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Evaluation of the Effect of Soil Water Conditions on the Development and Water Requirements of Adult Oil Palm (*Elaeis guineensis* Jacq.) in the Northern Region of Colombia

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Abstract: Sustainable water management is a key approach for enhancing the productivity of oil palm trees while addressing the impacts of climate change and variability. Determining the water needs of a crop is crucial for the appropriate application of water. This research was carried out in two plantations in Agustín Codazzi, Colombia, using a completely randomized design. This study involved examining the impacts of five different water conditions (50, 150, 300, 450, and 600 L per day) on the growth and yields of mature oil palm trees (aged 10–17 years), and their water consumption was calculated using the water balance method. The results indicated that the crop was negatively affected by daily water applications of 300, 150, and 50 L per day, showing statistically significant differences ($p < 0.05$) when compared to the 450 and 600 L per day treatments, particularly in terms of leaf emergence, leaf area index, and yield (tons per hectare). The 50 L per day treatment resulted in the most substantial decrease in yield (around 26%), primarily attributed to a reduction in the number of bunches. The most favorable crop responses were observed with water applications of 450 and 600 L per day, aligning with the crop's potential evapotranspiration values (ranging between 5.4 and 5.7 mm per day) and yielding crop coefficients of 0.88 and 0.9, respectively. Notably, these values varied between dry and rainy seasons, peaking between December and March.

Keywords: oil palm crop evapotranspiration; water balance; water deficit; water excess

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1. Introduction

With the increasing impacts of climate change, water scarcity and more frequent droughts have become major concerns for agriculture, both globally and particularly in Colombia (especially in the northern Caribbean region) [1]. Regrettably, climate projections indicate that these conditions will worsen [2], especially in tropical regions where oil palm cultivation is prevalent. Consequently, production is expected to be impacted, with water shortage being a primary limiting factor for the optimal growth of oil palm [3]. According to Watson et al. [4], the ideal climate for the crop is gradually being affected, and is projected to worsen by 2030 and even more so by 2100 due to the impacts of climate change.

The Cesar department is situated in northern Colombia, making it vulnerable to the impacts of climate change. According to IDEAM and UNAL [5], a 2.5 °C increase in temperature is expected between 2011 and 2040 in the central and southern regions of the department, coupled with a 19% reduction in precipitation, particularly in the municipalities of Valledupar, San Diego, Agustín Codazzi, Becerril, and El Paso. The cultivation of oil palm holds significant importance for this department with its presence in 23 of the 25 municipalities, contributing to 66% of the region's GDP [6]. However, the current climate conditions, marked by reduced water availability and more than six dry months, pose a threat to the sustainability of the sector and local ecosystems.

Efficient crop irrigation is crucial for reducing vulnerability to water stress and improving crop production [7,8], as water deficit stress is the principal yield-limiting factor for oil palm crops [9]. Based on the findings of Álvarez et al. [10], optimizing water usage in irrigation management for oil palm cultivation in Colombia can lead to enhanced economic efficiency. This optimization can reduce the production cost of one ton of fresh fruit bunches (FFB) by 8 to 10% and increase the profitability of palm cultivation by 13%. Therefore, it is essential to understand the water demand of plants in varying climatic scenarios and how it impacts their development and yield [4]. However, in this region, there is still a lack of knowledge regarding these technical aspects, leading to the use of surface or pressurized irrigation without proper water balance measurement [9,11]. This can subject the oil palm to conditions of either water deficit or excess moisture, both adversely affecting its development.

In the context of the water requirements for oil palm, various studies have been conducted [12–20], mostly in Malaysia and India, using different methodologies such as soil–water balance, lysimeters, eddy covariance, and some computational models. It has been observed that the average evapotranspiration of oil palm trees in these regions is 4.1 mm per day (ranging from 3.5 to 5.5 mm per day) during rainy periods and 1.9 mm per day (0.6–2.9 mm) in the dry season. As for the crop coefficient, an average value of 0.9 has been documented under suitable conditions with a range of 0.8 to 1.0, decreasing to 0.1 in the dry season. In more recent studies, such as the one conducted by Watson et al. [4] in central Costa Rica using the APSIM computational tool, crop water consumption values ranging between 3.13 and 4.3 mm per day have been reported, with maximum values of 7 mm per day.

