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Original Article

# Irrigation strategies for giant umbu cultivation in the Brazilian semiarid region[1]

## Estratégias de irrigação no cultivo do umbu gigante no semiárido brasileiro

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*HIGHLIGHTS:*

*Applying 25% of reference evapotranspiration after full flowering stabilizes and increases both fruit and water productivity.*
*This strategy also enhances fruit commercial classification.*
*Years of severe drought negatively impact average fruit mass.*

**ABSTRACT:** The umbu tree is traditionally cultivated under rainfed conditions, offering production reliability; however, irrigation can improve yield by reducing production alternation and maintaining the standard fruit size characteristic of the giant umbu cultivar. This study aimed to identify the most effective irrigation strategy to enhance yield and production stability of the umbu tree cultivar BRS-68 over three production cycles. The experiment was conducted at the Federal Institute of Education, Science and Technology Baiano, Guanambi campus, using a randomized block design in a split-plot scheme over time with five replicates. Four irrigation strategies were applied to the main plots: E1 - rainfed; E2 - irrigation replacing 25% of reference evapotranspiration (ETo) applied until full flowering (ATF, 25% ETo); E3 - irrigation replacing 25% of ETo from full flowering to fruit harvest (AFC, 25% ETo); and E4 - irrigation replacing 50% of ETo from full flowering to harvest (AFC, 50% ETo). Three production cycles were considered as subplots: CI (2021-2022), CII (2022-2023), and CIII (2023-2024). Under rainfed conditions, fruit yield varied across cycles, while irrigation led to stabilization. Strategy E3 (AFC, 25% ETo) produced the highest fruit yield and water productivity, and the lowest water footprint, on average across the three cycles. Fruit mass was lowest during the driest cycle (2023-2024). The E3 strategy proved most effective in increasing yield, improving water productivity, reducing water footprint, minimizing production alternation, and producing fruits with superior commercial grading. It is therefore a viable option for integration into giant umbu production systems in the semiarid region.

**Key words:** *Spondias tuberosa*, Caatinga, evapotranspiration, water footprint, productivity

**RESUMO:** O umbuzeiro é cultivado sob sequeiro com segurança produtiva. Contudo, a irrigação pode aumentar a produtividade, reduzir a alternância de produção intrínseca da espécie e manter a massa média padrão de umbus gigantes. Objetivou-se definir a melhor estratégia de irrigação para aumentar a produtividade e estabilidade de produção do umbuzeiro cultivar BRS-68, durante três ciclos de produção. Conduziu-se experimento no Instituto Federal Baiano, Campus Guanambi, em esquema de parcelas subdivididas no tempo, no delineamento em blocos casualizados, com cinco repetições, quatro estratégias de irrigação dispostas nas parcelas - E1, sequeiro; E2, irrigação com 25% da evapotranspiração de referência (ETo) aplicada até a floração plena - ATF (25% ETo); E3, irrigação com 25% da ETo aplicada da floração plena até a colheita dos frutos - AFC (25% ETo); E4, irrigação com 50% da ETo da floração plena até a colheita - AFC (50% ETo); e, três ciclos de produção alocados nas subparcelas - CI, 2021-2022; CII, 2022-2023; e, CIII, 2023-2024. A produtividade de frutos alternou com ciclos sob sequeiro e estabilizou-se sob irrigação. As maiores produtividades de frutos, da água e menor pegada hídrica considerando a média dos três ciclos foram obtidas com E3, AFC (25% ETo). A massa do fruto foi menor no ciclo 2023-2024, mais seco. A estratégia de irrigação E3, AFC (25% ETo) assegura maior produtividade de frutos e da água, diminui a pegada hídrica, reduz a alternância de produção e possibilita obtenção de frutos com melhor classificação comercial, portanto, pode ser incorporada ao sistema de produção de umbu gigante.

**Palavras-chave:** *Spondias tuberosa*, Caatinga, evapotranspiração, pegada hídrica, produtividade

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## Introduction

The umbu tree (*Spondias tuberosa* Arruda Câmara), a member of the Anacardiaceae family, is native to Brazil's semiarid region (Mertens et al., 2017). This species holds significant social, ecological, cultural, and economic importance for the region, underscoring the need for research to support both its conservation and the expansion of commercial plantations to meet growing market demands for fresh and processed products.

Although scientific advancements have been made in areas such as plant propagation (Matos et al., 2020; Pires et al., 2020; Mendes & Souza, 2020; Neves et al., 2021; Neves et al., 2022), agronomic management (Santos et al., 2020; Donato et al., 2025), and fruit characterization and processing (Pereira et al., 2021; Santos et al., 2021; Calales et al., 2022; Saraiva et al., 2022; Donato et al., 2024), studies focusing on irrigation and the umbu tree's response to water availability during different developmental stages remain limited. As a result, there is insufficient data to establish effective irrigation scheduling guidelines.

Water scarcity is a major constraint on agricultural productivity in Brazil's semiarid regions, significantly impacting farmers' incomes (Souza et al., 2013). Although the umbu tree demonstrates notable drought-tolerance mechanisms - such as leaf abscission, xylopodia (i.e., specialized root structures for water and mineral storage) (Mitchell & Daly, 2015), and efficient transpiration control (Lima Filho & Aidar, 2016) - inadequate water supply can still negatively affect yields. This is especially relevant for commercial orchards, where fruit size, particularly of large or giant varieties, plays a key role in market value.

Numerous studies have shown that supplemental irrigation can improve yields across a range of crops (Cavalcanti et al., 2011; Simões et al., 2021). Moreover, irrigation can be managed to supply limited but strategically timed amounts of water - such as in regulated deficit irrigation (RDI) - to enhance crop profitability (Sampaio et al., 2010; Santos et al., 2014; Coelho et al., 2021).

Cavalcanti et al. (2011) demonstrated that supplemental irrigation significantly boosts umbu fruit production. However, there is a lack of research addressing key aspects such as extending the harvest period, reducing yield fluctuations, mitigating the impact of irregular rainfall, and increasing fruit mass during drought episodes. Consequently, informed irrigation practices in umbu orchards must consider the influence of soil water dynamics on yield, fresh and dry biomass of peel, pulp, and seeds, water productivity, and water footprint.

Although the umbu tree thrives under rainfed conditions due to its resilience, irrigation can enhance the production of premium giant fruits in high-value cultivars (Donato et al., 2024). These fruit types are especially attractive to the fresh fruit market. Therefore, commercial cultivation of such cultivars is recommended (Silva et al., 2024), particularly when compared to smaller-fruited varieties (Pereira et al., 2021). Nevertheless, long-term studies are required to test the hypotheses that irrigation can increase yield, maintain fruit mass, and reduce alternate bearing in giant umbu cultivars. Furthermore, irrigation becomes increasingly critical in the context of climate variability and intensifying drought conditions (Giorgi, 2019).

This study aims to identify the most effective irrigation strategies for enhancing fruit yield and stabilizing production of the umbu tree cultivar BRS-68 over three production cycles.

## Material and Methods

The study was conducted at the umbu tree genotype collection of the Federal Institute of Education, Science and Technology Baiano, Guanambi campus, located in the Ceraíma district of Guanambi, Brazil (14º 17' 38" S, 42º 41' 35" W; 545 m above sea level), from July 2021 to January 2024. The local climate is semiarid, with a well-defined dry season in winter and a rainy season from October to March. Based on data from the past 43 years, the region's average annual precipitation is 673.6 mm, and the average annual temperature is 26.1 ºC. Figure 1 presents the recorded variations in maximum and minimum temperatures, relative air humidity, reference evapotranspiration, and precipitation throughout the experimental period (July 7, 2021, to January 24, 2024). Total annual precipitation during this period was 542.49 mm in 2021 (from July 14 to December 31), 694.96 mm in 2022 (January 1 to December 31), 379.22 mm in 2023 (January 1 to December 31), and 193.64 mm in 2024 (January 1 to January 24).

The soil in the experimental area is classified as a Red-Yellow Latosol (Santos et al., 2025), corresponding to an Oxisol (Soil Survey Staff, 2022), with a medium texture. Its chemical attributes, assessed both before the start of the experiment and after three evaluation cycles, indicate high to very high fertility levels for Ca, Mg, P, and K (Table 1).

The study used the umbu tree cultivar BRS-68 (Santos et al., 2021), registered by Embrapa (EMBRAPA, 2019) and previously referred to as BGU68 (Santos et al., 1999) or EPAMIG-01 (Donato et al., 2022a, b). This cultivar has the potential to produce fruits classified as giant (≥ 75 g) (Donato et al., 2024). The orchard was established in 2007, with BRS-68 grafted onto umbu-cajazeira rootstock, in a quincunx planting arrangement with 8 × 8 × 8 × 8 m spacing. At the time of the evaluations across three harvests or production cycles, the orchard was 14, 15, and 16 years old, respectively. Cultural practices followed the management recommendations of Donato et al. (2019). As a native Brazilian species, the activity is registered in the Brazilian National System for the Management of Genetic Heritage and Associated Traditional Knowledge (SISGEN for short, in Portuguese) system under registry code AECB49B.

