety.

The entire setup was placed on a weighing platform (capacity: 4,000 kg; accuracy: 1.0 g), with mass variations recorded and stored every 5 min using a datalogger (CR1000 – Campbell®). A PVC reservoir was buried and installed flush with the soil surface. The space between the lysimeter walls and the surrounding soil was insulated with foam and straw to minimize lateral heat transfer. The evapotranspiration depth (mm, equivalent to L m⁻²) was calculated by dividing the daily mass variation of the lysimeter (kg of $H_2O$) by its surface area (2.4 m²). Crop evapotranspiration was estimated using the following equation: $ETc = P + I \pm Es - D \pm \Delta A$, where P is precipitation, I is irrigation depth, Es is surface runoff (assumed to be zero), D is drainage (measured), and ΔA is the change in soil water storage, calculated from the difference in lysimeter mass.

Irrigation of the lysimeter was conducted two to three times per week, replenishing 100% of the crop evapotranspiration (ETc) for the period to maintain soil moisture within the limits of readily available water (RAW), as recommended by Bernardo et al. (2019).

The microlysimeters were constructed using rigid PVC (Ø: 0.15 m; height: 0.15 m; area: 0.0176 m²) with a perforated cap at the bottom. A drainage layer (3 cm of fine gravel and geotextile fabric) was placed at the base to ensure proper drainage of excess water from rainfall. Each microlysimeter was filled with air-dried soil from the experimental area, weighing 3,050 g and having an average bulk density of 1,390 kg m⁻³. After filling, the soil was saturated by capillary rise and then covered with plastic film (to minimize evaporation) and left to drain freely until stabilization, at which point the pot capacity moisture content was recorded ($\theta_{Mpc}$ = 0.4029 m³ m⁻³) (Casaroli and van Lier 2008).

Nine microlysimeters were placed within the experimental area, positioned between plants along the crop rows. Before installing the microlysimeters, an auxiliary PVC sleeve (Ø: 0.20 m; height: 0.20 m) was inserted, with its bottom filled with fine gravel and sand to facilitate drainage and provide proper support. This ensured that the top edge of each microlysimeter was buried and remained flush with the soil surface.

Soil evaporation ($Ev_{ML}$, mm day⁻¹) was determined daily based on microlysimeter mass variation (kg $H_2O$) over an ≈ 18 h interval relative to its surface area. Water lost through $Ev_{ML}$ was manually replenished daily to maintain soil moisture at pot (or field) capacity.

## Tabulated crop coefficient - $Kc_{tab}$

The crop coefficient values for the initial, mid, and final stages represent the combined effects of soil evaporation and plant transpiration during each phenological stage (Table 1).

The initial- and mid-season Kc values remain constant throughout their respective stages. However, during the development and final stages, Kc should be linearly increased from the initial to the mid-season value and linearly decreased from the mid-season to the final value. Additionally, the final Kc value corresponds to the last day of the crop cycle.

**Table 1** Duration of phenological stages for sugarcane grown in tropical regions, irrespective of planting date (Allen et al. 1998; Table 12)

| Cycle | Initial | development | Mid-season | Final | Total |
|---|---|---|---|---|---|
| Plant cane | 50 | 70 | 220 | 140 | 480 |
| Ratoon cane | 30 | 50 | 180 | 60 | 320 |
| *$Kc_{tab}$ | 0.40 | | 1.25 | 0.75 | |
| *$H_{max}$ (m) | | | | | 3.0 |

Tabulated average crop coefficient values (Kctab) for each phenological stage (initial, mid-season, and final), and maximum crop height ($H_{max}$) (Allen et al. 1998; Table 12)

*Plant cane or ratoon cycle

## Single crop coefficient - $Kc_{SE}$

The single crop coefficient (Kc) for the initial stage was calculated based on soil wetting events caused by irrigation or rainfall. For the mid-season and final stages, Kc values were determined based on the climatic conditions of the study region. This adjustment is required because the tabulated values assume a minimum relative humidity ($RH_{min}$) of 45% and an average wind speed at 2 m height ($u_2$) of 2 m s⁻¹.

For the $Kc_{ini}$ calculation, average reference evapotranspiration during the initial stage was 3.67 and 4.64 mm day⁻¹ for the plant cane and ratoon cane cycles, respectively. For both cycles, the irrigation interval was 2.3 days (three times per week), with an average irrigation depth of 1.05 mm day⁻¹ for plant cane and 0.84 mm day⁻¹ for ratoon cane. During this stage, total rainfall amounted to 24.4 mm for the plant cane cycle and 56 mm for the ratoon cycle, corresponding to 0.53 and 1.93 mm day⁻¹, respectively. However, because wetting events were light to moderate (3–10 mm per event), $Kc_{ini}$ was estimated using Fig. 29 of FAO-56 Bulletin (Allen et al. 1998). This resulted in $Kc_{ini}$ values of approximately 0.77 and 0.67 for the plant cane and ratoon cane cycles, respectively. When only a fraction of the soil surface is wetted, the $Kc_{ini}$ value (Fig. 29; FAO-56) should be multiplied by the wetted surface fraction ($f_w$ = wetted area / planted area), which was 0.3 due to the drip irrigation method used. This adjustment resulted in revised $Kc_{ini}$ values of approximately 0.23 and 0.20 for the plant cane and ratoon cane cycles, respectively.

The average minimum relative humidity and wind speed differed from 45% to 2 m s⁻¹, respectively (Table 2). Therefore, the mid-season ($Kc_{mid}$) and end-season ($Kc_{fin}$) crop coefficients were determined using Eqs. (1) and (2):

$$K_{c\,mid} = K_{c\,mid\,(tab)} + [0{,}04\,(u_2 - 2) - 0{,}004\,(HR_{min} - 45)]\left(\frac{H_m}{3}\right)^{0{,}3} \quad (1)$$

$$K_{c\,fin} = K_{c\,fin\,(tab)} + [0{,}04\,(u_2 - 2) - 0{,}004\,(HR_{min} - 45)]\left(\frac{H_m}{3}\right)^{0{,}3} \quad (2)$$

where $Kc_{mid\,(Tab)}$ is the tabulated value for $Kc_{mid}$ (1.25), and $Kc_{fin\,(Tab)}$ is the tabulated value for $Kc_{fin}$ (0.75); $u_2$ is the average daily wind speed at 2 m above grass reference surface (m s⁻¹); $RH_{min}$ is the average daily minimum relative humidity (%); and Hm is the average plant height (m). The plant height value used in the equation was obtained experimentally.

**Table 2** Average minimum relative humidity ($RH_{min}$, %), wind speed at 2 m height ($u_2$, m $s^{-1}$), average ($H_m$, m) and maximum ($H_{max}$, m) plant height, estimated basal crop coefficient ($Kcb_e$), and maximum crop coefficient ($Kc_{max}$) for each phenological stage and crop cycle of sugarcane

| Cycle/phase | $RH_{min}$ | $u_2$ | $H_m$ | $H_{max}$ | $Kcb_e$ | $Kc_{max}$ |
|---|---|---|---|---|---|---|
| *Plant cane* | | | | | | |
| Initial | 48.11 | 0.26 | 0.23 | 0.66 | 0.15 | 1.15 |
| Development | 42.09 | 0.09 | 1.11 | 1.66 | 0.65 | 1.15 |
| Mid-season | 62.10 | 0.32 | 2.81 | 3.66 | 1.14 | 1.19 |
| Final | 36.90 | 0.61 | – | – | 0.73 | 1.18 |
| *Ratoon cane* | | | | | | |
| Initial | 37.76 | 0.60 | – | – | 0.15 | 1.19 |
| Development | 42.36 | 0.40 | 1.13 | 1.74 | 0.64 | 1.16 |
| Mid-season | 68.76 | 0.19 | 2.18 | 2.62 | 1.13 | 1.18 |
| Final | 18.31 | 0.14 | 2.65 | 2.85 | 0.67 | 1.23 |

## Dual crop coefficient - $Kc_{dual}$

The dual crop coefficient is the sum of the basal crop coefficient (Kcb), which represents transpiration, and the soil evaporation coefficient (Ke). Both coefficients were calculated using the equations described in FAO-56 Bulletin (Allen et al. 1998) and were experimentally parameterized using lysimetry and microlysimetry results.

According to the FAO-56 Bulletin, Kcb values are tabulated for sub-humid climatic conditions. However, when relative humidity differs from 45%, wind speed is greater or less than 2 m $s^{-1}$, and the tabulated values for mid-season ($Kcb_{mid}$) and end-season ($Kcb_{fin}$) are equal to or greater than 0.45, an adjustment should be made using the following equation:

$$Kcb_e = K_{cb\,(tab)} + [0.04\,(u_2 - 2) - 0.004\,(RH_{min} - 45)]\left(\frac{H_m}{3}\right)^{0,3} \quad (3)$$

where Kcb $_{(tab)}$ refers to the tabulated values for $Kcb_{mid}$ (1.20) and $Kcb_{fin}$ (0.70); $u_2$ (m $s^{-1}$) is the average daily wind speed at 2 m above grass reference surface (Table 2); $RH_{min}$ (%) is the average daily minimum relative humidity (Table 2); and $H_m$ (m) is the average plant height, obtained experimentally (Table 2). For $Kcb_{ini}$, the tabulated value of 0.15 is used (Allen et al. 1998; Table 17). The resulting estimated basal crop coefficient ($Kcb_e$) values are shown in Table 2.

The procedure for calculating Ke according to the FAO-56 Bulletin ($Ke_e$) considers two conditions: a fully wet surface, in which Ke reaches its maximum value, and a drier condition, where soil moisture is depleted. The dual crop coefficient (Kcb+Ke) must not exceed the maximum crop coefficient ($Kc_{max}$) observed after rainfall or irrigation. Thus, Ke was calculated using the following equation:

$$Ke_e = K_r\,(Kc_{max} - K_{cb}) \leq f_{ew}\,Kc_{max} \quad (4)$$

where Kr is the evaporation reduction coefficient (dimensionless), which depends on the cumulative depth of water depleted (evaporated) from the soil surface layer (Allen et al. 1998; Eq. 74). The term $f_{ew}$ is the fraction of soil that is both exposed and wetted (Allen et al. 1998; Eq. 75). $Kc_{max}$ was obtained using Eq. 72 from FAO-56 Bulletin (Allen et al. 1998). The $H_m$ values used for the final stage of the plant cane cycle (2.81 m) and for the initial stage of the ratoon cycle (0.726 m) were estimated. For the plant cane cycle, the $H_m$ value from the previous phenological stage was used, whereas for the ratoon cycle, a polynomial equation was applied to estimate $H_m$ up to the 30th day after cutting (Fig. S2; supplementary material). The $Kc_{max}$ values are presented in Table 2.

For the experimentally obtained $Kc_{dual}$ values ($Kc_{dual\ E}$), the following set of equations was used:

$$Kc_{dual\ E} = K_{cb} + K_e \quad (5)$$

$$K_{cb} = \frac{T}{ETo} \quad (6)$$

$$T = ETc_L - Ev_{ML} \quad (7)$$

$$K_e = \frac{Ev_{ML}}{ETo} \quad (8)$$

where Kcb is the basal crop coefficient (dimensionless), T is plant transpiration (mm), ETo is reference evapotranspiration estimated using the FAO Penman–Monteith equation (mm), $ETc_L$ is crop evapotranspiration obtained from lysimetry (mm), $Ev_{ML}$ is soil evaporation obtained from microlysimetry (mm), and Ke is the soil evaporation coefficient (dimensionless).

## Irrigation

Additionally, to compare the Kc values obtained using different methods, irrigation depths were simulated using a soil water balance approach based on agrometeorological data (ETc and rainfall) and soil physical–hydraulic properties. The the readily available water (RAW) was determined from these soil properties.

### Statistical analysis

For biometric, yield, and juice quality variables, means and standard deviations were calculated for each evaluation time. In addition, regression equations were fitted to biometric means as a function of time after planting (plant cane) or cutting (ratoon cane).