On the other hand, considering that atmospheric demand significantly impacts the water needs of plants (see Foong [21], as cited by Carr [16]; Lee and Izwanizam [22]), it is crucial to determine these needs based on the specific conditions of each region. In a 33-year study in Malaysia, Lee and Izwanizam [22] found that variations in oil palm evapotranspiration were mainly influenced by climatic conditions. They observed that, during dry months, the evapotranspiration rate increased by 6.5 to 7.5 mm per day, while it dropped to 3.0 to 3.5 mm per day during the monsoon season.

All of these studies have been carried out under climatic and agronomic conditions different from those in Colombia. Additionally, these studies have not established a correlation between crop water consumption and yield, and the minimum amount of water required for sustainable crop production is still unknown [16]. Therefore, this project, with the aim of contributing to increasing the efficiency of water use in the palm agroindustry in Colombia, took the determination of water requirements of the adult oil palm *Elaeis guineensis* and its crop coefficient (Kc) under the current conditions of the region, as well as evaluating the effects of different soil water conditions on the development and productivity of the crop, as its objectives.

2. Materials and Methods

2.1. Location of the Study Area

The research was conducted in the La Cartuja and Oleoflores palm plantations, situated 20 km from the municipality of Agustín Codazzi in the department of Cesar, Colombia. The location is 10°02′05.06″ north latitude and 73°14′13.66″ west longitude, with an elevation of 81 m above sea level (Figure 1). The study areas have an average annual precipitation of 1520 mm, an average temperature of 29.5 °C, 80% relative humidity, and a mean reference evapotranspiration (ETo) of 6.5 mm per day, with a maximum of 10 mm per day.

This study encompassed oil palm crops with different age ranges in two plantations. In La Cartuja plantation (P1), an 8.1 ha plot planted with the Deli x Avros cultivar since 2012 was chosen, with a planting density of 143 palms per hectare. Meanwhile, in the Oleoflores plantation (P2), a 15 ha plot with the same cultivar planted since 2007 was selected. Within both plantations, the same sprinkler irrigation system is employed, with each emitter benefiting three palms. Due to the range of the sprinklers, there is no overlap between them (partial wetting coverage; see Figure 2). This study was conducted over a period of two and a half years, from October 2021 to April 2024, and involved monitoring crop age ranges of 10–12 years in P1 and 15–17 years in P2.