The experiment was conducted by using a split-plot scheme arranged in a randomized block design with five replicates, with each experimental unit consisting of one plant. Four irrigation strategies were assigned to the main plots: E1: rainfed (no irrigation); E2: ATF (25% ETo) - irrigation replacing 25% of reference evapotranspiration (ETo) during the vegetative dormancy period, up to full flowering; E3: AFC (25% ETo) - irrigation replacing 25% of ETo from full flowering until fruit harvest; and E4: AFC (50% ETo) - irrigation replacing 50% of

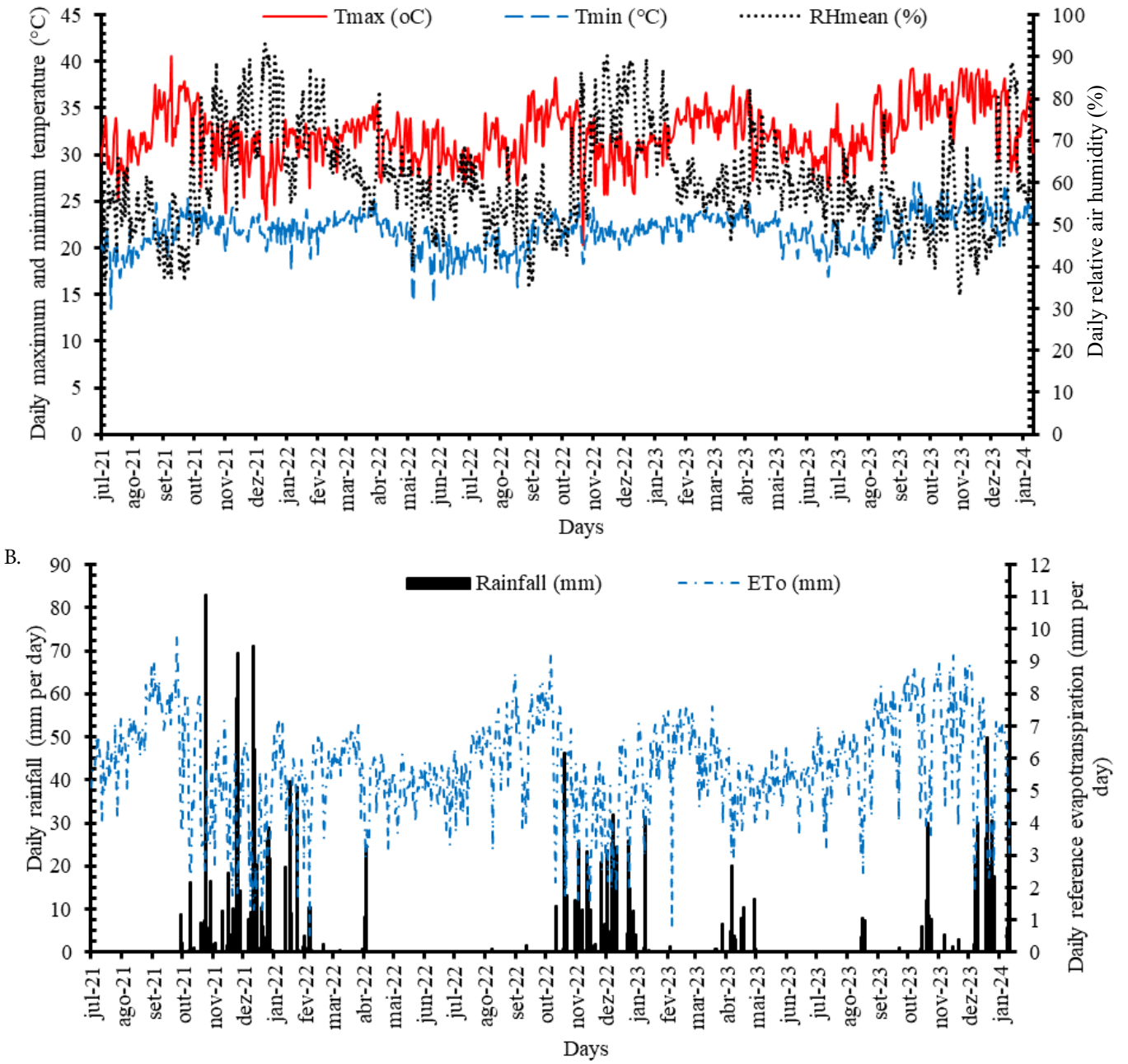



**Figure 1.** Daily meteorological data recorded during the experimental period in Guanambi, Bahia state, Brazil, from July 14, 2021, to January 24, 2024. (A) Maximum ($T_{max}$) and minimum ($T_{min}$) air temperatures and mean relative air humidity ($RH_{mean}$). (B) Daily rainfall and reference evapotranspiration (ETo)

**Table 1.** Chemical and textural attributes of the soil cultivated with the umbu tree cultivar BRS-68, based on samples collected from the 0-0.20 m soil layer before the implementation of the experiment (BEI) and after three evaluation cycles (AEC)

| Time | pH[1] | OM[2] | P[3] | K[3] | Na[3] | Ca[4] | Mg[4] | Al[4] | H+Al[5] | SB | CEC | V | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (g dm$^{-3}$) | (mg dm$^{-3}$) | | | (cmol$_c$ dm$^{-3}$) | | | | | | (%) | |
| BEI | 7.2 | 17.0 | 49.0 | 415.7 | 0.1 | 3.3 | 1.2 | 0 | 1.3 | 5.6 | 6.9 | 81.7 | 0 |
| AEC | 6.7 | 17.5 | 54.2 | 272.2 | 0.1 | 3.2 | 1.2 | 0 | 1.3 | 5.3 | 6.6 | 79.8 | 0 |

| | B[6] | Cu[3] | Fe[3] | Mn[3] | Zn[3] | Prem[7] | EC | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|---|
| | (mg dm$^{-3}$) | | | | | (mg L$^{-1}$) | (dS m$^{-1}$) | (g dm$^{-3}$) | | |
| BEI | 0.4 | 0.6 | 31.8 | 57.8 | 83.1 | 40.7 | 0.5 | 660 | 120 | 220 |
| AEC | 0.3 | 0.8 | 41.5 | 44.9 | 4.1 | 40.7 | 0.3 | - | - | - |

[1]pH in water; [2]Colorimetry; [3]Extractant - Mehlich-1; [4]Extractant: KCl 1 mol L$^{-1}$; [5]pH SMP; [6]Extractant - $CaCl_2$; [7]Extractant - $Ca(H_2PO_4)_2$, 500 mg L$^{-1}$ of P in HOAc 2 mol L$^{-1}$; equilibrium P solution; SB - Sum of bases; t - Effective CEC = SB; CEC - Cation exchange capacity at pH 7; V - Base saturation; m - Aluminum saturation; P-rem - Remaining phosphorus; EC - Electrical conductivity

ETo from full flowering to harvest. The subplots consisted of three production cycles: CI: 2021-2022; CII: 2022-2023; and CIII: 2023-2024.

Strategy E2: ATF (25% ETo) was applied during vegetative dormancy, defined as the 30 days preceding full flowering, corresponding on average to the phenological period between

July and August. Strategies E3: AFC (25% ETo) and E4: AFC (50% ETo) were implemented from full flowering to the harvest of physiologically mature fruits, which on average corresponded to the phenological period between September and February of the following year. Full flowering was defined as the stage in which at least 50% of the plant canopy exhibited visible flowers.

Plants were irrigated by using a micro-sprinkler system with one emitter per plant, a flow rate of 103 L $h^{-1}$, and an operating pressure of 200 kPa. Water volume varied according to irrigation time. The water used for irrigation came from the Ceraíma Dam, a reservoir that supplies freshwater to the Ceraíma Irrigated Perimeter. The water was classified as C1S1 - low salinity and low sodium concentration - according to the classification by Ayers & WestCot (Bernardo et al., 2019) (Table 2).

For irrigation management, daily ETo data were obtained from an automatic weather station located 100 m from the experimental area (Figure 1B). ETo was estimated using the standard FAO Penman-Monteith method. The daily ETo values were integrated on a weekly basis and multiplied by either 0.25 or 0.50, depending on the supplemental irrigation strategy applied. To calculate the irrigation water depth, an application efficiency of 85% and a location coefficient (Kl) of 0.785 were used, determined according to Eq. 1, since the area wetted by the micro-sprinkler was greater than the shaded area (Bernardo et al., 2019):

$$Kl = 0.0109P + 0.30 \text{ for } 20\% < P < 65\% \quad (1)$$

where:

Kl - location coefficient (dimensionless);

P - percentage of wetted or shaded area (%).