The means and standard deviations of water requirements, by phase and crop cycle, obtained using different crop coefficients, were compared, and the differences were quantified. To evaluate the performance of the weighing lysimeter in estimating crop evapotranspiration in terms of both precision and accuracy, regression equations and statistical indices were generated, including the coefficient of determination ($R^2$), bias (systematic error), mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), Pearson correlation coefficient (r), and the agreement index “d” (Willmott et al. 1985).

## Results

### Crop growth, yield, and technological variables

In the plant cane cycle, plant height (H) and leaf area index (LAI) reached their maximum values at 383 and 332 days after planting (DAP), respectively. Maximum H and LAI values were 3.38 m and 4.99. In the ratoon cycle, maximum values were observed at 316 days after cutting (DAC), with H = 2.65 m and LAI = 4.48 (Fig. 1a). Within the lysimeter, only two biometric evaluations were conducted per cycle. In the plant cane cycle, measurements were taken at 144 DAP (H = 1.39 ± 0.12 m; LAI = 2.92 ± 0.11) and 383 DAP (H = 3.21 ± 0.13 m; LAI = 4.51 ± 0.09). In the ratoon cycle, measurements were performed at 154 DAC (H = 1.97 ± 0.13 m; LAI = 3.24 ± 0.11) and 316 DAC (H = 2.49 ± 0.12 m; LAI = 4.37 ± 0.09). These values fell within the standard deviation range observed for the field-grown plants (Fig. 1a).

Yield (+ 13.2%), fiber content (+ 14.7%), and juice purity (+ 1.1%) were higher in the plant cane cycle compared to the ratoon cane cycle (Fig. 1b). Conversely, the ratoon cane cycle showed higher values for recoverable total sugar (+ 17.5%), POL (+ 10.3%), and °Brix (+ 13.7%) (Fig. 1b). Within the lysimeter, values for these variables remained within one standard deviation of the corresponding field means for both the plant cane (Y = 212.03 Mg $ha^{-1}$; RTS: 133.64 kg $Mg^{-1}$; POL: 16.52%; °Brix: 18.03; Fiber: 12.88%; Purity: 91.98%) and ratoon cane cycles (Y = 179.31 Mg $ha^{-1}$; RTS: 164.01 kg $Mg^{-1}$; POL: 18.48%; °Brix: 20.99; Fiber: 11.23%; Purity: 91.07%).

### Agrometeorological data

Figure 2 shows the meteorological variables measured during the plant cane and ratoon cane cycles. Solar radiation varied between phenological stages, ranging from 15.7 to 18.9 MJ $m^{-2}$ $day^{-1}$ in the plant cane cycle, and from 15.3 to 18.4 MJ $m^{-z}$ $day^{-1}$ in the ratoon cane cycle (Fig. 2a). Average air temperature ranged from 22.8 to 24.6 °C (plant cane) and from 20.7 to 25.0 °C (ratoon cane) (Fig. 2b). Wind

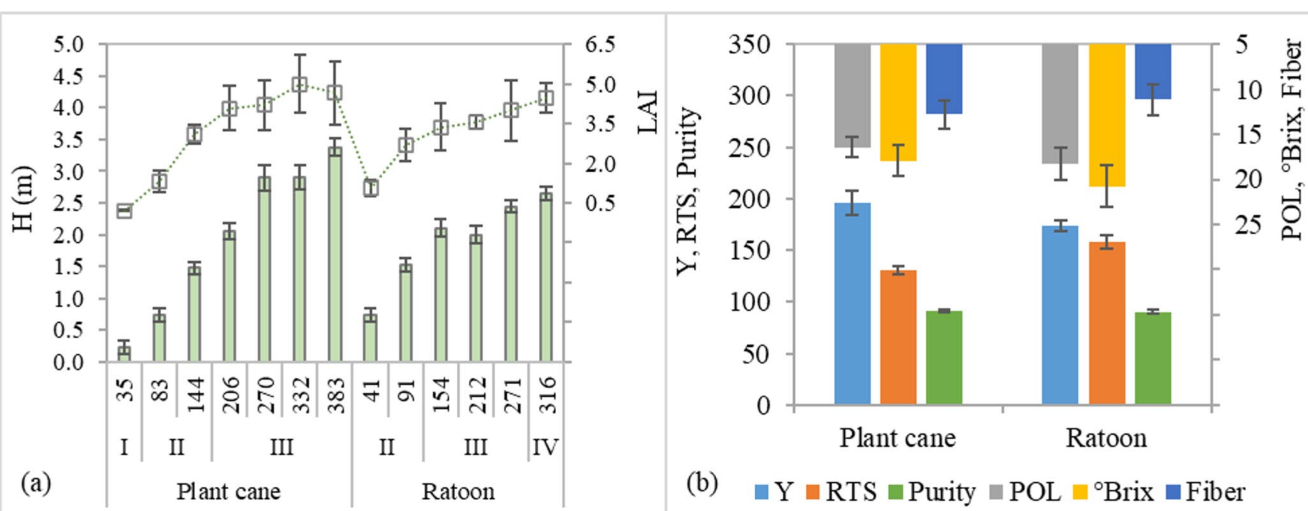



**Fig. 1** Biometric evaluations: plant height (H; green bars) and leaf area index (LAI; squares connected by a dotted line). **b** Yield (Y, Mg $ha^{-1}$) and technological parameters: recoverable total sugar (RTS, kg $Mg^{-1}$), purity (%), POL (%), °Brix, and fiber (%). Data are shown for plant cane and ratoon cycles across phenological stages (I–IV) and days after planting or cutting. *Vertical bars represent standard deviation*

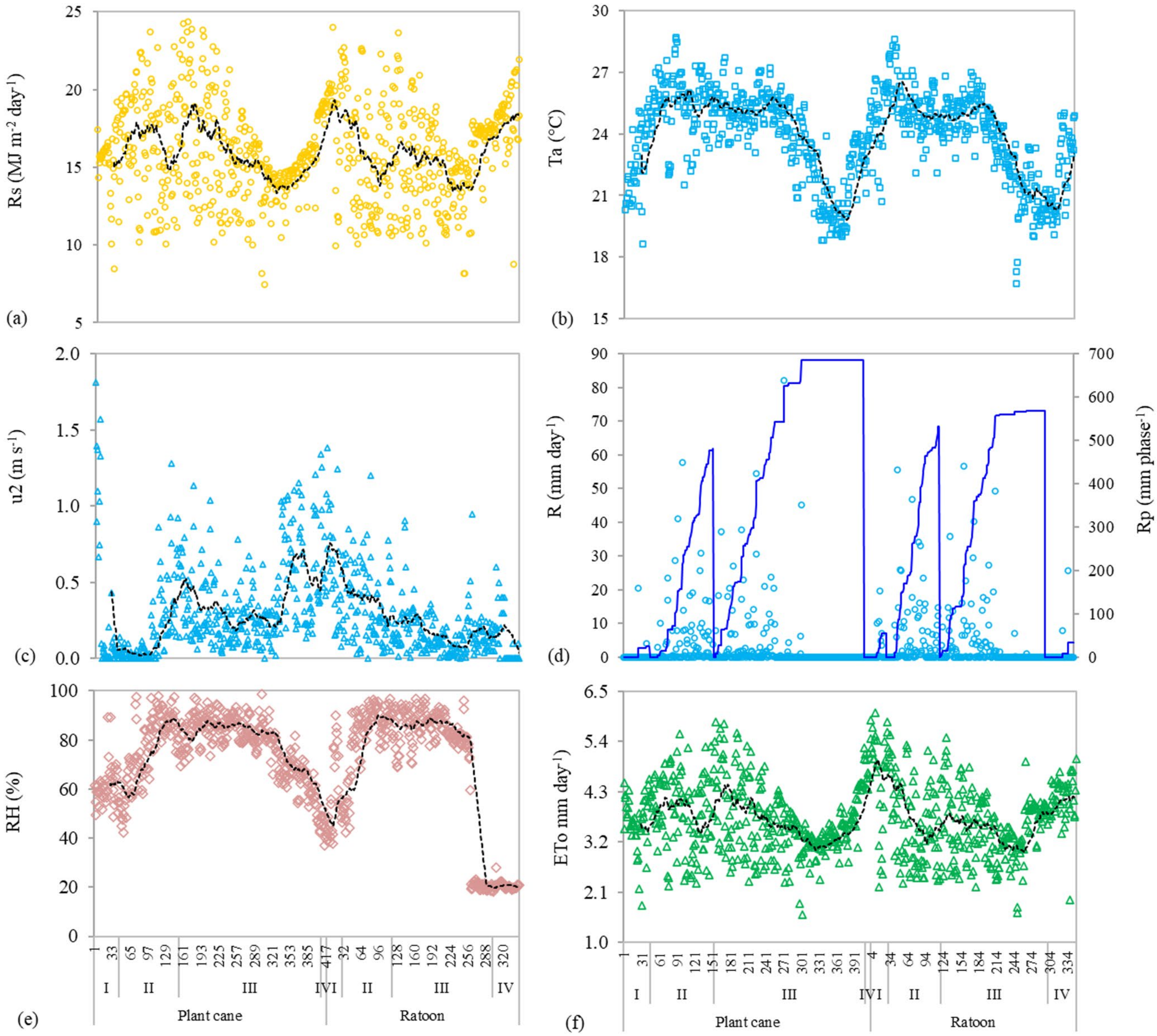



**Fig. 2** Daily average values of solar radiation (Rs) (**a**), mean air temperature (Ta) (**b**), wind speed ($u_2$) (**c**), rainfall (R) (**d**), relative humidity (RH) (**e**), and reference evapotranspiration (ETo) (**f**). The black dotted line represents the 30-day moving average, and the blue solid line represents accumulated rainfall by phenological stage (Rp)

speed varied from 0.18 to 0.65 m $s^{-1}$ (plant cane) and from 0.12 to 0.58 m $s^{-1}$ (ratoon cane) (Fig. 2c). Daily maximum rainfall reached 82 mm $day^{-1}$ in the plant cane cycle and 57 mm $day^{-1}$ in the ratoon cane cycle (Fig. 2d). The highest accumulated rainfall occurred during phase III (plant cane: 684.8 mm; ratoon cane: 567.8 mm) (Fig. 2d). Total rainfall was similar between cycles (plant cane: 1,189 mm; ratoon cane: 1190 mm). Relative humidity ranged from 45.5% to 77.6% (plant cane) and from 20.5% to 80.9% (ratoon cane), with the lowest and highest values coinciding with the dry and rainy seasons, typical of the region's Aw climate (Fig. 2e). Atmospheric water demand, expressed as reference evapotranspiration, ranged from 3.6 to 4.8 mm $day^{-1}$ (plant cane) and from 3.5 to 4.6 mm $day^{-1}$ (ratoon cane), with the highest demand recorded during phase IV (plant cane) and phase I (ratoon cane) (Fig. 2f).