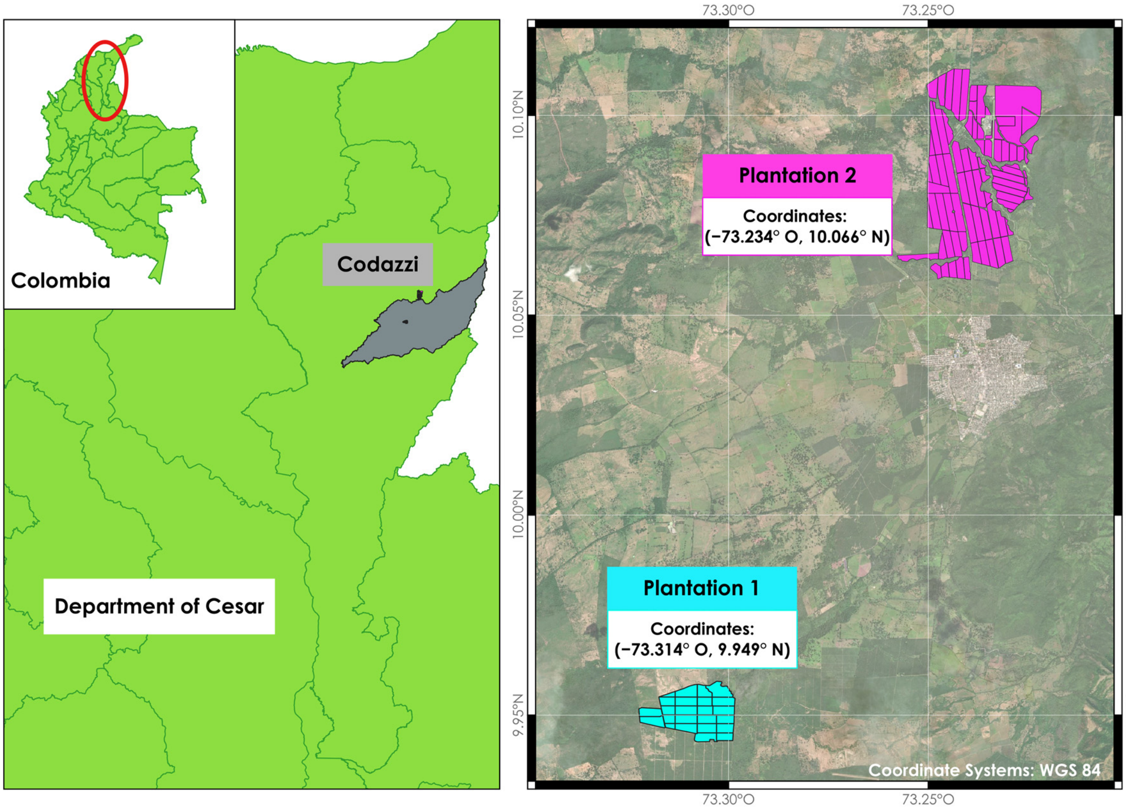


Figure 1. Location of the study area.

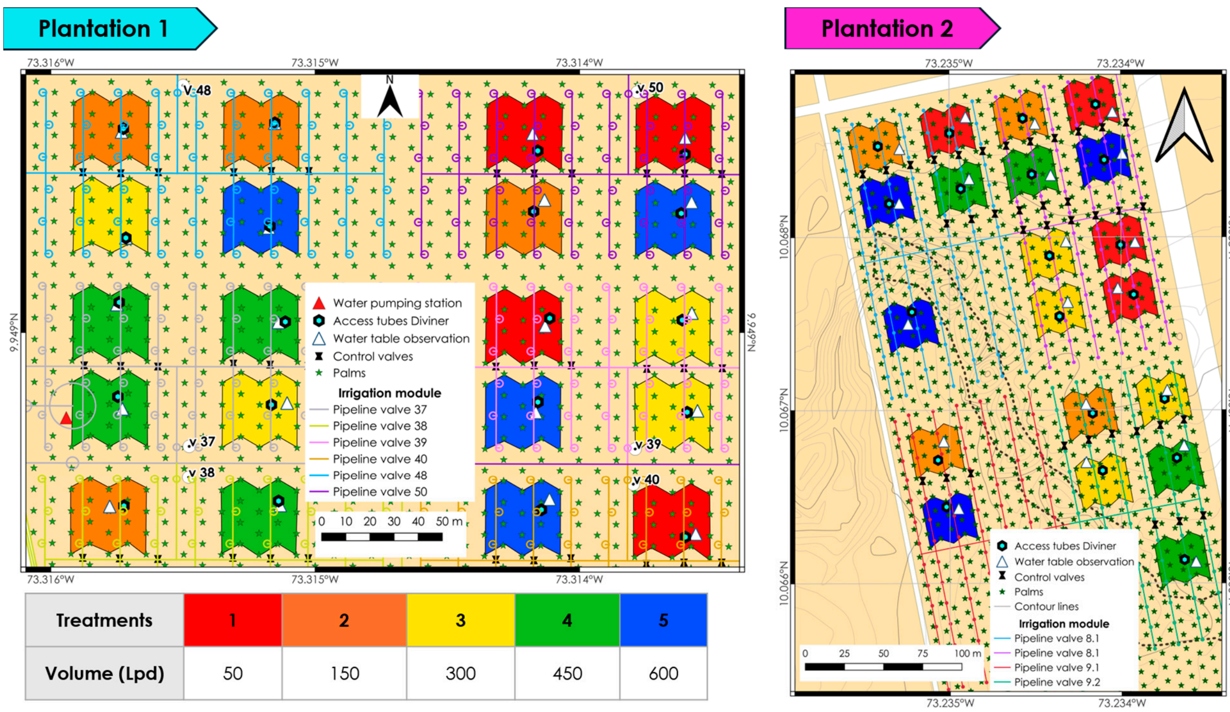


Figure 2. Map of treatments established in the two plantations: P1 and P2.

2.2. Soil Physicochemical Parameters

The experimental design for each study area involved conducting a physicochemical characterization of the soil (Table 1). In both plantations, the soils displayed medium textures, high bulk densities, and low total porosity, which are characteristic of the region [23]. Their soil water retention capacity is moderate, and their basic infiltration is classified as slow [24].

Table 1. Soil physicochemical characterization for plantations 1 and 2.