Irrigation time was calculated using Eq. 2 (adapted from Santos et al., 2014):

$$Ti = \frac{\sum ETo \times Rp \times Ap}{Ne \times q \times Ea} \quad (2)$$

where:

Ti - irrigation time (hours);

ETo - reference evapotranspiration (mm per day);

**Table 2.** Chemical attributes and classification of the water from the Ceraíma Dam used for irrigating 'BRS-68' umbu trees in the experiment. Guanambi, Bahia state, Brazil, 2024

| Attributes | Value |
|---|---|
| pH (dimensionless) | 7.3 |
| CE (dS $m^{-1}$ at 25 °C) | 0.161 |
| Ca (mg $L^{-1}$) | 23.87 |
| Mg (mg $L^{-1}$) | 10.34 |
| K (mg $L^{-1}$) | 14.08 |
| Na (mg $L^{-1}$) | 20.92 |
| Carbonate (mg $L^{-1}$) | 0.00 |
| Bicarbonate (mg $L^{-1}$) | 134.22 |
| Chloride (mg $L^{-1}$) | 141.72 |
| SAR ($(mmol_c\ L^{-1})^{1/2}$) | 0.91 |
| SARco ($(mmol_c\ L^{-1})^{1/2}$) | 0.56 |
| Classification | C1S1 (low salinization risk)* |

*SAR - Sodium adsorption ratio; $SAR_{co}$ - Corrected sodium adsorption ratio. The C1S1 classification, based on the U.S. Salinity Laboratory Staff criteria, indicates low salinity (C1), as the electrical conductivity of 0.161 dS $m^{-1}$ falls within the 0-0.250 dS $m^{-1}$ range, and low sodium hazard (S1), as the SAR value of ≈0.91 falls within the 0-10 range

Rp - ETo replacement ratio, according to treatment (decimal);

Ap - area occupied by each plant ($m^2$), calculated as the theoretical area of an equilateral triangle with 8 × 8 × 8 m spacing; Ap = 55.4 $m^2$;

Ne - number of emitters per plant (Ne = 1);

q - emitter flow rate (L $h^{-1}$), q = 103 L $h^{-1}$; and,

Ea - application efficiency (decimal), Ea = 0.85.

Irrigation was applied weekly based on the accumulated evapotranspiration over the period and considering the application efficiency.

For the E2 (ATF - 25% ETo) strategy, irrigation was applied from 07/14/2021 to 09/02/2021 in the first cycle, from 06/28/2022 to 09/01/2022 in the second cycle, and from 06/28/2023 to 09/06/2023 in the third cycle. In strategies E3 (AFC - 25% ETo) and E4 (AFC - 50% ETo), irrigation was applied from 09/09/2021 to 02/03/2022 in the first cycle, from 09/15/2022 to 01/18/2023 in the second cycle, and from 09/06/2023 to 01/24/2024 in the third cycle.

In the event of rainfall during irrigation periods, the precipitation amount was subtracted from the reference evapotranspiration to adjust the irrigation time accordingly. Based on the data in Figure 1, the total annual precipitation recorded during the experimental period (07/14/2021 to 01/24/2024) - corresponding to the duration of irrigation strategy implementation - was 542.49 mm in 2021, 694.96 mm in 2022, 379.22 mm in 2023, and 193.64 mm in 2024. When considering the total rainfall during the specific periods in which irrigation strategies were applied, the values were 784.57 mm in Cycle I (07/14/2021 to 03/02/2022), 483.12 mm in Cycle II (06/28/2022 to 01/18/2023), and 397.33 mm in Cycle III (06/28/2023 to 01/24/2024). Variations in the end dates of irrigation applications were due to differences in harvest duration. These data resulted in the total water volumes (rainfall and rainfall plus irrigation) applied to the plants, as shown in Table 3, corresponding to the respective periods in which each irrigation strategy was implemented.

Soil water content was monitored during the first two evaluation cycles, while fruit mass, dry matter content, fruit yield, water productivity, and water footprint were assessed across all three evaluation cycles.

The gravimetric method was used to monitor soil moisture. Soil samples were collected weekly, 24 hours before and 24 hours after irrigation, for each irrigation strategy during the first and second evaluation cycles. Samples were taken at a distance of 1 m from the micro-sprinkler and the plant trunk, at depths of 0-0.20, 0.20-0.40, and 0.40-0.60 m, using three plants representative of each irrigation strategy (E1, E2, E3, and E4). For strategy E1 (rainfed), moisture was monitored in the 0-0.20 m and 0.20-0.40 m layers during the first evaluation cycle. Three composite samples, each composed of three subsamples per depth per strategy, were stored in sealed, waterproof plastic bags and transported to the laboratory. There, the wet mass and dry mass were determined after oven-drying the samples at 105 °C for 24 hours, until reaching a constant weight. Gravimetric water content was calculated using Eq. 3:

**Table 3.** Applied irrigation depths (Irr.), recorded precipitation (Prec.) and accumulated depths (Accum. = Prec. + Irr.), in mm, in the three evaluation cycles during the period of application of the irrigation strategies

| Irrigation strategies | Cycles | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | I (07/14/2021 to 03/02/2022) | | | II (06/28/2022 to 01/18/2023) | | | III (06/28/2023 to 01/24/2024) | | |
| | Irr. | Prec. | Accum. | Irr. | Prec. | Accum. | Irr. | Prec. | Accum. |
| E1, rainfed | 0.00 | 784.5 | 784.5 | 0.00 | 483.1 | 483.1 | 0.00 | 397.3 | 397.3 |
| E2, ATF (25% ETo) | 179.6 | 784.5 | 964.1 | 186.6 | 483.1 | 669.7 | 195.9 | 397.3 | 593.2 |
| E3, AFC (25% ETo) | 188.4 | 784.5 | 972.9 | 138.8 | 483.1 | 621.9 | 217.9 | 397.3 | 615.2 |
| E4, AFC (50% ETo) | 376.8 | 784.5 | 1,161.3 | 277.6 | 483.1 | 760.7 | 435.9 | 397.3 | 833.2 |

Irrigation strategies: E1 - Rainfed; E2 - ATF (25% ETo); E2 - Irrigation replacing 25% of the reference evapotranspiration (ETo) with application starting 30 days before the beginning of flowering in the region until full flowering ; E3 - AFC (25%ETo): Irrigation replacing 25% of ETo from full flowering until fruit harvest; E4 - AFC (50%ETo): Irrigation replacing 50% of ETo from full flowering until fruit harvest; evaluation cycles: I (07/14/2021 to 03/02/2022), II (06/28/2022 to 01/18/2023), III (06/28/2023 to 01/24/2024); Periods of application of irrigation strategies in the cycles: Cycle I - E2 (07/14/2021 to 09/02/2021), E3 and E4 (09/09/2021 to 03/02/2022); Cycle II - E2 (06/28/2022 to 09/01/2022), E3 and E4 (09/15/2022 to 01/18/2023); Cycle III - E2 (06/28/2023 to 09/06/2023), E3 and E4 (09/06/2023 to 01/24/2024)

$$CWC = \frac{(a - b)}{b} \quad (3)$$

where:

CWC - gravimetric water content (kg kg$^{-1}$);
a - mass of the wet sample (kg); and,
b - mass of the dry sample at 105 °C (kg).

Soil bulk density for each depth was determined using undisturbed samples collected with a Uhland-type extractor. Each sample had a known cylinder volume, and the dry mass was used in Eq. 4:

$$Ds = \frac{a}{b} \quad (4)$$

where:

Ds - soil bulk density (kg dm$^{-3}$);
a - mass of the dry sample at 105 °C (kg); and,
b - volume of the cylinder (m$^3$).

The bulk density values for the 0-0.20 m, 0.20-0.40 m, and 0.40-0.60 m layers were 1.65, 1.68, and 1.67 kg dm$^{-3}$, respectively. The soil water contents retained at 10 and 1,500 kPa were 0.253 and 0.125 m$^3$ m$^{-3}$, respectively, resulting in a total water-holding capacity (TWC) of 76.8 mm for the umbu tree's effective rooting depth of 0.60 m. This TWC value was used for irrigation scheduling purposes.

Using the gravimetric moisture and soil density values determined for each depth, soil moisture was converted to a volumetric basis using Eq. 5 and presented graphically.

$$VWC = GWC \times Ds \quad (5)$$

where:

VWC - volumetric water content (m$^3$ m$^{-3}$);
GWC - gravimetric water content (kg kg$^{-1}$); and,
Ds - soil bulk density (kg dm$^{-3}$).

Water density was assumed to be 1.0 kg dm$^{-3}$.

Crop's nutritional management followed the recommendations of Donato et al. (2022b). Organic fertilization was carried out during the dry season, when plants were in the vegetative dormancy stage, to ensure greater operational efficiency. Complementary chemical fertilization was applied during the rainy season, during the growth and fruit-filling stages.

The following variables were evaluated: fresh mass of seed (FMS), peel (FMPL), pulp (FMPP), and fruit (FMF); dry mass of seed (DMS), peel (DMPL), pulp (DMPP), and fruit (DMF), expressed in grams; and dry matter content of seed (DMCS), peel (DMCPL), pulp (DMCPP), and fruit (DMCF), expressed as percentages. For this purpose, 30 representative fruits were collected at the physiological maturity stage - known as the "swollen" stage - indicating commercial ripeness or near ripeness (Saraiva et al., 2022), characterized by green peel and initial softening of the pulp, as used by Deus et al. (2025). Each fruit was weighed to determine its individual fresh mass, then pulped to separate the seed, peel, and pulp. Each part was weighed and then dried in an oven at 65 °C until constant weight was achieved, after which dry mass and dry matter content were calculated for each component and the whole fruit.