## Lysimetry and microlysimetry

In the plant cane cycle, the lysimeter lost an average of 8.9 kg $day^{-1}$ of water; in the ratoon cane cycle, this value was 6.7 kg $day^{-1}$. The phenological stage with the highest water losses was stage III for both cycles (plant cane: 10.2 kg $day^{-1}$; ratoon cane: 8.3 kg $day^{-1}$) (Fig. 3a). Soil water loss due to evaporation, recorded in the microlysimeters averaged 0.012 kg $day^{-1}$ (plant cane) and 0.003 kg $day^{-1}$ (ratoon

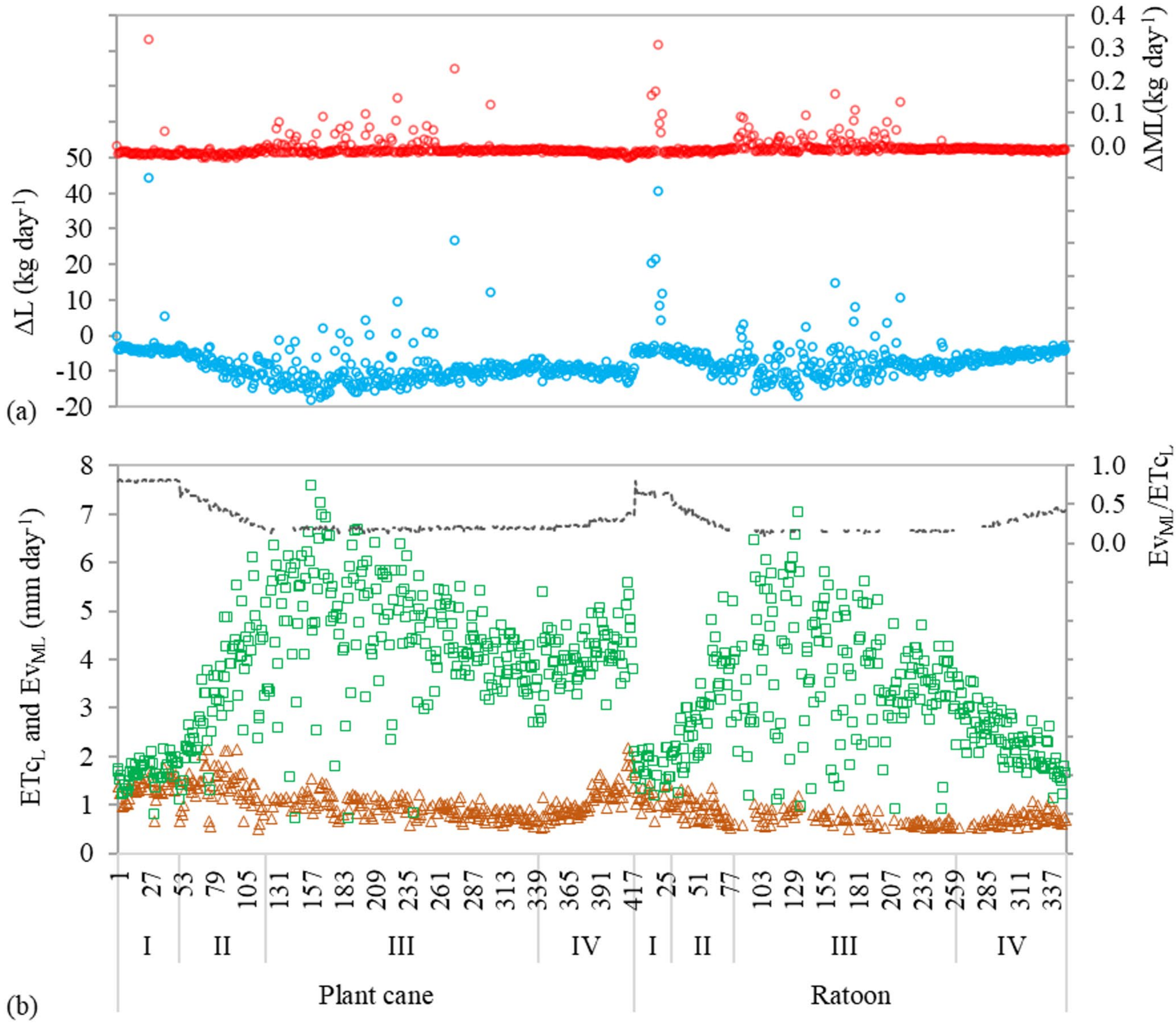



**Fig. 3** Variation in lysimeter mass (ΔL, kg day$^{-1}$; ○) and microlysimeter mass (ΔML, kg day$^{-1}$; ○) (**a**); crop evapotranspiration measured by lysimetry ($ETc_L$, mm day$^{-1}$; □), soil evaporation measured by microlysimetry ($Ev_{ML}$, mm day$^{-1}$; △), and the $Ev_{ML}/ETc_L$ ratio (**b**); as a function of days after planting or cutting, phenological stages (I, II, III, IV), and crop cycles (plant cane and ratoon cane)

cane). The highest losses occurred during stage II in both cycles (plant cane: 0.023 kg day$^{-1}$; ratoon cane: 0.015 kg day$^{-1}$) (Fig. 3a).

Crop evapotranspiration measured by the lysimeter ($ETc_L$, mm day$^{-1}$) revealed total water requirements of 1,756.5 mm and 1,201.4 mm per cycle, corresponding to average daily values of 3.9 mm day$^{-1}$ and 3.1 mm day$^{-1}$ for the plant cane and ratoon cane cycles, respectively (Fig. 3b). The highest averages were recorded during stage III (plant cane: 4.61 mm day$^{-1}$; ratoon: 3.75 mm day$^{-1}$) (Fig. 3b). Soil evaporation ($Ev_{ML}$, mm day$^{-1}$) averaged 1.1 and 0.8 mm day$^{-1}$ for the plant cane and ratoon cane cycles, respectively (Fig. 3b). In the plant cane cycle, stages I and II exhibited the highest evaporation rates (≈1.35 mm day$^{-1}$. Similarly, stage I stood out in the ratoon cane cycle (1.12 mm day$^{-1}$) (Fig. 3b). The $Ev_{ML}/ETc_L$ ratio was approximately 0.3 in both cycles (plant cane: 0.33; ratoon: 0.29). Higher values were observed during the initial stages of each cycle (plant cane: 0.81, 0.44, 0.19, and 0.26; ratoon cane: 0.65, 0.32, 0.15, and 0.32 for stages I–IV, respectively). A slight increase from stage III to stage IV was observed in both cycles (Fig. 3b).

## Single crop coefficient

The crop coefficients determined by lysimetry showed average values of 0.45, 0.87, 1.27, 1.12, and 0.98 for phenological stages I, II, III, IV, and the final stage of the plant cane cycle, respectively; and 0.35, 0.73, 1.10, 0.65, and 0.21 for the corresponding stages and final stage of the ratoon cane cycle (Fig. 4a).

The final $Kc_L$ values for both cycles (plant cane: 0.97; ratoon cane: 0.50) were determined using a linear regression equation based on days after planting (DAP) or cutting (DAC), using measurements obtained at 418 DAP and 320 DAC (Fig. 5).

The $Kc_L$ values were close to the FAO tabulated values in the plant cane cycle (I: 0.40; II: 0.83; III: 1.25; IV: 1.11; final: 0.97) (Fig. 4b). In contrast, values were lower in the ratoon cane cycle (I: 0.40; II: 0.83; III: 1.25; IV: 0.88; final: 0.51), although all remained within one standard deviation of the $Kc_L$ means (Fig. 4). These differences in average values during stage IV and the final stage are attributed to the shorter duration of stage IV in the plant cane cycle and the longer duration of this stage in the ratoon cane cycle relative to the average cycle length established by FAO (Table 1). Thus, although the duration of the phenological stages was similar to the tabulated values, maturation and harvest occurred at different times than those indicated by FAO.

Values estimated using the FAO equations ($Kc_{SE}$: I = 0.23; II = 0.72; III = 1.19; IV = 0.98; final = 0.78) were lower than both $Kc_L$ and $Kc_{tab}$ in the plant cane cycle. However, they

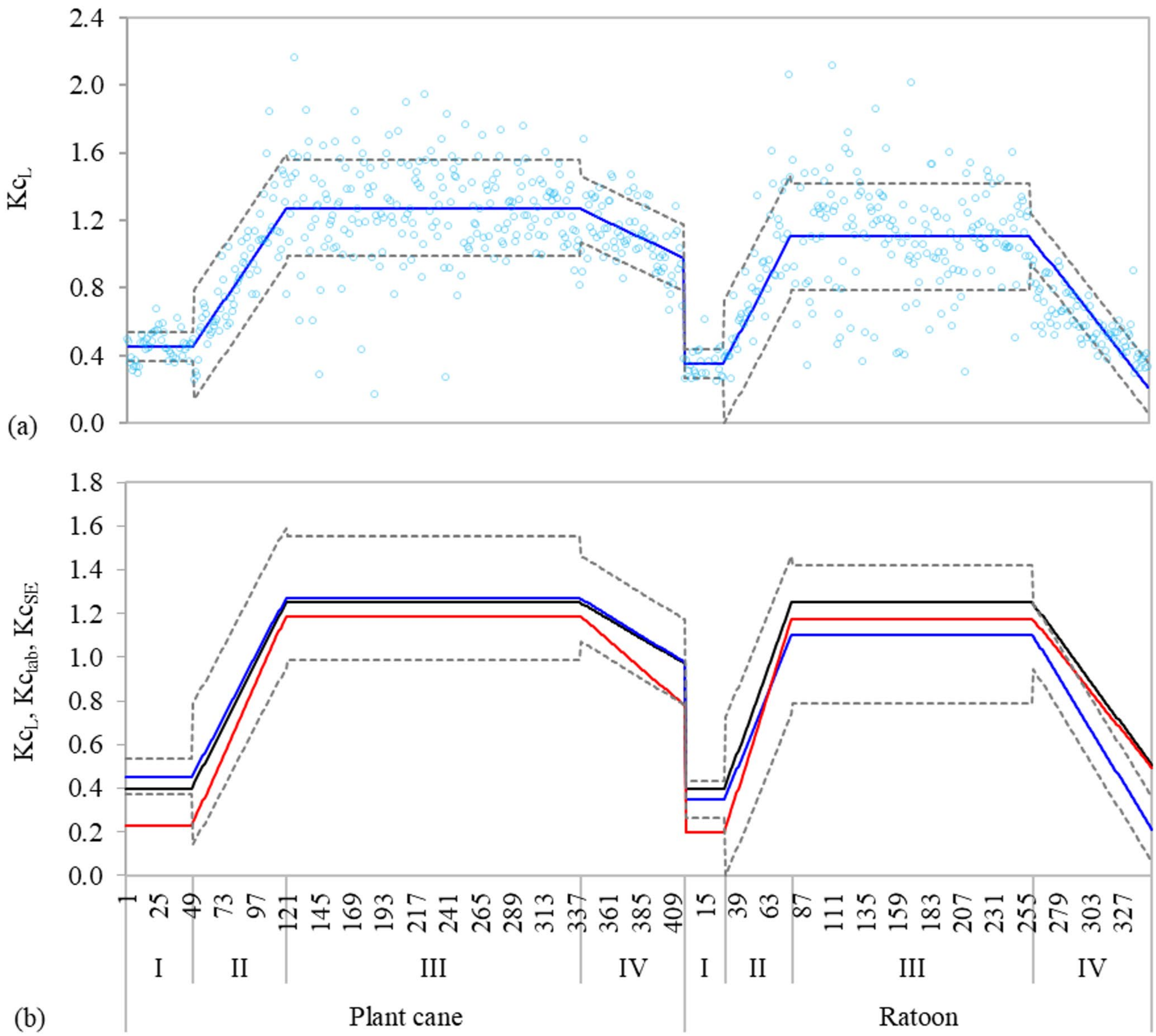



**Fig. 4** Daily ($Kc_L$; ○) and average ($Kc_L$; ▬) crop coefficient values obtained by lysimetry, with their standard deviation (___) (**a**). Average crop coefficient values obtained by lysimetry ($Kc_L$; ▬), tabulated by FAO ($Kc_{tab}$; ▬), and estimated using FAO-recommended equations ($Kc_{SE}$; ▬), including the standard deviation of $Kc_L$ averages (___) (**b**). *The "x" axis represents the days after planting/cutting, the phenological phases and the crop cycle*