Soil Physical Properties							
Plantation	**Texture**	**Slope (%)**	**Bulk Density ($g\ cm^{-3}$)**	**Basic Infiltration ($mm\ h^{-1}$)**	**Porosity (%)**	**TAW [1] (mm)**	**RAW [2] (mm)**
P1	Loam	<1%	1.7	1.19	0.36	59	30
P2	Loamy sand	1–5%	1.6	5.55	0.4	85	42.5

Soil Chemical Properties													
Parameter	**pH**	**OM [3]**	**EC [4]**	**CEC [5]**	**K**	**Ca**	**P**	**S**	**B**	**Fe**	**Cu**	**Mn**	**Zn**
Unit	-	%	$dS\ m^{-1}$		$cmol\ kg^{-1}$					$mg\ kg^{-1}$			
Threshold	6.5	4	<4	20	0.4	1	20	15	0.5	30	1.5	5	2
P1	7.8	0.9	0.5	8.3	0.2	8.6	30.2	16.9	0.3	19.0	1.3	26.1	1.2
P2	7.0	2.3	0.8	10.3	0.5	11.8	178.2	18.4	0.6	10.3	0.6	35.0	4.0

[1] TAW: total available water; [2] RAW: readily available water; [3] OM: organic matter; [4] EC: electrical conductivity; [5] CEC: cation exchange capacity.

Regarding the chemical analysis of the soil, both plantations indicate a neutral to slightly alkaline pH, low organic matter content (OM), and ideal electrical conductivity (EC). The cation exchange capacity (CEC) is low, and the soil shows high to medium levels of calcium (Ca), phosphorus (P), sulfur (S), and manganese (Mn), with low levels of potassium (K), boron (B), iron (Fe), copper (Cu), and zinc (Zn) for oil palm cultivation [25]. The formulation of the nutrition plan for these areas by each plantation was based on careful consideration of these parameters.

2.3. Experimental Design

The crop water requirement was determined for two age ranges: 10 to 12 years (at P1) and 15 to 17 years (at P2).

Based on the topographical surveys, soil conditions, and irrigation system configurations in both plantations, a completely randomized experimental design (CRD) was independently defined for P1 and P2. This design consisted of five treatments and four replications, resulting in a total of 20 experimental units (EUs) comprising eighteen palms, with six designated as effective experimental palms. The treatments corresponded to five water conditions, represented by the application of water volumes equal to 50, 150, 300, 450, or 600 L per palm/day (Lpd). Each EU has a sprinkler irrigation system with partial coverage distributed through PVC pipes. The treatments were controlled by opening valves installed in each lateral line (Figure 2). Irrigation was applied using the daily water balance to guarantee the corresponding water volumes for each treatment.

2.4. Soil Water Availability Measurements

The soil water content (SWC) was measured using the Diviner 2000 portable soil moisture probe from Sentek Technologies. The logger converted the probe readings to volumetric SWC data using the calibration option for mineral soil supplied by the manufacturer. An access tube was installed in each experimental unit (EU) to provide a total of 20 measurement points. These tubes were strategically positioned 2 m from the palm stem, near the root zone of one of the effective palms in each EU. Moisture readings were taken at a depth of 100 cm, with measurements at 10 cm intervals, through the soil profile.

The area was irrigated with sprinklers (mini-Wobbler), each of which covered three palms. The opening and closing of the irrigation lateral were controlled by ¾-inch ball valves. Additionally, an observation well was installed in each EU to monitor water table (WT) fluctuations. Throughout the evaluation period, the water table remained below 2 m, allowing us to disregard water contributions by capillarity.

Readings were taken daily (Monday to Friday) between 7 and 9 am, and the data were downloaded for processing to determine the daily changes in soil moisture and the available water (AW) for each treatment. A moisture deficit in each treatment was identified when the AW in the soil dropped below the readily available water.

2.5. Determination of Crop Evapotranspiration (ETc) by the Water Balance Method

Average values of the evapotranspiration rate of the oil palms for the two age ranges were determined using the water balance method (Equation (1)) for each of the treatments. The change of soil moisture in the root zone (ΔHs) was recorded daily using the moisture probe. Precipitation was measured through a rain gauge installed approximately 50 m from the two experimental areas, which was used to determine the effective precipitation (Pe) using the number curve method proposed by the Soil Conservation Service (SCS) [26]. To estimate the net irrigation amount (Irr), the irrigation times of each treatment and the efficiency obtained in the diagnosis carried out by the plantation were considered. Capillary contributions (Ac) in the two plantations were assumed to be insignificant as the WT remained below 2 m throughout the project.