The total number of fruits (NF) harvested per plant was counted. Fresh matter yield (FMY) and dry matter yield (DMY), expressed in kg per plant, were estimated based on NF, the average fresh fruit mass, and fruit dry matter content.

Water productivity (rainwater + irrigation water), expressed in kg ha$^{-1}$ mm$^{-1}$, was estimated based on fresh matter (WPFM) and dry matter (WPDM), using the ratio between fruit yield and the total gross water depth applied (Table 3) for each irrigation strategy (Fernández et al., 2020).

In addition, the total water footprint (WF) - defined as the sum of the green water footprint ($WF_{green}$) and blue water footprint ($WF_{blue}$) - was calculated based on rainfall during the experimental period ($WF_{green}$) and irrigation volumes ($WF_{blue}$). Results were expressed in liters of water required to produce 1 kg of fruit, i.e., the ratio between water volume (L ha$^{-1}$) and yield (kg per plant).

Irrigation water productivity (WPi) and irrigation water footprint (WFi) - equivalent to the blue water footprint - were also calculated based on both fresh matter (FM) and dry matter (DM) for the three irrigation strategies that involved water application.

Data were subjected to the Lilliefors test for normality. When a normal distribution was confirmed, analysis of variance (ANOVA) was conducted (F test, $p \leq 0.05$). In cases of significant interactions between factors, the factors were further decomposed, and means were compared using the Tukey test ($p \leq 0.05$). For independent effects of irrigation strategies and evaluation cycles, means were also compared using the Tukey test ($p \leq 0.05$). All analyses were performed using SAEG software, version 9.0. Descriptive statistics

(percentages) were also used for irrigation water productivity and blue water footprint data.

## Results and Discussion

The interaction between irrigation strategies and evaluation cycles significantly affected DMCF, DMCPL, NF, FMY, DMY, WPDM, WPFM, FMS, DMPL, and both WFFM and WFDM in the umbu tree cultivar BRS-68 ($p \leq 0.05$) (Table 4).

Fresh masses of fruits (FMF), peel (FMPL), and pulp (FMPP), as well as dry masses of fruits (DMF) and pulp (DMPP), varied independently of the factors studied. DMS varied only across evaluation cycles. DMCPP varied with irrigation strategies, while DMCS was not influenced by any of the studied factors ($p \leq 0.01$).

There were interactions between irrigation strategies and evaluation cycles in the expression of 57.89% of the evaluated traits in the umbu tree cultivar BRS-68. However, when considering the isolated effect of irrigation strategies, they accounted for 89.47% of the cases that demonstrated an irrigation effect on trait expression, with the exception of DMS and DMCS.

The effects of irrigation - particularly on fruit production and water productivity - suggest that, when properly managed, water supply can serve as an effective strategy to mitigate abiotic stress, especially during more severe droughts, such as in the 2023-2024 harvest (cycle III). In 2023, an El Niño event coincided with a delayed onset of the rainy season and low rainfall - phenomena expected to increase in frequency and intensity due to climate variability (Giorgi, 2019). Thus, well-planned water management contributes to minimizing water deficits, the greatest limitation to plant productivity in semiarid regions, and to boosting fruit production (Cavalcanti et al., 2011).

The evaluation cycle, whether analyzed in interaction or isolation, also influenced 89.47% of the traits expressed by the cultivar BRS-68, with the exception of DMCPP and DMCS. This suggests that climate variability and depletion of water reserves in years of high productivity contribute to production alternation - an inherent feature of perennial species such as the umbu tree. However, practices such as irrigation and fertilization may help reduce this effect (Donato et al., 2022b; Donato & Neves, 2023).

For E1 (rainfed), all 11 evaluated traits varied across production cycles. In E2 (ATF - 25% ETo), where 25% of ETo was replaced until full flowering, DMPL, DMCF, DMCPL, WPFM, and WFDM varied across cycles. In E3 (AFC - 25% ETo), with irrigation from full flowering to harvest, FMS, DMPL, and NF were affected. In E4 (AFC - 50% ETo), where 50% of ETo was applied from full flowering to harvest, FMS, DMPL, and DMCPL varied (Table 5). These results indicate that E3 and E4, which include irrigation during the critical flowering-to-harvest window, help stabilize trait expression and reduce production alternation-particularly in FMY and DMY-confirming the findings reported by Donato & Neves (2023).

**Table 4.** Analysis of variance of fruit fresh mass (FMF), fruit dry mass (DMF), seed fresh mass (FMS), seed dry mass (DMS), peel fresh mass (FMPL), peel dry mass (DMPL), pulp fresh mass (FMPP), and pulp dry mass (DMPP); fruit dry matter content (DMCF), seed dry matter content (DMCS), peel dry matter content (DMCPL), and pulp dry matter content (DMCPP); number of fruits (NF); fresh fruit yield (FFY) and dry mass yield (DMY); water productivity in fresh matter (WPFM), water productivity in dry matter (WPDM); green plus blue water footprint in fresh matter (WFFM) and green plus blue water footprint in dry matter (WFDM), evaluated in the umbu tree cultivar BRS-68 as a function of the factors irrigation strategies (EIR) and evaluation cycles

| SV | DF | Mean square | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | FMF | FMS | FMPL | FMPP | DMF | DMS | DMPL |
| Blocks | 4 | 643.17$^{*}$ | 14.88$^{**}$ | 54.14$^{**}$ | 356.77$^{**}$ | 21.68$^{**}$ | 2.16$^{**}$ | 3.66$^{**}$ |
| EIR | 3 | 850.48$^{*}$ | 4.61$^{ns}$ | 46.51$^{*}$ | 388.61$^{*}$ | 13.17$^{*}$ | 0.33$^{ns}$ | 1.28$^{ns}$ |
| Error A | 12 | 204.65 | 2.84 | 11.23 | 89.41 | 3.64 | 0.48 | 0.45 |
| CYCLE | 2 | 3655.3$^{**}$ | 60.28$^{**}$ | 814.27$^{**}$ | 1175.23$^{**}$ | 138.52$^{**}$ | 7.55$^{**}$ | 47.23$^{**}$ |
| EIR×CYCLE | 6 | 180.76$^{ns}$ | 8.93$^{*}$ | 13.80$^{ns}$ | 59.55$^{ns}$ | 3.79$^{ns}$ | 0.88$^{ns}$ | 1.62$^{*}$ |
| Error B | 32 | 133.16 | 3.01 | 12.21 | 49.63 | 4.69 | 0.40 | 0.61 |
| Total | 59 | - | - | - | - | - | - | - |
| CV (%) | | 15.52 | 16.24 | 14.86 | 17.74 | 17.78 | 15.77 | 20.44 |
| | | DMPP | DMCF | DMCS | DMCPL | DMCPP | NF | FMY |
| Blocks | 4 | 4.92$^{**}$ | 10.07$^{**}$ | 121.22$^{**}$ | 21.35$^{**}$ | 13.16$^{**}$ | 279820.4$^{ns}$ | 1334.00$^{ns}$ |
| EIR | 3 | 4.18$^{**}$ | 10.76$^{**}$ | 26.95$^{ns}$ | 7.62$^{**}$ | 6.22$^{**}$ | 928095.4$^{**}$ | 5183.94$^{**}$ |
| Error A | 12 | 0.69 | 1.52 | 24.94 | 0.93 | 0.79 | 163989.7 | 917.235 |
| CYCLE | 2 | 9.60$^{**}$ | 47.59$^{**}$ | 39.82$^{ns}$ | 109.88$^{**}$ | 5.79$^{ns}$ | 94370.10$^{**}$ | 1430.14$^{**}$ |
| EIR×CYCLE | 6 | 0.64$^{ns}$ | 4.88$^{**}$ | 21.41$^{ns}$ | 21.13$^{**}$ | 2.96$^{ns}$ | 131480.8$^{**}$ | 1242.72$^{**}$ |
| Error B | 32 | 0.83 | 1.22 | 22.09 | 3.18 | 2.01 | 11356.09 | 192.899 |
| Total | 59 | - | - | - | - | - | - | - |
| CV (%) | | 21.16 | 6.68 | 12.21 | 11.23 | 12.94 | 22.28 | 38.74 |
| | | DMY | WPFM | WPDM | WFFM | WFDM | - | - |
| Blocks | 4 | 42.05$^{ns}$ | 138.3517$^{ns}$ | 4.4962$^{ns}$ | 9695762$^{ns}$ | 0.4545×10$^{9ns}$ | - | - |
| EIR | 3 | 124.21$^{**}$ | 523.9502$^{**}$ | 14.8713$^{**}$ | 0.3252×10$^{8**}$ | 0.1080×10$^{10**}$ | - | - |
| Error A | 12 | 25.60 | 101.9975 | 3.0278 | 5547659 | 0.2397×10$^{9}$ | - | - |
| CYCLE | 2 | 66.48$^{**}$ | 324.6654$^{**}$ | 13.0741$^{**}$ | 0.2386×10$^{8**}$ | 0.1055×10$^{10**}$ | - | - |
| EIR×CYCLE | 6 | 45.62$^{**}$ | 163.9418$^{**}$ | 6.2039$^{**}$ | 0.1201×10$^{8**}$ | 0.4029×10$^{9**}$ | - | - |
| Error B | 32 | 6.69 | 23.0138 | 0.8384 | 1524068 | 0.7013×108 | - | - |
| Total | 59 | - | - | - | - | - | - | - |
| CV (%) | | 44.06 | 49.42 | 56.55 | 50.52 | 55.62 | - | - |