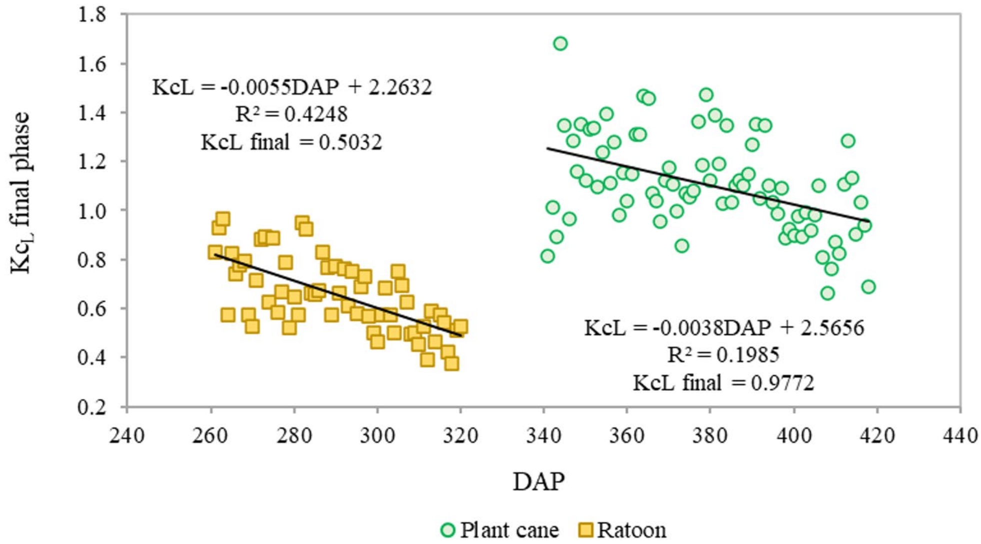



**Fig. 5** Average crop coefficient values obtained by lysimetry for the final stage (IV) of the plant cane and ratoon cane cycles. *Black line: linear regression trend line. The "x" axis represents the days after planting/cutting*

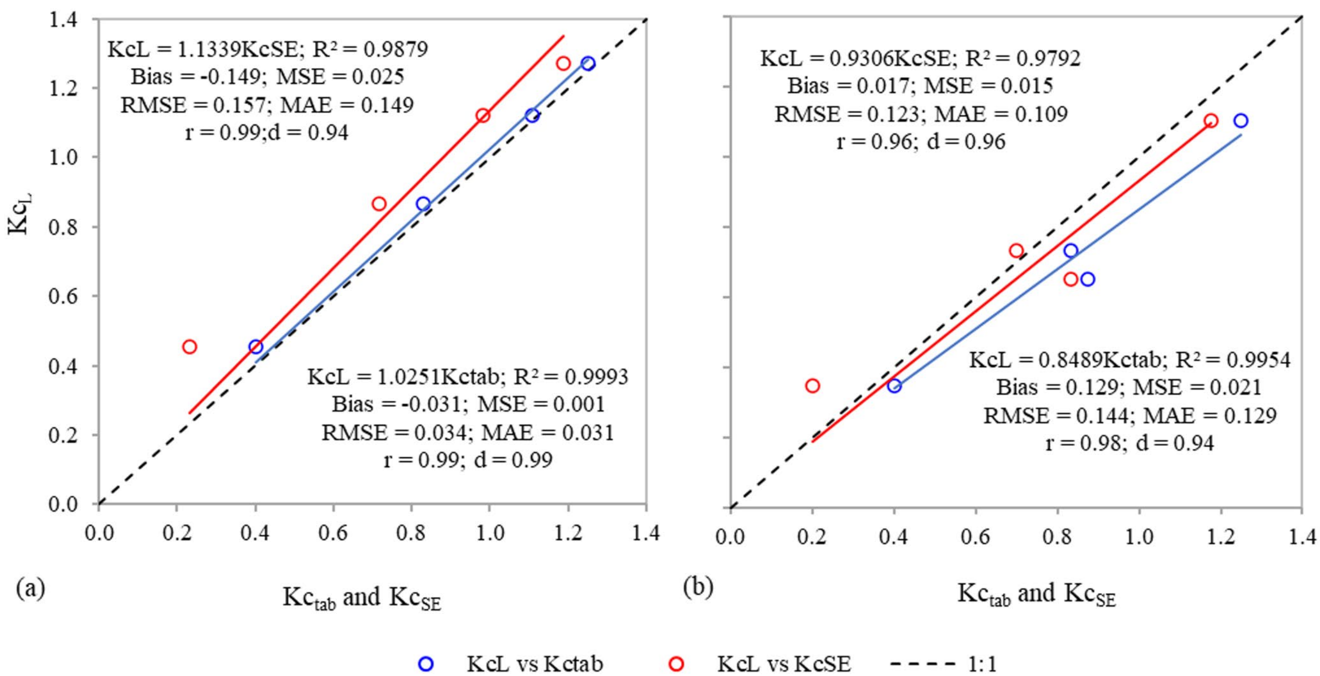



**Fig. 6** Single crop coefficient values obtained by lysimetry ($Kc_L$) in comparison to tabulated ($Kc_{tab}$) and estimated ($Kc_{SE}$) values, according to FAO-56 Bulletin (Allen et al. 1998), for the plant cane (**a**) and ratoon cane (**b**) cycles. The graphs display the linear regression equations and their coefficients of determination ($R^2$), along with statistical indices including bias, mean squared error (MSE), root mean squared error (RMSE), mean absolute error (MAE), Pearson's correlation coefficient (r), and the index of agreement (**d**)

remained within one standard deviation of the $Kc_L$ means (Fig. 4b). In the ratoon cane cycle ($Kc_{SE}$: I = 0.20; II = 0.70; III = 1.18; IV = 0.83; final = 0.49), the values were underestimated compared to $Kc_{tab}$ in all stages (Fig. 4b). In comparison with $Kc_L$, $Kc_{SE}$ values were lower only during stages I and II, whereas they were higher in the remaining stages (Fig. 4b).

Using $Kc_L$ as the reference, statistical indices were used to assess its relationship with $Kc_{tab}$ and $Kc_{SE}$ across different phenological stages and crop cycles (Fig. 6). Linear regression analysis indicated positive relationships for all comparisons ($Kc_L$ vs. $Kc_{tab}$ and $Kc_L$ vs. $Kc_{SE}$) in both crop cycles. In the plant cane cycle, the $Kc_L$ vs. $Kc_{tab}$ relationship showed a slope closest to the 1:1 line (1.025). In the ratoon cycle, the closest fit to the 1:1 line was observed for the $Kc_L$ vs. $Kc_{SE}$ relationship (0.931). Additionally, all coefficients of determination were $R^2 > 0.97$, indicating low data dispersion (Fig. 6).

In the plant cane cycle, the lowest errors were observed in the comparison between $Kc_L$ and $Kc_{tab}$, which also showed higher correlation and a better index of agreement (Fig. 6a). In contrast, in the ratoon cane cycle, the lowest errors were recorded for $Kc_L$ vs. $Kc_{SE}$, which also showed higher correlation but a lower index of agreement (Fig. 6b).

## Dual crop coefficient - $Kc_{dual}$

Daily values of the basal (Kcb), evaporation (Ke), and dual ($Kc_{dual}$ = Kcb + Ke) crop coefficients obtained experimentally, estimated, and tabulated are shown in Fig. 7. Kcb values were lower during the initial and final stages of both crop cycles (plant cane and ratoon cane). A marked increase occurred during stage II, with peak values in stage III (Fig. 7). In contrast, Ke values were higher during the initial stages (I and II), decreased in the mid-season stage (III), and increased again during the final stage (IV) (Fig. 7). Nevertheless, the experimental ($Kc_{dual\ E}$) and estimated ($Kc_{dual\ e}$) values of the dual crop coefficient followed a pattern similar to the FAO-56 tabulated values ($Kc_{tab}$) in both crop cycles (Fig. 7).

In the plant cane cycle, regression analysis showed that both $Kcb_{tab}$ and $Kcb_e$ values were overestimated compared

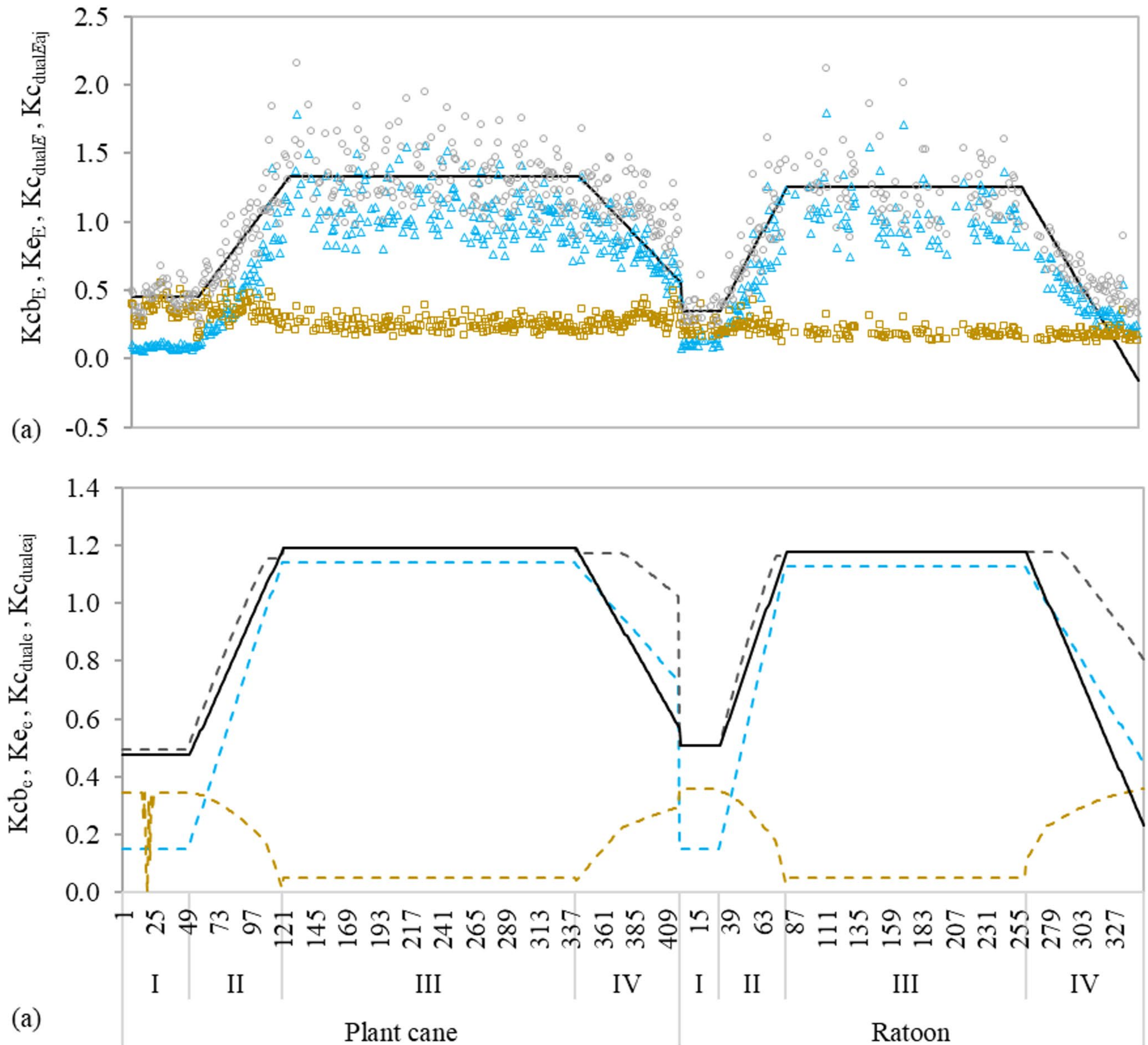
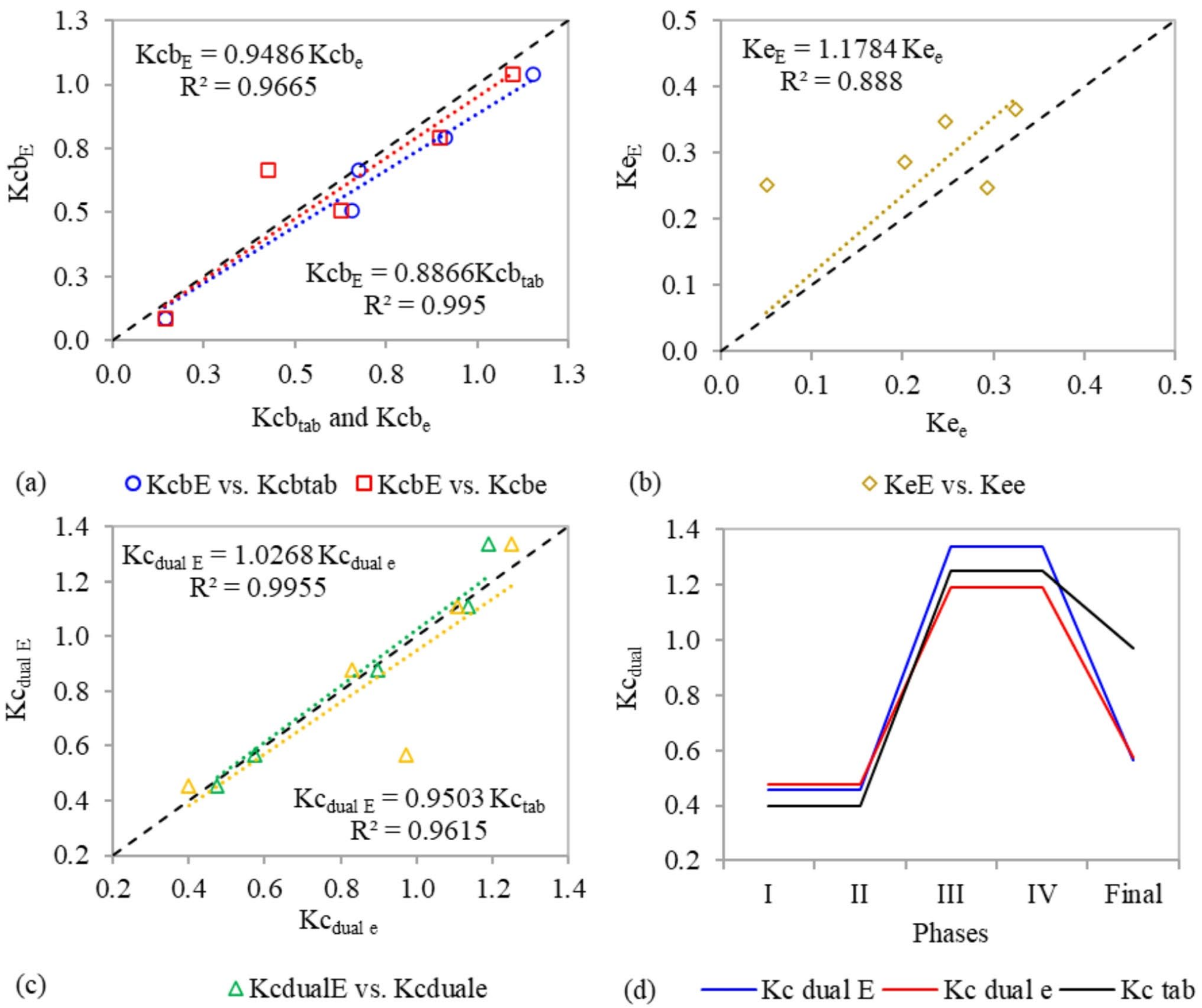