Runoff (R) and deep percolation (D) were calculated as the difference between the applied water and the moisture stored in the soil at the effective rooting depth (60 cm). During the rainy season, R was determined using the number curve method, which considers the hydrological condition of the soils, the quality of the crop covers, and the slope. It also allows for correction using the antecedent soil moisture (soil in normal, saturated, or dry conditions). Deep percolation losses were calculated based on the water available between the field capacity (FC) and permanent wilting point (PWP) for each soil type in both plantations. Any water exceeding this range was considered to be lost through percolation.

$$\text{ETc} = \text{Pe} + \text{Irr} + \text{Ac} - \text{D} - \text{R} - \Delta\text{Hs} \quad (1)$$

Here, ETc = crop evapotranspiration (mm per day); Pe = effective precipitation (mm per day); Irr = net irrigation applied (mm per day); ΔHs = soil moisture delta (mm per day); Ac = capillary contribution of the water table (mm per day) $\equiv 0$; D = deep percolation measured at a depth of 100 cm (mm); R = surface runoff (mm).

Parallel to the daily monitoring of water balance, the reference evapotranspiration (ETo) was calculated using the Penman–Monteith method [27]. For this purpose, a meteorological station was set up near the experimental areas, located 6 km from P1 and 15 km from P2, to record temperature, solar radiation, wind speed, and relative humidity data. These ETo values were related to crop evapotranspiration (ETc) to obtain the crop coefficient (Kc), as per Equation (2).

$$\text{Kc} = \text{ETc}/\text{ETo} \quad (2)$$

Here, Kc = crop coefficient; ETc = crop evapotranspiration (mm per day); ETo = reference evapotranspiration (mm per day).

2.6. Measurement of Crop Development and Production

2.6.1. Vegetative Measures

Palm growth was assessed semiannually from March 2022 (at 10 and 15 years of crop age for P1 and P2, respectively) to April 2024 (when the crops in P1 and P2 were 12 and 17 years old, respectively). During this period, vegetative measurements including rachis length (RL), number of leaflets (n), leaflet width (W) and length (L), petiole width (Pw), and thickness (Pt) were taken on leaf 17 of the selected effective palms in each experimental area. Leaf number (NL) and emitted leaves (LE) were also quantified. The collected data were used to calculate the leaf area index (LAI) and the dry weight of the fronds (FDW) using Equations (4) and (6) [28–30]. Additionally, the number of unopened leaves (spear leaf) was counted weekly.

$$LA17 = 0.55 \times (LW) \times n \quad (3)$$

$$LAI = LA17 \times SD/1000 \quad (4)$$

Here, LA17 = leaf area of leaf 17 (m^2); L = average length of the six largest central leaflets (m); W = average with of the six largest central leaflets (m); n = number of leaflets of the leaf 17; LAI = leaf area index; SD = seeding density (palms ha^{-1}).

$$DW17 = 0.1023\ (Pw \times Pt) + 0.2062 \quad (5)$$

$$FDW = DW17 \times EL \quad (6)$$

Here, DW17 = dry weight of the leaf 17 (kg); Pw = width of the cross-section of the petiole (cm); Pt = thickness of the cross-section of the petiole (cm); FDW = dry weight of the fronds (kg $palm^{-1}$ $year^{-1}$); EL = emitted leaves per year.

2.6.2. Crop Production and Oil Potential

The fresh fruit bunch (FFB) yield was determined by conducting harvesting events every 10 to 12 days in the two experimental areas. During these events, the number of bunches (NB) and bunch weight (BW) were recorded for each of the experimental palms. Production data were analyzed for each treatment using data from 24 effective palm trees. The bunch weight was measured using a digital hook scale, and the collected data were used to quantify the total yields in tons per hectare (t ha^{-1}).

For the oil content analysis, 60 bunches (three bunches per experimental unit) were collected from both plantations. These bunches were analyzed using the bunch analysis methodology developed by Cenipalma [31], which quantifies the content of oil per bunch of fresh fruit (Oil/FFB). Additionally, the percentage of normal fruit to fresh fruit bunch (NF/FFB) of mesocarp to normal fruit (Mes/NF) and of oil to mesocarp (Oil/Mes) ratios were also determined.

2.6.3. Statistical Analysis

Statistical analyses were performed using SAS 9.3 to identify the effects of treatments on each response variable. The process began with a descriptive analysis of each variable, utilizing summary statistics such as mean, median, and quantiles. Additionally, interval ranges were established for all response variables, including water requirement values, and outliers were identified using graphical tools such as box plots.