SV - Sources of variation; DF - Degrees of freedom; CV - Coefficient of variation; $^{ns}$ - Not significant, * - Significant at $p \leq 0.05$, ** - Significant at $p \leq 0.01$ by F test

**Table 5.** Means of seed fresh mass (FMS), peel dry mass (DMPL), fruit dry matter content (DMCF), peel dry matter content (DMCPL), number of fruits (NF), fresh fruit yield (FFY), dry mass yield (DMY), water productivity in fresh matter (WPFM), water productivity in dry matter (WPDM), green plus blue water footprint in fresh matter (WFFM), and green plus blue water footprint in dry matter (WFDM), evaluated in the umbu tree cultivar BRS-68 as a function of the interaction between irrigation strategies and evaluation cycles

| Variables | Evaluation cycles | Irrigation strategies | | | |
|---|---|---|---|---|---|
| | | E1, rainfed | E2, ATF (25% Eto) | E3, AFC (25% Eto) | E4, AFC (50% Eto) |
| FMS (g) | I | 10.15 aA | 10.46 aA | 10.57 aB | 9.97 aA |
| | II | 12.40 abA | 12.33 abA | 14.47 aA | 11.10 bA |
| | III | 7.24 bB | 9.85 abA | 8.70 abB | 10.90 aA |
| DMPL (g) | I | 3.02 aB | 3.66 aB | 3.46 abAA | 3.16 aB |
| | II | 5.19 abA | 6.27 aA | 4.62 bA | 6.07 aA |
| | III | 2.09 aB | 2.29 aC | 3.14 aB | 2.83 aB |
| DMCF (%) | I | 15.07 aB | 14.79 aB | 14.75 aA | 14.92 aB |
| | II | 18.71 aA | 19.27 aA | 15.09 bA | 18.59 aA |
| | III | 16.70 aB | 17.79 aA | 16,16 aA | 16.92 aA |
| DMCPL (%) | I | 14.10 aB | 14.69 aB | 14.01 aA | 14.27 aB |
| | II | 19.39 aA | 20.84 aA | 14.23 bA | 19.80 aA |
| | III | 14.31 aB | 14.16 aB | 16.41 aA | 14.29 aB |
| NF (unit) | I | 362.00 bB | 218.50 bA | 712.49 aAB | 358.00 bA |
| | II | 1,033.50 aA | 188.00 dA | 592.00 bB | 385.50 cA |
| | III | 468.00 bB | 85.50 cA | 870.00 aA | 466.00 bA |
| FMY (kg per plant) | I | 27.74 bB | 18.47 bA | 60.36 aA | 28.54 bA |
| | II | 77.51 aA | 15.31 cA | 55.04 abA | 32.72 bcA |
| | III | 20.52 bcB | 4.55 cA | 55.77 aA | 33.62 abA |
| DMY (kg per plant) | I | 4.22 bB | 2.69 bA | 8.86 aA | 4.23 bA |
| | II | 14.58 aA | 2.93 cA | 8.32 bA | 6.02 bcA |
| | III | 3.50 bcB | 0.81 cA | 8.94 aA | 5.30 abA |
| WPFM (kg $ha^{-1}$ $mm^{-1}$) | I | 6.36 aB | 3,451 aA | 11.16 aA | 4.42 aA |
| | II | 28.88 aA | 4.11 cA | 15.93 bA | 7.74 bcA |
| | III | 9.30 abB | 1.38 bA | 16.31 aA | 7.26 bA |
| WPDM (kg $ha^{-1}$ $mm^{-1}$) | I | 0.97 aB | 0.50 aA | 1.64 aA | 0.65 aA |
| | II | 5.43 aA | 0.79 cA | 2.41 bA | 1.42 bcA |
| | III | 1.59 abB | 0.25 bA | 2.61 aA | 1.14 abA |
| WFFM (L $kg^{-1}$) | I | 4,609.59 aA | 3,058.86 abB | 926.57 cA | 2,365.20 bcA |
| | II | 523.50 aB | 2,467.91 aB | 628.24 aA | 1,314.48 aA |
| | III | 3,425.94 bA | 7,382.63 aA | 1,090.91 cA | 1,528.54 bcA |
| WFDM (L $kg^{-1}$) | I | 30,734.40 aA | 20,582.09 abB | 6,253.58 bA | 15,852.63 bA |
| | II | 2,819.83 aB | 12,774.68 aB | 4,263.85 aA | 7,047.35 aA |
| | III | 21,783.40 bA | 41,940.92 aA | 6,683.19 cA | 9,942.69 bcA |

Irrigation strategies: E1 - Rainfed; E2 - ATF (25% ETo): Irrigation replacing 25% of the reference evapotranspiration (ETo) until full flowering; E3 - AFC (25%ETo): Irrigation replacing 25% of ETo from full flowering to fruit harvest; E4 - AFC (50%ETo): Irrigation replacing 50% of ETo from full flowering to fruit harvest; Evaluation cycles: I (07/14/2021 to 03/02/2022), II (06/28/2022 to 01/18/2023), III (06/28/2023 to 01/24/2024); Periods of application of irrigation strategies in the cycles: cycle I - E2 (07/14/2021 to 09/02/2021), E3 and E4 (09/09/2021 to 03/02/2022); cycle II - E2 (06/28/2022 to 09/01/2022), E3 and E4 (09/15/2022 to 01/18/2023); cycle III - E2 (06/28/2023 to 09/06/2023), E3 and E4 (09/06/2023 to 01/24/2024). Means followed by equal uppercase letters in the columns for evaluation cycles and equal lowercase letters in the rows for irrigation strategies do not differ statistically by the Tukey test at $p \leq 0.05$

The positive practical effect of irrigation (Table 5) lies primarily in stabilizing fruit yields. While the rainfed treatment (E1) showed large yield fluctuations across cycles, the irrigation strategies - particularly E3 (AFC, 25% ETo) and E4 (AFC, 50% ETo) - maintained statistically stable FMY throughout the three harvests. Among the strategies, E3 resulted in the highest average yield (57.06 kg per plant), significantly surpassing E2 (12.78 kg per plant) and E4 (31.63 kg per plant).

This benefit extends to the efficient use of water and its practical implications. E3 not only improved yield but also maximized WPFM and reduced WFFM, requiring fewer liters of water per kilogram of fruit produced. In practical terms, this means that even in years with limited or irregular rainfall, adopting E3 ensures higher and more stable production. This predictability helps mitigate the risks of production alternation and climate variability, thereby enhancing the orchard's profitability.

Under E1, BRS-68 showed higher values for FMS, DMPL, DMCF, DMCPL, NF, FMY, DMY, WPFM, and WPDM during cycle II, which had intermediate rainfall (483.12 mm, Table 3). However, WFFM and WFDM were lower in this cycle. Similarly, under E4, DMPL, DMCF, and DMCPL also peaked in cycle II. The highest values of fruit and water productivity, along with the lowest water footprint, were observed in cycle II under rainfed conditions compared to cycles I and III. This supports the understanding that umbu production is strongly influenced by environmental conditions (Santos et al., 1999), agronomic practices such as irrigation and fertilization (EMBRAPA, 2019), and the biennial bearing habit typical of woody perennials (Donato et al., 2022b; Donato & Neves, 2023).

Trait expression in BRS-68 varied across irrigation strategies and cycles. In cycle I, FMS was consistent across treatments, while DMPL, DMCF, and DMCPL showed similarity in cycles I and III. In cycle II, FMS was highest under E3 compared to E4, while in cycle III, FMS was higher under E4 than E1. E3 also resulted in lower DMPL in cycle II compared to E2 and E4, along with lower DMCF and DMCPL. Cycle II exhibited the

greatest variability among irrigation strategies for these traits. E3 produced lower values for DMCF (15.09%) and DMCPL (14.23%), which were similar to those reported by Donato et al. (2022b) for the same cultivar and location under dryland conditions (14.26 and 14.46%, respectively). Additionally, FMS (14.47 g) and DMPL (4.62 g) observed for E3 in cycle II exceeded the values reported by the same authors (5.78 and 2.35 g, respectively).

For yield-related variables-NF, FMY, and DMY-strategy E3 resulted in higher values during cycle I. In cycle II, the descending order for NF and FMY was E1 > E3 > E4 > E2. In cycle III, E3 yielded higher values than E1 and E2 for all three variables. Overall, when considering all evaluation cycles, the ranking for NF and FMY was E3 > E1 > E4 > E2. This indicates that E3 (AFC, 25% ETo) led to the highest yield, while E2 (ATF, 25% ETo) resulted in the lowest, suggesting that irrigation applied only until flowering is insufficient. Thus, irrigation using AFC (25% ETo) is recommended for productive management of the umbu cultivar BRS-68.