**Fig. 7** Daily values of the experimentally determined basal crop coefficient ($Kcb_E$; △), soil evaporation coefficient ($Ke_E$; □), and dual crop coefficient ($Kc_{dual\ E}$; ○), along with $Kc_{dual\ E}$ values adjusted to the average per phenological stage ($Kc_{dual\ E}$ adj; ▬) (**a**). Daily estimated values of the basal crop coefficient ($Kcb_e$; - - -), soil evaporation coefficient ($Ke_e$; - - -), and dual crop coefficient ($Kc_{dual\ e}$; - - -), as well as $Kc_{dual\ e}$ values adjusted to the average per phenological stage ($Kc_{dual\ e}$ adj; ▬) (**b**). *The x-axis represents days after planting (plant cane) or cutting (ratoon cane), phenological stages (I, II, III, IV), and crop cycles (plant cane or ratoon cane)*

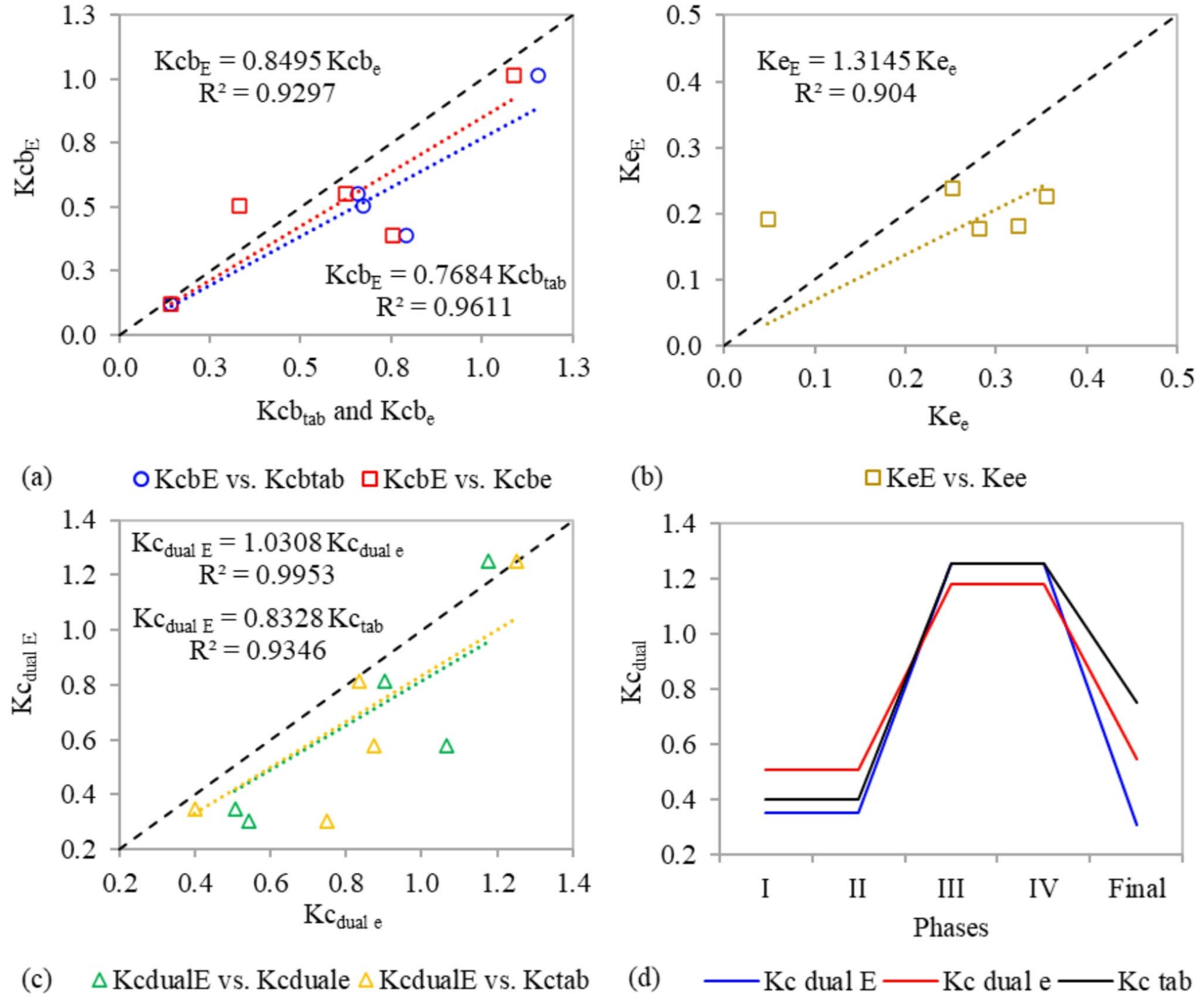
to the experimental basal crop coefficient ($Kcb_E$) (Fig. 8a). On the other hand, $Ke_e$ values were underestimated compared with the experimental evaporation coefficient ($Ke_E$) (Fig. 8b). On average, $Kc_{dual\ E}$ values were higher than $Kc_{tab}$ and lower than $Kc_{dual\ e}$ (Fig. 8c and d). Statistical indices (Bias, MSE, RMSE, and MAE) indicated similar error magnitudes for $Kc_{tab}$ vs. $Kc_{dual\ E}$ and for $Kc_{tab}$ vs. $Kc_{dual\ e}$ (Fig. 8). The best correlation (r and R²) and agreement (d) values were observed in the relationship between $Kc_{tab}$ and $Kc_{dual\ E}$ (Fig. 8).

In the ratoon cane cycle, the same analyses showed that $Kcb_{tab}$ and $Kcb_e$ were overestimated relative to the experimental basal crop coefficient ($Kcb_E$) (Fig. 9a). A similar pattern was observed for $Ke_e$ relative to the experimental evaporation coefficient ($Ke_E$) (Fig. 9b). $Kc_{dual\ E}$ values were overestimated compared to $Kc_{tab}$ and underestimated compared to $Kc_{dual\ e}$ (Fig. 9c and d). Statistical indices (Bias, MSE, RMSE, and MAE) indicated comparable errors between $Kc_{tab}$ and $Kc_{dual\ E}$, as well as between $Kc_{tab}$ and $Kc_{dual}$ e (Fig. 9). Notably, $Kc_{tab}$ showed higher correlation (r




| $Kc_{tab}$ vs. | Bias | MSE | RMSE | MAE | r | R² | d |
|---|---|---|---|---|---|---|---|
| $Kc_{dual\ E}$ | 0.132 | 0.039 | 0.197 | 0.186 | 0.909 | 0.827 | 0.916 |
| $Kc_{dual\ e}$ | 0.119 | 0.040 | 0.201 | 0.172 | 0.887 | 0.786 | 0.900 |

**Fig. 8** Plant cane cycle: experimentally determined basal crop coefficient values ($Kcb_E$) compared with estimated ($Kcb_e$) and tabulated values ($Kcb_{tab}$) (**a**). Relationship between experimental ($Ke_E$) and estimated ($Ke_e$) soil evaporation coefficients (**b**). Correlation between experimental ($Kc_{dual\ E}$) and estimated ($Kc_{dual\ e}$) dual crop coefficients (**d**). Schematic comparison of experimental ($Kc_{dual\ E}$), estimated ($Kc_{dual\ e}$), and FAO-56 tabulated ($Kc_{tab}$) dual crop coefficients




| $Kc_{tab}$ vs. | Bias | MSE | RMSE | MAE | r | $R^2$ | d |
|---|---|---|---|---|---|---|---|
| $Kc_{dual\ E}$ | -0.052 | 0.055 | 0.234 | 0.203 | 0.778 | 0.605 | 0.873 |
| $Kc_{dual\ e}$ | 0.127 | 0.051 | 0.227 | 0.198 | 0.831 | 0.691 | 0.857 |

**Fig. 9** Ratoon cane cycle: experimentally determined basal crop coefficient values ($Kcb_E$) compared with estimated ($Kcb_e$) and tabulated values ($Kcb_{tab}$) (**a**). Relationship between experimental ($Ke_E$) and estimated ($Ke_e$) soil evaporation coefficients (**b**). Correlation between experimental ($Kc_{dual\ E}$) and estimated ($Kc_{dual\ e}$) dual crop coefficients (**d**). Schematic comparison of experimental ($Kc_{dual\ E}$), estimated ($Kc_{dual\ e}$), and FAO-56 tabulated ($Kc_{tab}$) dual crop coefficients

and $R^2$) than $Kc_{dual\ e}$ and better agreement (d) with $Kc_{dual\ E}$ (Fig. 9).

## Simulated irrigation

The use of different crop coefficients (Kc) led to different irrigation depths throughout the plant cane and ratoon cane cycles (Fig. 10). Using tabulated Kc values ($Kc_{tab}$) as a reference, total irrigation depths were 776.5 mm for plant cane and 604 mm for ratoon cane (Fig. 10). In the plant cane cycle, the highest irrigation depths occurred when using crop coefficients determined by lysimetry ($Kc_L$ = +10.3%) and the experimental dual coefficient ($Kc_{dual\ E}$ = +6.6%) (Fig. 10). In contrast, water savings were achieved when using the estimated single ($Kc_{SE}$ = −11.2%) and estimated dual ($Kc_{dual\ e}$ = −0.8%) crop coefficients (Fig. 10). For the ratoon cane cycle, all crop coefficients indicated lower irrigation depths than $Kc_{tab}$ (Fig. 10). The differences were −27.1% ($Kc_L$), −13.6% ($Kc_{SE}$), −20.1% ($Kc_{dual\ E}$), and −21.1% ($Kc_{dual\ e}$).