The highest values of FMY and NF under E3 were observed in cycles I (60.36 kg per plant and 712.49 fruits) and III (55.77 kg per plant and 870 fruits). Under E1, the highest values were recorded in cycle II (77.51 kg per plant and 1,033.50 fruits). The three-cycle averages for FMY and NF under E1 and E3 align with values previously reported for the same cultivar and location under rainfed conditions, grafted onto umbu rootstock. For example, in the 2021-2022 harvest, the reported yield was 50.57 kg per plant and 693 fruits, values that fall within the yield variation recorded across nine consecutive cycles for BRS-68. During that period, yields ranged from 36.51 to 252.60 kg per plant and from 409 to 3,344 fruits per plant (Donato & Neves, 2023).

Conversely, the values obtained under E2 and E4 fell below the lower limit of that historical range. The low yield observed with irrigation before flowering (E2 - ATF, 25% ETo) can be attributed to increased leaf production and vegetative growth, which alters source-sink dynamics to the detriment of flowering, ultimately reducing yield. Typically, the umbu tree blooms during the dry season, relying on carbohydrate reserves stored in its tuberous roots, and flowering precedes leaf emergence (Donato et al., 2019). For example, in mango trees - also members of the Anacardiaceae family - Figueirêdo et al. (2020) found that excessive water functions as a stress factor, leading to stomatal closure, likely due to oxygen deficiency. This process interferes with $CO_2$ assimilation and reduces photoassimilate production.

In the current study, irrigation from full flowering to harvest under E4 (AFC, 50% ETo) led to overirrigation. However, it did not cause saturation or oxygen deficiency. Instead, it promoted vegetative growth and altered source-sink balance, reducing fruit development and yield. Importantly, no losses from deep percolation or nutrient leaching were observed. Soil moisture levels recorded during the first and second evaluation cycles (discussed later in this section, Figure 2), particularly in the 0.40-0.60 m soil layer, remained within the soil's water-holding capacity.

Reducing production alternation while maintaining higher yields during years when rainfed trees in the region produce fewer fruits - which increases market prices - can enhance net profitability for producers (Donato & Neves, 2023).

The highest productivity with the lowest irrigation depth (AFC, 25% ETo) applied after flowering, as well as under rainfed conditions in cycle II, can be attributed to the species' inherent drought tolerance (Lima Filho & Aidar, 2016). Flowering can occur even in the absence of rain due to carbohydrate reserves stored in tubers and the species' natural production alternation. Furthermore, compared to other genotypes, the BRS-68 cultivar shows greater drought responsiveness, characterized by faster stomatal closure under water stress, rapid recovery of transpiration after rehydration, lower transpiration under optimal moisture conditions (Silva et al., 2009), and sustained positive net photosynthesis, instantaneous carboxylation efficiency, and water use efficiency even under increased vapor pressure deficit (Donato et al., 2022a).

This increase in yield under AFC (25% ETo) corroborates findings by Cavalcanti et al. (2011) and EMBRAPA (2019). Moreover, irrigation reduced production alternation across all irrigation strategies. Although yields did not exceed the highest value ever recorded under rainfed conditions for this cultivar (Donato & Neves, 2023), they were higher than those previously reported under irrigation (EMBRAPA, 2019). Yields in umbu trees are highly variable due to the species' biological traits (Donato & Neves, 2023), meteorological conditions during the cycle (Donato et al., 2019), and nutritional or other limiting factors (Santos et al., 2020). Since irrigation helps mitigate the negative effects of climate-related stress - especially water shortages during fruit development - it is a recommended strategy for improving production stability in giant umbu orchards.

Green + blue water productivity (WP), based on both fresh and dry matter, was similar across evaluation cycles for the three irrigation strategies. However, under rainfed conditions (E1), WP was highest in cycle II (2022-2023), which also had the highest fruit yield under this strategy. In cycle I (2021-2022), which recorded the highest rainfall (784.57 mm, Table 3), WPFM and WPDM were similar among all strategies (E1 to E4). In cycle II, higher WP values were observed under E1, followed by E3 and E2, which were statistically similar to E4. In cycle III (2023-2024), the driest year with only 397.33 mm of rainfall (Table 3), WPFM and WPDM were higher under E3 compared to E2 and E4. A similar trend was reported by Mangalassery et al. (2019) in cashew trees, where irrigation with 20 and 40% of crop evapotranspiration was beneficial in increasing nut yield by 53.5% and 34.1%, respectively, with an increase in WP.

Regarding the water footprint based on fresh and dry matter, values were similar across evaluation cycles under the E3 and E4 irrigation strategies. Under rainfed conditions (E1), the lowest water footprint values - indicating greater water savings - were recorded in cycle II, which experienced intermediate precipitation (483.12 mm, Table 3). In contrast, the highest values of WFFM and WFDM were observed under E2 in cycle III, the driest cycle, reflecting greater water consumption. When comparing irrigation strategies, WFFM and WFDM were similar among strategies in cycle II. In cycle III, WFFM and WFDM were lower under E3 than under E2

and E1. A similar pattern was seen for WFFM in cycle I, while for WFDM in cycle I - which was also relatively dry - the lowest values occurred under E3 compared to E1. These results confirm that E3 led to better water use efficiency across varying precipitation conditions.

Among the irrigation strategies, E3 proved the most favorable for increasing WP and reducing WF. This finding aligns with the principles of climate-smart agriculture, which emphasizes improving water productivity and reducing environmental footprints - particularly critical in semiarid regions characterized by low and irregular rainfall (Zuñinga et al., 2017; Golla, 2021) and increasingly affected by climate change (Giorgi, 2019).

Higher WF values under E1 indicate that more water was needed to produce one ton of fresh or dry matter (Fernández et al., 2020). This is likely due to the plant's use of water for non-productive physiological functions, particularly water replenishment in xylopodia. As Bleninger & Kotsuka (2015) note, WF can estimate the total water use in a production system or specific crop. In the current study, WPDM varied across cycles, likely influenced by water accumulation in xylopodia from the previous cycle.

The E3 strategy also provided higher irrigation water productivity (WPi) and lower irrigation water footprint (WFi) - referring specifically to blue water use - on both fresh and dry matter bases, considering all evaluation cycles of BRS-68 (Table 6). These differences were most evident in cycle III, which recorded the lowest precipitation. E3 yielded an average WPFM of 58.36 kg ha$^{-1}$ mm$^{-1}$ across cycles, 324.31% higher than E2 (12.49 kg ha$^{-1}$ mm$^{-1}$) and 259.25% higher than E4 (16.25 kg ha$^{-1}$ mm$^{-1}$). The average WFFM for E3 was 176.89 L kg$^{-1}$, which was 579.89% lower than E2 (1,202.62 L kg$^{-1}$) and 262.74% lower than E4 (641.63 L kg$^{-1}$). Thus, the indicators of fruit yield, rainwater plus irrigation (Table 5) and irrigation only (Table 6) confirm the E3 strategy as more fit to the production system of the umbu tree cultivar BRS-68 under irrigation.

FMF, FMPL, and FMPP were higher under E3 compared to E1, regardless of the evaluation cycle. In contrast, DMF and DMPP were higher under E4 than under E1. DMCPP was higher under E4 and E2 compared to E3 (Table 7). FMF, FMPP,

**Table 6.** Means of irrigation water productivity in fresh matter (WPFM) and dry matter (WPDM), blue water footprint in fresh matter (WFFM), blue water footprint in dry matter (WFDM), and their respective percentual variation evaluated in umbu tree cultivar BRS-68 under three irrigation strategies and three evaluation cycles

| Variables | Evaluation cycles | Irrigation strategies | | | Percentage difference - Δ (%) | |
|---|---|---|---|---|---|---|
| | | E2 | E3 | E4 | E3-E2 | E3-E4 |
| WPFM (kg ha$^{-1}$ mm$^{-1}$) | I | 18.51 | 57.66 | 13.64 | 211.52 | 322.90 |
| | II | 14.77 | 71.36 | 21,22 | 383.04 | 236.37 |
| | III | 4.18 | 46.06 | 13.89 | 1,001.18 | 231.70 |
| Mean | | 12.49 | 58.36 | 16.25 | 367.31 | 259.25 |
| WPDM (kg ha$^{-1}$ mm$^{-1}$) | I | 2.70 | 8.47 | 2.02 | 213.40 | 318.26 |
| | II | 2.83 | 10.79 | 3.90 | 280.97 | 176.37 |
| | III | 0.75 | 7.39 | 2.19 | 887.29 | 237.41 |
| Mean | | 2.09 | 8.88 | 2.71 | 324.11 | 228.22 |
| WFFM (L kg$^{-1}$) | I | 540.23 | 173.42 | 733.38 | -211.52 | -322.90 |
| | II | 676.88 | 140.13 | 471.36 | -383.04 | -236.37 |
| | III | 2,390.76 | 217.11 | 720.15 | -1,001.18 | -231.70 |
| Mean | | 1,202.62 | 176.89 | 641.63 | -579.89 | -262.74 |
| WFDM (L kg$^{-1}$) | I | 3,701.31 | 1,181.02 | 4,939.74 | -213.40 | -318.26 |
| | II | 3,530.65 | 926.75 | 2,561.28 | -280.97 | -176.37 |
| | III | 13,367.35 | 1,353.94 | 4,568.38 | -887.29 | -237.41 |
| Mean | | 6,866.44 | 1,153.90 | 4,023.13 | -495.06 | -248.65 |