Within the phenological stages of the plant cane cycle, when using $Kc_{tab}$, no irrigation was recommended for stage

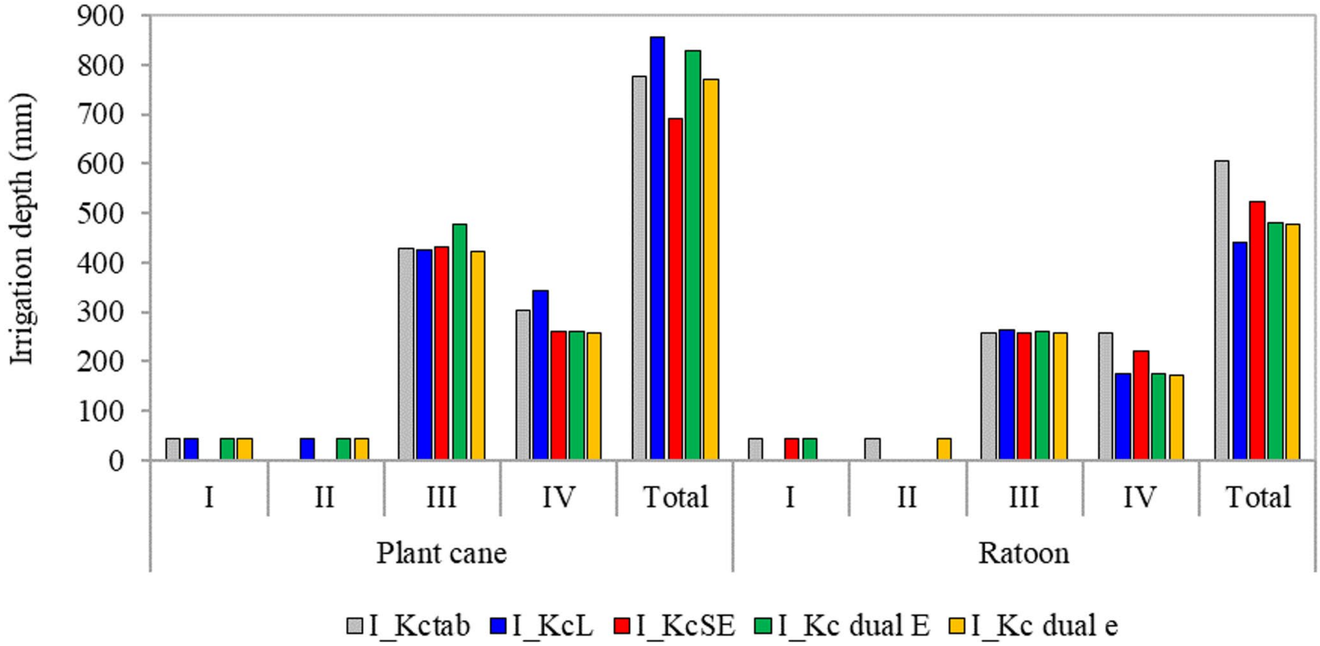



**Fig. 10** Irrigation depth (mm) by phenological stage and total values for the plant cane and ratoon cane cycles, using different crop coefficients: FAO-56 tabulated ($Kc_{tab}$); determined by lysimetry ($Kc_L$); simple estimated ($Kc_{SE}$); dual experimental ($Kc_{dual\ E}$); and dual estimated by equations ($Kc_{dual\ e}$). *The acronym I_Kc represents the irrigation depth performed for each Kc*

II. Similarly, no irrigation was recommended for stages I and II when using $Kc_{SE}$. Nevertheless, the greatest percentage differences within this cycle were observed in stage IV ($Kc_L = +13.2\%$; $Kc_{SE} = -14.6\%$; $Kc_{dual\ E} = -14.1\%$; $Kc_{dual\ e} = -14.9\%$). In the ratoon cane cycle, irrigation was not recommended during stage I when using $Kc_L$ and $Kc_{dual\ e}$, and during stage II when using $Kc_L$, $Kc_{SE}$, and $Kc_{dual\ E}$. The largest percentage differences were again observed in stage IV ($Kc_L = -31.4\%$; $Kc_{SE} = -14.4\%$; $Kc_{dual\ E} = -31.6\%$; $Kc_{dual\ e} = -32.3\%$) (Fig. 10).

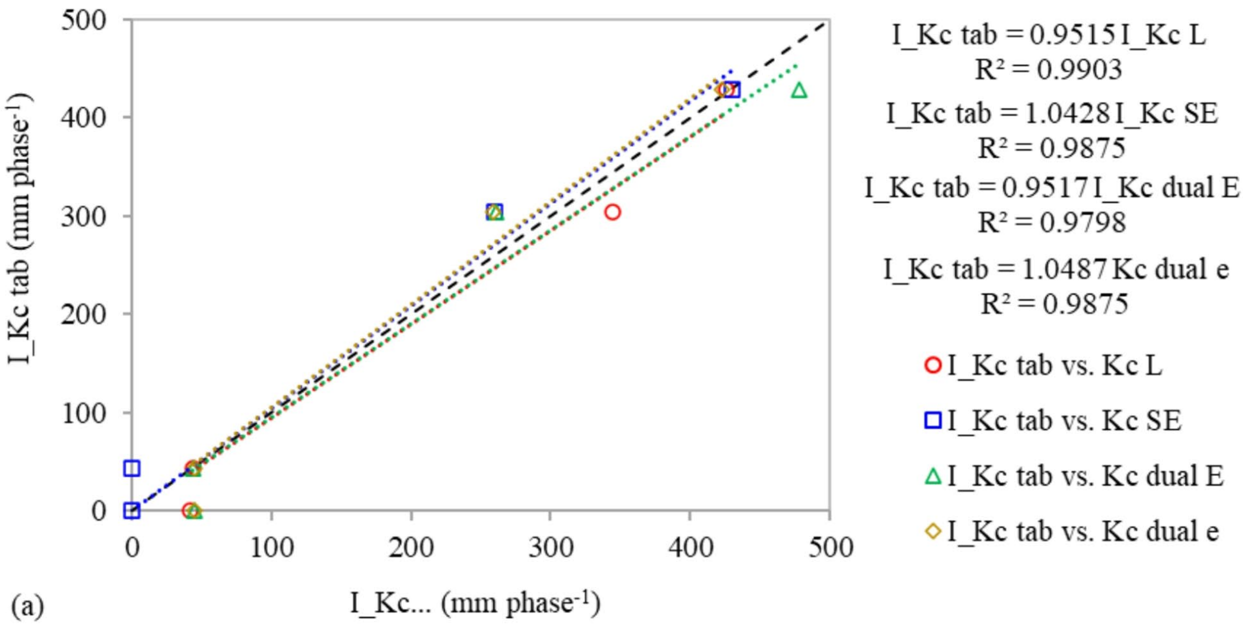
Regression analysis of irrigation depths obtained using different Kc values showed a good linear fit, with slope coefficients close to 1.0 and $R^2$ values > 0.98 (plant cane) and > 0.93 (ratoon cane) (Fig. 11). In the plant cane cycle, statistical indices indicated the lowest errors for irrigations depths estimated using $Kc_{tab}$ and $Kc_L$, with high correlation (r) and a high agreement index (d) (Fig. 11). In the ratoon cane cycle, the lowest errors and the highest r and d values were observed for $Kc_{tab}$ and $Kc_{SE}$ (Fig. 11).

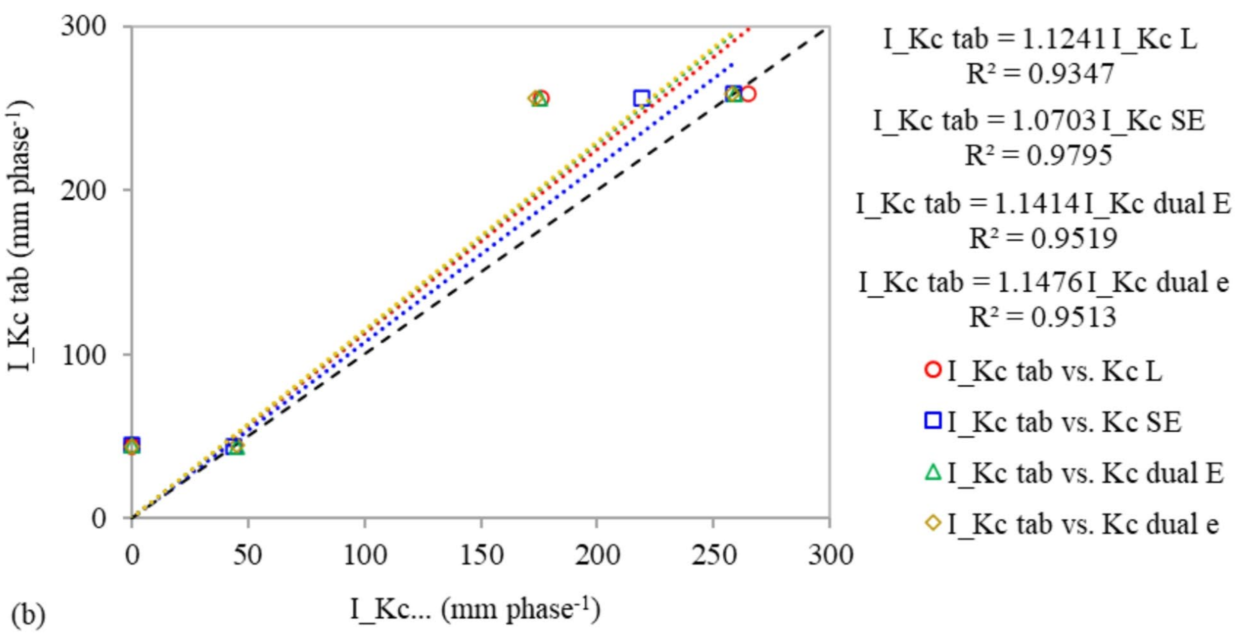
## Discussion

### Plants and the growing environment

Sugarcane (*Saccharum* spp.) agronomic performance is strongly influenced by agrometeorological variables, including rainfall, air temperature, relative humidity, solar radiation, growing degree days, water deficit, and actual evapotranspiration (Casaroli et al. 2023). These factors jointly affect crop development and yield. In addition, edaphoclimatic factors are also crucial for achieving high yields. Favorable conditions include an annual rainfall of approximately 1500 mm, a maximum temperature of 30 °C, an average temperature of around 24.1 °C, a minimum temperature of 18.1 °C, solar radiation of 18.2 MJ $m^{-2}$ $day^{-1}$, and wind speed of approximately 1.3 m $s^{-1}$, as well as soils with higher clay content, organic carbon, and cation exchange capacity (Capuchinho et al. 2025). Marin and Nassif (2013) observed average temperatures above 21 °C, suitable for two sugarcane cropping cycles. Air temperature is a key climatic factor for vegetative development (Kirubakaran et al. 2013) and for the photosynthetic process (Sanghera 2020).