Irrigation strategies: E2 - ATF (25%ETo): Irrigation replacing 25% of reference evapotranspiration (ETo) until full flowering; E3 - AFC (25%ETo): Irrigation replacing 25% of ETo from full flowering until fruit harvest; E4 - AFC (50%ETo): Irrigation replacing 50% of ETo from full flowering until fruit harvest; Evaluation cycles: I (07/14/2021 to 03/02/2022), II (06/28/2022 to 01/18/2023), III (06/28/2023 to 01/24/2024); Periods of application of irrigation strategies in the cycles: cycle I - E2 (07/14/2021 to 09/02/2021), E3 and E4 (09/09/2021 to 03/02/2022); cycle II - E2 (06/28/2022 to 09/01/2022), E3 and E4 (09/15/2022 to 01/18/2023); cycle III - E2 (06/28/2023 to 09/06/2023), E3 and E4 (09/06/2023 to 01/24/2024)

**Table 7.** Means of fruit fresh mass (FMF), peel fresh mass (FMPL), pulp fresh mass (FMPP), fruit dry mass (DMF), pulp dry mass (DMPP), and pulp dry matter content (DMCPP) of fruits from the umbu tree cultivar BRS-68 as a function of irrigation strategies, and of FMF, FMPL, FMPP, DMF, DMPP, and seed dry mass (DMS) as a function of the evaluation cycles

| | FMF | FMPL | FMPP | DMF | DMPP | DMS | DMCPP |
|---|---|---|---|---|---|---|---|
| | (g) | | | | | | (%) |
| Irrigation strategies | | | | | | | |
| E1, rainfed | 64.24 b | 20.95 b | 33.24 b | 10.85 b | 3.59 b | - | 10.83 ab |
| E2, ATF (25%ETo) | 73.00 ab | 23.73 ab | 38.05 ab | 12.53 ab | 4.34 ab | - | 11.65 a |
| E3, AFC (25%ETo) | 80.70 a | 24.84 a | 43.90 a | 12.27 ab | 4.44 ab | - | 10.15 b |
| E4, AFC (50%ETo) | 79.42 ab | 24.48 ab | 43.65 a | 13.04 a | 4.85 a | - | 11.25 a |
| Evaluation cycles | | | | | | | |
| I | 80.37 a | 23.31 b | 46.49 a | 11.92 b | 4.77 a | 3.81 b | |
| II | 83.80 a | 29.97a | 41.24 a | 14.93 a | 4.64 a | 4.74 a | |
| III | 58.85 b | 17.21c | 31.39 a | 9.68c | 3.51 b | 3.57 b | |

Irrigation strategies: E1 - Rainfed; E2, ATF (25%ETo): Irrigation replacing 25% of reference evapotranspiration ( ETo ) until full flowering; E3 - AFC (25%ETo): Irrigation replacing 25% of ETo from full flowering until fruit harvest; E4 - AFC (50%ETo): Irrigation replacing 50% of ETo from full flowering until fruit harvest; Evaluation cycles: I (07/14/2021 to 03/02/2022), II (06/28/2022 to 01/18/2023), III (06/28/2023 to 01/24/2024); Periods of application of irrigation strategies in the cycles: cycle I - E2 (07/14/2021 to 09/02/2021), E3 and E4 (09/09/2021 to 03/02/2022); cycle II - E2 (06/28/2022 to 09/01/2022), E3 and E4 (09/15/2022 to 01/18/2023); cycle III - E2 (06/28/2023 to 09/06/2023), E3 and E4 (09/06/2023 to 01/24/2024). Means followed by the same lowercase letters in the columns for irrigation strategies and for evaluation cycles do not differ statistically by the Tukey test at 5% significance

and DMPP values were lower in cycle III across all irrigation strategies, while FMPL and DMF were highest in cycle II, followed by cycles I and III. DMS was also higher in cycle II.

According to the classification proposed by Donato et al. (2024), the MFF values of BRS-68 obtained under E1 (64.24 g) and E2 (73.00 g) fall into the "Large" class (50-75 g), while those observed under E3 (80.70 g) and E4 (79.42 g) are in the "Giant" class (75-100 g). Regarding the effect of cycle, MFF in cycles I (80.37 g) and II (83.80 g) also fall into the "Giant" class, while in cycle III (58.50 g), MFF is classified as "Large." This last cycle had the lowest precipitation. Despite irrigation, other factors - such as the delayed onset of rainfall and frequent intense heat waves during the 2023 El Niño year - contributed to reduced fruit weight. Much lower MFF values were reported by Silva et al. (2024) in Petrolina, PE, Brazil (44.1 g), and by Donato et al. (2022b) in Nova Porteirinha, MG, Brazil (45.68 g), highlighting the influence of local conditions.

The results show that both irrigation strategy and evaluation cycle independently influenced FMF expression in BRS-68. Strategies E3 and E4, as well as cycles I and II, resulted in FMF in the "Giant" class, while E1, E2, and cycle III yielded fruits in the "Large" class. Although FMF shows greater heritability and stability than yield (Santos, 1999), it is also affected by environmental and management factors (Donato & Neves, 2023). FMF is a genetic trait (Oliveira et al., 2004) associated with the ecoregions of origin of the accessions (Santos et al., 1999; Balbino et al., 2018), although Silva et al. (2024) suggest that FMF, soluble solids, and titratable acidity are homogeneously distributed across the Caatinga biome.

In all strategies and cycles, BRS-68 expressed its potential to produce fruits in the "Large" and "Giant" categories (Donato et al., 2024), consistent with the average MFF of 72.98 g observed for the same cultivar grafted onto umbu, and similar to values recorded over nine consecutive production cycles (75.54-95.14 g; Donato & Neves, 2023). These FMF values are considerably higher than those of common fruits; for example, in six municipalities of Paraíba state, Brazil, Pereira et al. (2021) reported MFFs of 14.9 g in Pocinhos and 23 g in Queimadas.

FMPL ranged from 20.95 g (E1) to 24.84 g (E3), FMPP from 33.24 g (E1) to 43.90 g (E3), FMF from 10.85 g (E1) to 13.04 g (E4), DMPP from 3.59 g (E1) to 4.85 g (E4), and DMCPP from 10.15% (E3) to 11.65% (E2). Overall, E1 resulted in lower FMPL and FMPP than E3, and lower DMF and DMPP than E4, with the lowest DMCPP in E3. Compared to Donato et al. (2022b), who evaluated the same cultivar grafted onto umbu and grown under dryland conditions, the present values were higher for FMPL (vs. 16.36 g), lower for FMPP (vs. 51.79 g), higher for DMF (vs. 7.23 g), lower for DMPP (vs. 5.05 g), and higher for DMCPP (vs. 9.70%).

Thus, E3 (AFC, 25% ETo), which replaces 25% of the reference evapotranspiration after flowering, is the most suitable for achieving higher fruit and water productivity, reducing the water footprint, and producing fruits classified as "Giant" in the cultivation of BRS-68. Additionally, this strategy mitigates production alternation, providing greater yield stability and predictability for farmers.

Maintaining the average FMF within the "Giant" class through E3 ensures a consistent standard for commercialization, resulting in higher profitability. This is especially relevant in years of extreme drought, as observed in cycle III, when rainfed conditions (E1) led to reduced fruit availability and lower FMF.

Thus, although BRS-68 is well adapted to rainfed conditions due to its high drought tolerance, the use of supplemental irrigation during fruit development - such as the E3 strategy - emerges as a viable solution to mitigate water scarcity impacts. In the context of climate change and increasing aridity in the Brazilian semiarid region, adopting E3 contributes to the sustainability of agricultural systems. These findings underscore the importance of implementing efficient water management practices tailored to local climate conditions, promoting a more resilient and productive agriculture. Further research should evaluate the applicability of this strategy in other umbu cultivars and growing environments to confirm the robustness and generalizability of the current findings.