Plant height is a direct indicator of the vegetative growth of sugarcane. Studies have shown that water availability has a significant impact on this variable. Sugarcane plants (var. CTC-4) cultivated under field conditions in Goiás, Brazil, reached higher maximum plant height (plant cane: 4.1 m; ratoon cane: 3.6 m) and leaf area index (plant cane: 5.5; ratoon cane: 7.7) than those observed in the present study (Fig. 1). However, the same authors reported lower yields (plant cane: 115 Mg $ha^{-1}$; ratoon cane: 63 Mg $ha^{-1}$). These results were obtained under average solar radiation of 17.5 MJ $m^{-2}$ $day^{-1}$ (plant cane) and 16.4 MJ $m^{-2}$ $day^{-1}$ (ratoon cane), mean air temperature of 23.9 °C, wind speed of 0.8–2.2 m $s^{-1}$, total rainfall of 1923.6 mm (plant cane) and 1390.2 mm (ratoon cane), and relative humidity




| I_Kctab vs. | Bias | MSE | RMSE | MAE | r | d |
|---|---|---|---|---|---|---|
| | ...Plant cane... | | | | | |
| **I_KcL** | 19.962 | 850.723 | 29.167 | 21.247 | 0.993 | 0.993 |
| **I_KcSE** | -21.760 | 986.812 | 31.414 | 22.648 | 0.992 | 0.992 |
| **I_Kc dual E** | 12.835 | 1580.014 | 39.749 | 34.502 | 0.978 | 0.988 |
| **I_Kc dual e** | -1.513 | 1017.332 | 31.896 | 24.008 | 0.989 | 0.991 |
| | ...Ratoon... | | | | | |
| **I_KcL** | -40.834 | 2618.731 | 51.174 | 43.869 | 0.964 | 0.947 |
| **I_KcSE** | -20.516 | 843.776 | 29.048 | 20.596 | 0.983 | 0.982 |
| **I_Kc dual E** | -31.142 | 2140.815 | 46.269 | 31.746 | 0.947 | 0.951 |
| **I_Kc dual e** | -31.832 | 2199.838 | 46.902 | 32.014 | 0.946 | 0.949 |

**Fig. 11** Regression analysis and statistical indices between the simulated irrigation depths based on different crop coefficients for each phenological stage of the plant cane (**a**) and ratoon cane (**b**) cycles. Crop coefficients used: FAO-56 tabulated ($Kc_{tab}$); determined by lysimetry ($Kc_L$); simple estimated ($Kc_{SE}$); dual experimental ($Kc_{dual\ E}$); and dual estimated ($Kc_{dual\ e}$). *The acronym I_Kc represents the irrigation depth performed for each Kc*

of 60–65%. It is noteworthy that solar radiation and air temperature were within the range observed in the present study; however, different values were recorded for wind speed (higher), total rainfall (lower), and relative humidity (lower) (Fig. 2) (Casaroli et al. 2023).

Under field conditions (var. CTC-4; Goiás, Brazil), Caetano et al. (2024) reported mean air temperatures of 22.9 °C (plant cane) and 23.8 °C (ratoon cane), within the range observed in the present study, and total rainfall of 1778.6 mm (plant cane) and 1477.6 mm (ratoon cane), both higher than those recorded herein. At harvest, they reported soluble solids contents of 23.7 °Brix (plant cane) and 24.8 °Brix (ratoon cane), which exceeded the values observed in the present study (Fig. 1b).

When sugarcane (var. RB867515) was grown in 200-liter containers, the average biometric values for plant height (plant cane: 1.30 m; ratoon cane: 1.11 m) and leaf area index (plant cane: 3.47; ratoon cane: 2.84) reported by Antunes Júnior et al. (2021b) were lower than those observed in the present study (Fig. 2), even when compared to the biometric values of plants cultivated within the lysimeter, both in the plant cane (height: 3.21 m; LAI: 4.51) and in ratoon cane (height: 2.49 m; LAI: 4.37) cycles. Additionally, the °Brix values (plant cane: 16.94; ratoon cane: 19.0) were below the averages found in this study, while fiber content (plant cane: 13.65%; ratoon cane: 14.50%) and purity (plant cane and ratoon approximately 90%) showed values similar to those recorded in this study (Fig. 1). Antunes Júnior et al. (2021a) reported no significant differences between the two crop cycles in terms of agrometeorological variables such as solar radiation (15 MJ $m^{-2}$ $day^{-1}$), air temperature (23 °C), and relative humidity (70%); with temperature and humidity values within the range observed in the present study, and solar radiation slightly lower (Fig. 2).

Other authors also reported plant height and leaf area index (LAI) values lower than those observed in the present study, such as Singh et al. (2018), who found a plant height of 2.12 m in the control treatment and 2.29 m under 75% irrigation, and Libardi et al. (2019), who reported LAI values of 2.7 for var. CTC9005HP, 3.2 for var. RB966928, and 3.9 for var. SP87365. These results were all from the plant cane cycle and were more comparable to those obtained from plants grown within the lysimeter.

The yield results obtained in the present study (Fig. 1) were higher than those reported by Singh et al. (2018) in India (plant cane: 77.7 Mg $ha^{-1}$) under 75% crop water requirement. These values were somewhat closer to those observed by Dingre and Gorantiwar (2021), who reported yields of 181.5 Mg $ha^{-1}$ under full irrigation, with reductions observed under water deficits of 30% (157.1 Mg $ha^{-1}$) and 60% (107.4 Mg $ha^{-1}$).

In the present study, Recoverable Total Sugar (RTS) values were lower than those reported by Pereira et al. (2017). In their study, RTS in plant cane (RB varieties) ranged from 144.4 to 147.8 kg $t^{-1}$. By contrast, lower RTS values were reported for the ratoon cycle under lysimetric conditions (Fig. 1). This difference may be attributed to distinct edaphoclimatic conditions, as the study by Pereira et al. (2017) was conducted in the municipality of Rio Largo (state of Alagoas, Brazil), on a Latossolo Amarelo Argissólico Coesivo with a medium to clayey texture, under a hot and semi-humid climate, with an average annual rainfall of 1818 mm (Souza et al. 2004).

In terms of water availability, both cycles received rainfall depths exceeding 1000 mm, with well-distributed precipitation throughout the crop cycle, as recommended for sugarcane cultivation (Marin and Nassif 2013), particularly during the phenological stage of full vegetative development (Gobo et al. 2018).

At certain points during both cycles, solar radiation fell below the ideal range (18–36 MJ $m^{-2}$ $day^{-1}$) (Marafon 2012; Araújo et al. 2017). However, no clear effect on crop development was detected in the present study. Nevertheless, it is worth noting that solar energy is essential for photosynthesis and, in the case of sugarcane, also plays a key role in tiller production, activation of basal buds, acceleration of stalk growth, and overall green biomass accumulation (Araújo et al. 2017; Monteiro 2012).

Relative air humidity (RH) remained within the recommended range (45–85%) (Mata 2018), except during the ratoon cycle (RH $<$ 40%). It is essential to note that RH levels between 80% and 85% favor stalk elongation during the growth period. In contrast, values between 45% and 65% are recommended during the ripening phase or under limited water availability (Mata 2018). However, this expected response pattern of stalk elongation and ripening associated with RH ranges was not evident in the present study.

Wind speed values were low (0.65 m $s^{-1}$) in both crop cycles, suggesting that this variable may have positively influenced crop performance by enhancing energy exchange and carbon dioxide supply for photosynthesis (Silva et al. 2021).

The interaction between incoming solar radiation and leaf area index is fundamental in regulating crop evapotranspiration by controlling both energy availability and canopy transpiration capacity (Pilau and Angelocci 2015; Costa et al. 2016; van Hoek Dijke et al. 2020). As leaf area index increases, a larger fraction of radiation is intercepted by the canopy, which enhances transpiration while simultaneously reducing soil evaporation through shading. This dynamic shift in the energy balance reflects the transition from a soil-dominant to a vegetation-dominant evaporation process as the crop reaches full canopy cover (Allen et al. 1998; Libardi et al. 2019).

Sugarcane water use regulates yield and juice quality by controlling biomass accumulation, assimilate partitioning, and ripening dynamics (Alamilla-Magaña et al. 2016; Mohanraj et al. 2021). Adequate water availability is essential for sustaining photosynthesis and stalk growth. In contrast, a controlled water deficit during the final growth stages triggers a physiological shift from vegetative growth to ripening, enhancing sucrose accumulation and increasing °Brix and Pol (Bastidas-Obando et al. 2017; Mohanraj et al. 2021; Antunes Júnior et al. 2021b). This drying-off strategy enhances carbohydrate conversion efficiency and links crop evapotranspiration to coordinated yield and juice-quality responses (Bastidas-Obando et al. 2017; Pereira et al. 2024; Namdarian et al. 2024; Raheja et al. 2025). In ratoon cycle, the established root system and extended effective growth period compensate for reduced vegetative expansion, resulting in higher sugar content and earlier technical maturity (Casaroli et al. 2019; Antunes Junior et al. 2021a). Under these conditions, surface drip irrigation enhances yield and juice quality by reducing soil evaporation and improving water use efficiency (Antunes Junior et al. 2021b; Wonprasaid et al. 2023).

## Water losses through evaporation and transpiration

Sugarcane varieties grown in drums exhibited evapotranspiration rates of 9.2 and 8.4 L day$^{-1}$ (IAC911099), 8.2 and 7.9 L day$^{-1}$ (RB867515), and 7.6 and 6.6 L day$^{-1}$ (IAC87336) for the plant cane and ratoon cane cycles, respectively (Antunes Júnior et al. 2021b). These values were lower than those observed in the present study only for the IAC87336 variety (Fig. 3).

Libardi et al. (2019) reported an evapotranspiration rate of 3.0 L day$^{-1}$ during the initial phase of sugarcane, increasing to 6.9 L day$^{-1}$ in the subsequent phase. In the present study, ETc values were lower in Phase I and higher in Phase II for both crop cycles (Fig. 3). This abrupt increase from one phase to the next can be explained by the rapid rise in leaf area density over a short period (Fig. 1). Antunes Júnior et al. (2021a) also attributed this variation in water loss to varietal differences, as the genotype evaluated exhibited a greater number of tillers, resulting in higher water demand in both cycles.

Using lysimeters, Daniel et al. (2023) reported soil evaporation values ranging from 1.9 to 4.6 mm day$^{-1}$, which were higher than those obtained in the present study using microlysimeters (Fig. 3b). The same authors also used microlysimeters with and without drainage and two diameters (100 and 150 mm). For non-drained units, evaporation rates were 2.1 and 5.7 mm day$^{-1}$ for 100- and 150-mm diameters, respectively. In contrast, for the drained ones, values ranged from 2.0 to 4.8 mm day$^{-1}$, representing an 11.40% increase relative to lysimeter measurements. Overall, the evaporation rates reported by the authors were higher than those measured by our microlysimeters in both crop cycles (Fig. 3b).

Sugarcane evapotranspiration (ETc) can range from 1.6 to 7.1 mm day$^{-1}$ (Yadeta et al. 2021), with the upper limit exceeding the maximum values observed in the present study (plant cane: 4.6 mm day$^{-1}$; ratoon cane: 3.7 mm day$^{-1}$) (Fig. 3). Goshehgir et al. (2021) reported ETc values of 8.3 mm day$^{-1}$ for sugarcane cultivated in lysimeters in Iran, which were higher than the averages obtained in both crop cycles of this study (Fig. 3a). Using two lysimeters, Santos et al. (2017) recorded mean ETc values (4.8 mm day$^{-1}$) for sugarcane that were similar to those found in the present research (Fig. 3).

Dingre and Gorantiwar (2020) identified a total water requirement of 1,387 mm for the plant cane and 1,291 mm for the ratoon cane cycle. Compared to the values obtained in the present study, the demand was lower for the plant cane and higher for the ratoon cane (Fig. 3b). These authors also reported that the highest water demand occurred during the full ground cover stage (886.6 mm). This value was lower than the total demand observed in Phase III of the plant cane cycle (1084.4 mm) but higher than that observed in the ratoon cane cycle (757.6 mm) in the present study. According to Resende et al. (2021), the average water demand was higher in both cycles (plant cane: 1195 mm; ratoon cane: 1188 mm) in Alagoas, Brazil.

Differences in the crop coefficient (Kc) between plant and ratoon cane are primarily associated with physiological and structural contrasts in canopy development and root system dynamics (Pissolato et al. 2021; Xu et al. 2021). Ratoon crops often exhibit faster early canopy closure and altered stomatal regulation, a factor that can modify crop evapotranspiration relative to plant cane (Casaroli et al. 2019; Xu et al. 2021; Antunes Júnior et al. 2021b). These physiological and structural contrasts result in different Kc curves and water requirement across crop cycles and phenological stages (Antunes Júnior et al. 2021a, b).