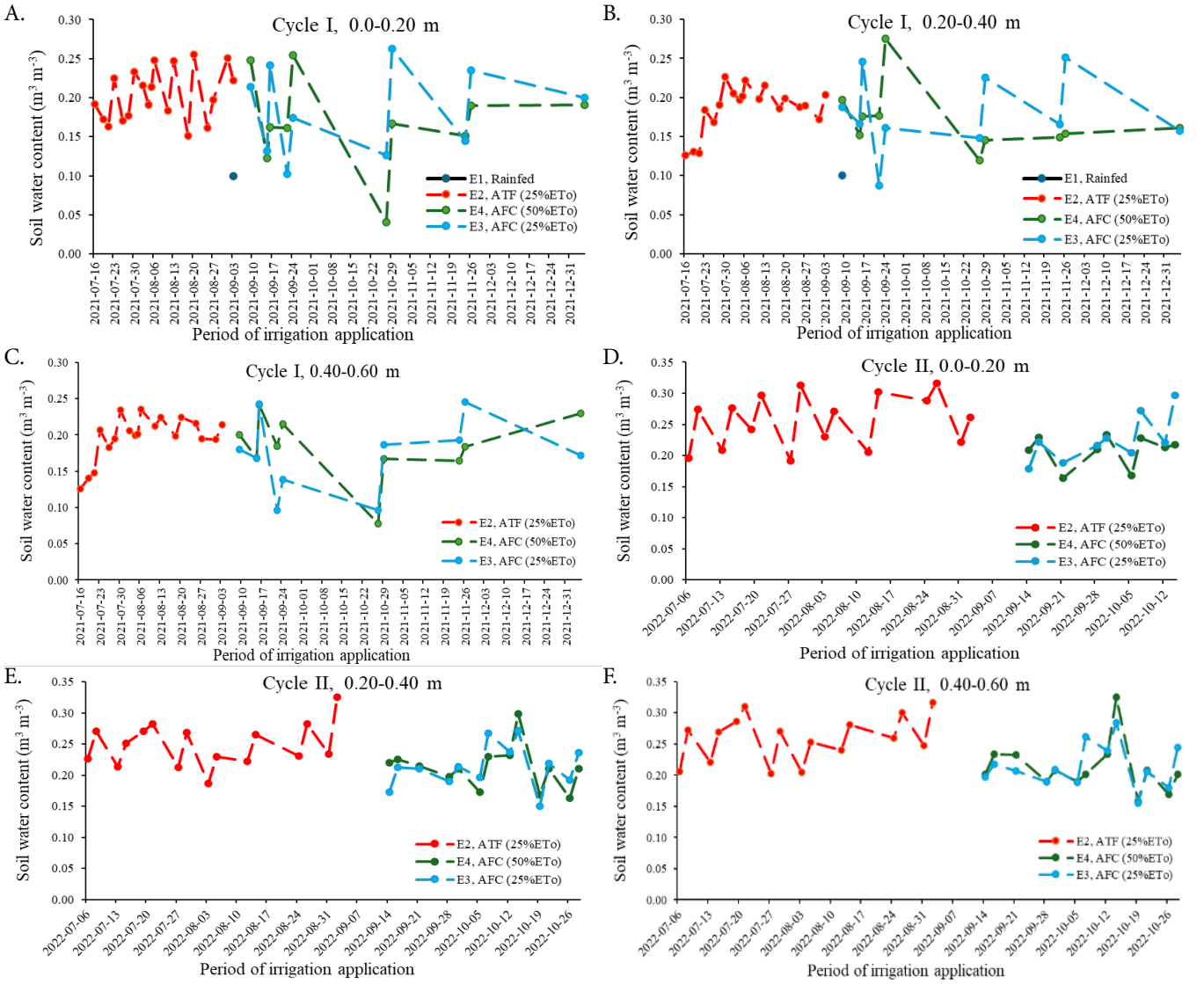
To complement the analysis, soil moisture data under the different irrigation strategies are presented in Figure 2. At the beginning of cycle I (07/14/2021 to 03/02/2022), under E1 (rainfed), soil moisture was 0.10 $m^3\ m^{-3}$ in both the 0-0.20 m (Figure 2A) and 0.20-0.40 m (Figure 2B) soil layers. For E2 (ATF, 25% ETo), applied from 07/14/2021 to 09/02/2021-during a dry period - soil moisture in the 0-0.20 m layer (Figure 2A) ranged from 0.15 to 0.25 $m^3\ m^{-3}$, fluctuating between 0.16 and 0.24 $m^3\ m^{-3}$ 24 hours before and after each weekly irrigation event. In the 0.20-0.40 m (Figure 2B) and 0.40-0.60 m (Figure 2C) layers, values varied from 0.16 to 0.22 $m^3\ m^{-3}$ and from 0.18 to 0.23 $m^3\ m^{-3}$, respectively.

For E3 (AFC, 25% ETo) and E4 (AFC, 50% ETo), applied from 09/09/2021 to 02/03/2022, soil moisture varied as follows: in the 0-0.20 m layer (Figure 2A), from 0.12 to 0.24 $m^3\ m^{-3}$ in E3 and from 0.12 to 0.20 $m^3\ m^{-3}$ in E4; in the 0.20-0.40 m layer (Figure 2B), from 0.14 to 0.24 $m^3\ m^{-3}$ in E3 and from 0.12 to 0.19 $m^3\ m^{-3}$ in E4; and in the 0.40-0.60 m layer (Figure 2C), from 0.13 to 0.19 $m^3\ m^{-3}$ in E3 and from 0.16 to 0.23 $m^3\ m^{-3}$ in E4.

All moisture values recorded immediately after irrigation events remained within the soil's water storage capacity (Bernardo et al., 2019), and were close to field capacity (0.253 $m^3\ m^{-3}$). This confirms that the lower yields observed under the E2 and E4 irrigation strategies were caused by changes in source-sink relationships (Donato et al., 2019), rather than by water losses due to deep percolation or leaching.

In the second evaluation cycle (06/28/2022 to 01/18/2023), during the application of the E2 strategy (ATF, 25% ETo) from 06/28/2022 to 09/01/2022 - a period without rainfall - soil moisture 24 hours before and after weekly irrigation events ranged as follows: 0.19 to 0.31 $m^3\ m^{-3}$ in the 0-0.20 m layer (Figure 2D); 0.21 to 0.28 $m^3\ m^{-3}$ in the 0.20-0.40 m layer (Figure 2E); and 0.20 to 0.31 $m^3\ m^{-3}$ in the 0.40-0.60 m layer (Figure 2F). These values exceeded field capacity 24 hours after irrigation, likely due to water redistribution within the soil profile.

For the E3 (AFC, 25% ETo) and E4 (AFC, 50% ETo) strategies, applied between 09/15/2022 and 01/18/2023, soil moisture variations before and after irrigation events were generally: 0.17 to 0.29 $m^3\ m^{-3}$ (E3) and 0.16 to 0.22 $m^3\ m^{-3}$ (E4) in the 0-0.20 m layer (Figure 2D); 0.15 to 0.27 $m^3\ m^{-3}$ (E3) and 0.17 to 0.23 $m^3\ m^{-3}$ (E4) in the 0.20-0.40 m layer (Figure 2E);




A - Evaluation cycle I (July 14, 2021 to March 2, 2022); Soil layer 0 to 0.20 m; Irrigation strategies: E1, Rainfed, E2, ATF (25% ETo): Irrigation replacing 25% of reference evapotranspiration ( ETo ) until full flowering (July 14, 2021 to September 2, 2021); E3, AFC (25% Eto):Irrigation replacing 25% of ETo from full flowering until fruit harvest (September 9, 2021 to March 2, 2022); E4, AFC (50% Eto): Irrigation replacing 50% of ETo from full flowering until fruit harvest (September 9, 2021 to March 2, 2022); B - Cycle I; Soil layer 0.20 to 0.40 m; E1, E2, E3 and E4; C - Cycle I; Soil layer 0.40 to 0.60 m; E2, E3 and E4; D - Cycle II (06/28/2022 to 01/18/2023); Soil layer 0 to 0.20 m; E2 (28/06/2022 to 18/01/2023), E3 and E4 (15/09/2022 to 18/01/2023); E - Cycle II; Soil layer 0.20 to 0.40 m; E2, E3 and E4; F - Cycle II; Soil layer 0 to 0.20 m; E2, E3 and E4

**Figure 2.** Gravimetrically estimated soil moisture content in the 0.0-0.20 m, 0.20-0.40 m, and 0.40-0.60 m soil layers under cultivation of the umbu tree cultivar BRS-68, subjected to four irrigation strategies across two evaluation cycles

and 0.18 to 0.26 $m^3$ $m^{-3}$ (E3) and 0.20 to 0.24 $m^3$ $m^{-3}$ (E4) in the 0.40-0.60 m layer (Figure 2F).

The results indicate that soil moisture levels were consistently higher than those recorded under dry conditions, due to the effects of irrigation. Greater variability was observed under strategies E3 and E4, which were applied partially during the rainy periods of each evaluation cycle, compared to strategy E2, which was implemented entirely during the dry periods of both cycles. The most pronounced fluctuations in soil moisture under E3 and E4 occurred in October of both cycles. In contrast, cycle II, which experienced intermediate rainfall relative to cycles I and III, showed smaller differences between moisture values measured 24 hours before and after irrigation events.

## Conclusions

1. The irrigation strategy replacing 25% of reference evapotranspiration (AFC, 25% ETo), applied from full flowering to harvest, ensures higher fruit yield and water productivity, reduces the water footprint, minimizes production alternation across cycles, and enables the production of fruits with superior commercial classification.

2. This strategy (AFC, 25% ETo) can be effectively incorporated into the giant umbu production system to enhance yield stability and improve fruit quality standards.

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Joel da Silva de Deus, and Ednei de Souza Pires; supervision and funding acquisition: Sérgio Luiz Rodrigues Donato

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