### Crop coefficient determinations

Libardi et al. (2019) reported differences of up to 40% between FAO-recommended crop coefficient (Kc) values and those obtained experimentally by lysimetry during early sugarcane development (up to 46 days after transplanting).

For the RB966928 variety, Kc ranged from 1.02 to 1.28. These values were higher than those in the present study (Fig. 4). On the other hand, smaller variations were reported by Martins et al. (2022) (ranging from 0.92 to 1.21; average: 1.01 ± 0.08) and Silva et al. (2014) (mean Kc: 0.99; ranging from 0.56 to 1.43). Using lysimetry, Yadeta et al. (2021) obtained higher Kc values than those recommended by FAO-56 during sprouting (2%), development (1%), and maturation (30%). However, Kc values were 30% lower during the tillering phase.

The Kc values during the full ground cover stage, both for plant cane (estimated: 1.19; lysimeter: 1.27) and ratoon cane (estimated: 1.18; lysimeter: 1.10), were consistent with findings from various authors, who reported a range of 0.91–1.67 (Inman-Bamber and McGlinchey 2003; Marin et al. 2020; Dingre and Gorantiwar 2020; Martins et al. 2022).

The basal crop coefficient (Kcb) of sugarcane during the vegetative development stage of the plant cane cycle was approximately 10% (lysimeter) and 5% (estimated) lower than the tabulated Kcb value from FAO-56. For the ratoon cycle, Kcb values were 11.7% (lysimeter) and 5.8% (estimated) lower than those from FAO-56 (Allen et al. 1998). These findings are consistent with those of Martins et al. (2022), who reported a Kcb value approximately 14% lower than the FAO-56 adjusted value. Furthermore, other authors (Bastidas-Obando et al. 2017) also reported lower average Kcb values for both irrigated and non-irrigated sugarcane compared to the FAO-56.

When comparing ETc values obtained using the single- and dual-Kc methods, the dual-Kc method showed better performance (Silva et al. 2012b). On the other hand, Martins et al. (2022) emphasized that using adjusted FAO-56 Kc and Kcb values led to overestimations of sugarcane evapotranspiration.

Similar divergences between FAO-56 tabulated and experimentally derived Kc values have been reported across different crops and environments, including tomato, eggplant, melon, cotton, and sugarcane, with discrepancies reaching over 60% depending on crop stage and environmental conditions (Melo et al. 2013; Wu et al. 2019; Jakkannavar and Bhagwat 2020; Yadeta et al. 2021; Li et al. 2022; Shahrajabian and Sun 2024; Kavya and Mahadevaiah 2024).

Previous studies on sugarcane have incorporated error and agreement metrics to evaluate FAO-56 performance. For instance, Silva et al. (2012b) reported higher agreement between measured and estimated ETc using the dual crop coefficient approach ($R^2 = 0.64$) compared to the single coefficient method ($R^2 = 0.53$). Martins et al. (2022) showed that local calibration relative to FAO-56 tabulated values resulted in $R^2$ values ranging from 0.23 to 0.83, Willmott's index of agreement from 0.49 to 0.79, and RMSE from 0.20 to 0.70. Despite these advances, studies simultaneously evaluating multiple error metrics for experimentally determined vs. estimated crop and soil evaporation coefficients, and the resulting irrigation depths across phenological stages and crop cycles, remain limited.

## Irrigation management

The scientific literature suggests that synchronizing phenological stages with rainfall events is crucial for minimizing irrigation requirements during the sugarcane cycle, potentially resulting in water savings of 5–129 mm (Resende et al. 2021). In the present study, irrigation simulations indicated that irrigation was not required during the initial stages (I and II), depending on the crop coefficient (Kc) method used (Fig. 10).

The soil evaporation dynamics observed in this study reflect complex interactions between water inputs, redistribution, and drying patterns in space and time. Under surface drip irrigation, soil wetting patterns influence the evaporation coefficient (Ke) by controlling both the frequency and the spatial extent of surface moisture (Allen et al. 1998; Zheng et al. 2025). This localized wetting restricts evaporation to a fraction of the soil surface, which helps explain why our Ke and $Kc_{ini}$ estimates deviated from tabulated FAO-56 values, which assume full-surface wetting (Allen et al. 1998; Martínez and Reca 2014; Namdarian et al. 2024). These discrepancies are particularly evident during early growth stages, when canopy cover is limited, and the soil surface remains more exposed (Libardi et al. 2015; Phogat et al. 2016).

Furthermore, while commercial drip systems often follow high-frequency daily schedules to maintain a constantly moist surface, our experiment applied irrigation at two- to three-day intervals (Bernardo et al. 2019). Although this schedule ensured soil moisture remained within the range of readily available water, it modified the evaporation process. Daily irrigation typically sustains energy-limited evaporation. However, the longer intervals used here allowed brief surface drying. This schedule likely shifted the evaporation process toward a diffusion-limited regime between events (Allen et al. 1998; Hillel 1998). This transition effectively reduced total soil evaporation compared to high-frequency systems, as the soil surface resistance increased during the drying phases (Mellouli et al. 2000; Alcon et al. 2019; Guo and Li 2024). Consequently, our findings suggest that water management strategies in drip irrigation should account for both localized wetting and irrigation frequency to optimize water use efficiency.

In India, sugarcane cultivation (a 12-month cycle) exhibits a water demand ranging from 1600 to 2000 mm; however, after accounting for effective rainfall, irrigation during the cycle can be reduced to 1200–1600 mm (Dingre 2023). These values are higher than those observed in the present study (Fig. 10). Nevertheless, local edaphoclimatic conditions and the cultivar used directly influence irrigation requirements. Other factors also determine the irrigation timing, such as the appropriate planting season, phenological stages, crop age, and the balance between water availability and demand (Dingre 2023).

Dingre and Gorantiwar (2021) applied greater irrigation depths than those indicated in our simulations (tillering: 264.2 mm, development: 886.6 mm, and maturation: 137.4 mm), totaling 990.8 mm (excluding rainfall). This strategy resulted in the highest yield (181.5 Mg ha$^{-1}$) compared with the treatments receiving lower irrigation depths. Thus, proper management and efficient irrigation techniques can maximize yields by up to 38% in RB sugarcane varieties (Brazil) (Evangelista et al. 2023).

Marin et al. (2020) identified that the number of irrigation events throughout the cycle is also a factor to be considered. A reduction in stalk yield was observed in treatments where fewer than 17 irrigation applications were made. The authors also found that omitting a single irrigation during the sugarcane cycle may reduce yield by 5 t ha$^{-1}$ due to water deficit.

Irrigation simulations using the tabulated Kc method (Allen et al. 1998) resulted in higher irrigation depths in both cycles for most Kc approaches (except for lysimetry-derived Kc and the experimental dual Kc in plant cane). Marin et al. (2020) also observed this tendency toward overestimation, which may occur under conditions of high-water demand and poorly drained soils.

Regarding lysimeters, root confinement can alter root distribution and water uptake patterns compared to open-field conditions (Makkink et al. 1959; Mathers et al. 2007; Cai et al. 2018a; Riedl et al. 2022). Such confinement can promote edge effects, characterized by a high accumulation of root length density along the container walls, and induce mechanical stress and hormonal responses that inhibit leaf growth, tillering, stomatal opening, and biomass accumulation (Ismail et al. 1998; Magarey et al. 1999; Poorter et al. 2012; Cai et al. 2018b; Pissolato et al. 2021). As an adaptive response, plants tend to maintain the root-to-shoot ratio by reducing shoot development, resulting in smaller plants than those grown under field conditions (Magarey et al. 1999). Additionally, excessively long roots extending to the bottom of the device may interfere with the lysimeter weighing system, introducing errors in mass measurements and consequently biasing evapotranspiration estimates (Abd Elbasit and Ratshiedana 2024).

It is also important to highlight that the soil block enclosed within the lysimeter has lateral surfaces that do not exchange heat or mass with the surrounding soil, which may disturb natural microclimatic patterns in the adjacent profile. This condition can affect heat and water vapor transport, potentially leading to deviations in ETc estimates compared to the surrounding area (Allen et al. 2011; Olivier and Singels 2012; Riedl et al. 2022; Kavya and Mahadevaiah 2024; Li et al. 2025). Regarding the experimental scale, considering the small experimental area of this study, potential border effects may influence the results and should be acknowledged (Allen et al. 2011).

Some limitations should be acknowledged. The experiment was based on lysimeter measurements, which, although considered the standard method for determining crop evapotranspiration, represent point-scale observations and may not fully capture field-scale spatial variability, particularly regarding root distribution and soil heterogeneity. This limitation is especially relevant for sugarcane, a large and long-cycle crop, in which canopy development and root dynamics can vary substantially over space and time.

In addition, the relatively small experimental area may have increased the susceptibility to border effects and lysimeter-induced microclimatic disturbances due to restricted lateral heat and mass exchange. The study was also conducted at a single site and included one variety evaluated over two crop cycles, which may limit the assessment of genetic variability and interannual climatic influences on crop water use and irrigation depth requirements under different edaphoclimatic conditions.

Finally, when dual crop coefficients are derived, additional uncertainties associated with soil evaporation measurements, including representativeness and drainage constraints, should be recognized.

## Conclusions

The biometric assessments showed that sugarcane plants in the plant cane cycle were taller than those in the ratoon cane cycle. This pattern was also observed in the lysimeter-grown plants. Higher yields were observed in plant cane than in ratoon cane under both field and lysimeter conditions. Juice quality evaluations generally showed higher values in the ratoon cane cycle. The exceptions were fiber content and juice purity, which were higher in plant cane under both field and lysimeter conditions.

Overall, agrometeorological variables were similar between the plant cane and ratoon cane cycles. The main differences were observed in the maximum daily rainfall intensity (plant cane: 82 mm day$^{-1}$; ratoon cane: 57 mm day$^{-1}$) and relative air humidity (plant cane: 45–78%; ratoon cane: 20–81%). In addition, lower average solar radiation values were recorded during Phase III of the ratoon cane cycle.

Under lysimeter conditions, plant cane required approximately 33% more water per day than ratoon cane, resulting in a 46% higher seasonal water demand ($ETc_L$). The ratio of soil evaporation ($Ev_{ML}$: microlysimetry) to crop evapotranspiration ($ETc_L$: lysimetry) was approximately 0.3 in both cycles.

Single crop coefficient values obtained by lysimetry were similar to FAO-56 tabulated values in the plant cane cycle but were lower in the ratoon cane cycle. In contrast, the dual crop coefficient values were similar in both cycles.

Using crop coefficients determined by lysimetry and the experimental dual coefficient increased irrigation depths compared to the FAO-56 tabulated coefficients for the plant cane cycle. However, using the estimated single and dual crop coefficients led to water savings. For the ratoon cane cycle, all crop coefficient methods resulted in reduced irrigation depths compared with FAO-56 tabulated Kc. Nevertheless, the single crop coefficients obtained through lysimetry (I: 0.35; II: 0.73; III: 1.10; IV: 0.65; final: 0.21) resulted in the highest water savings.

The dual crop coefficient approach provides a more accurate representation of daily evapotranspiration by explicitly accounting for crop transpiration and soil evaporation, thereby improving irrigation scheduling under frequent irrigation and partial canopy cover conditions typical of the Brazilian savanna. However, despite its agreement with measured evapotranspiration, higher operational complexity and data requirements may restrict its use in routine irrigation management on a large scale. Under the evaluated conditions, the locally calibrated single crop coefficient offers a practical alternative with lower data requirements, supporting irrigation management and helping mitigate water deficit risks in commercial sugarcane systems.

For future research, evaluating additional sugarcane varieties and conducting experiments at multiple locations with contrasting soil types and across multiple crop cycles is recommended to assess the influence of broader edaphoclimatic conditions on the analyzed variables and the proposed coefficients.

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## Declarations

**Conflict of interest** The authors declare no competing interests.



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