Then, we performed an analysis of variance (ANOVA) for each response variable for plantations P1 and P2. We verified the model assumptions, including checking the normality of residuals using the Shapiro–Wilk test and distribution and probability plots, ensuring the independence of residuals through residual analysis, and testing for homogeneity of variances using Levene's Test. If the associated null hypothesis was rejected, the difference between treatments ($p < 0.05$) was determined using Tukey's multiple comparison test.

Finally, a two-way ANOVA was performed to examine the interaction between age and varying water volumes. It was checked whether the assumptions were met, and the Wald Test was then used to confirm the significance of these interactions.

3. Results

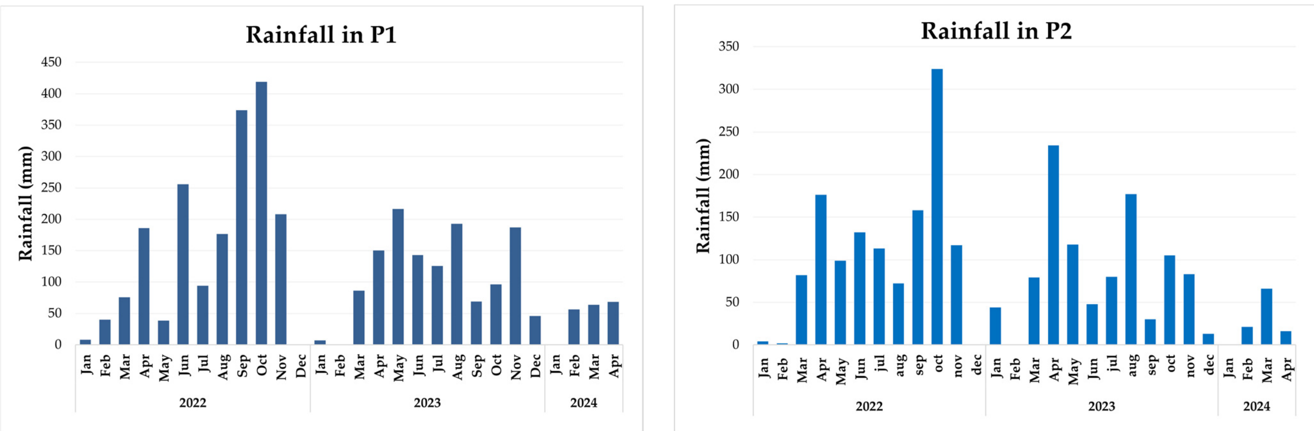
3.1. Weather Conditions during the Study Period

The climate of the experimental areas is classified as warm semi-arid [5]. Table 2 summarizes the climatological characteristics during the trial period (August 2022–March 2024), which significantly influence potential crop evapotranspiration in the region and, thus, are essential to understand [27]. Temperature (T °C), solar radiation (Rs), and wind speed (u2) presented minimal monthly variations but tended to be higher during the dry season (December–March). In contrast, relative humidity (RH) decreased during these months. This pattern changed during the rainy months (April–November), with higher relative humidity values and lower values for the other variables. The average ETo value was 7.4 mm per day, with the highest recorded values of 12.5 mm per day in February.

Table 2. Summary of climatological characteristics of the experimental area during the time of the trial (January 2022–March 2024).

Parameters	Average	Dry Season	Rainy Season
Solar radiation (W m^{-2})	412.02	430.2	402.2
Minimum temperature (°C)	24.1	23.2	24.6
Maximum temperature (°C)	34.8	36.2	33.8
Average temperature (°C)	28.8	29.1	28.4
Relative humidity (%)	79.3	71.2	84.9
Wind speed (km h^{-1})	1.2	1.7	0.84
ETo (mm per day)	7.4	7.8	7.2

Regarding rainfall (Figure 3) in 2022, cumulative values of 1876 mm and 1279 mm were recorded for P1 and P2, respectively. In 2023, there was a decrease in precipitation due to the occurrence of the El Niño phenomenon, which was classified as strong [32]. The values were 1320 mm for P1 and 1011 mm for P2, being lower than the average regional value of approximately 1520 mm [5]. Throughout the evaluation period, the dry season extended from December to March, followed by two distinct rainy seasons. The initial rainy season occurred between April and May, while the second took place from September to November. However, in 2023, there was lower rainfall intensity in July and September due to a climatic event.



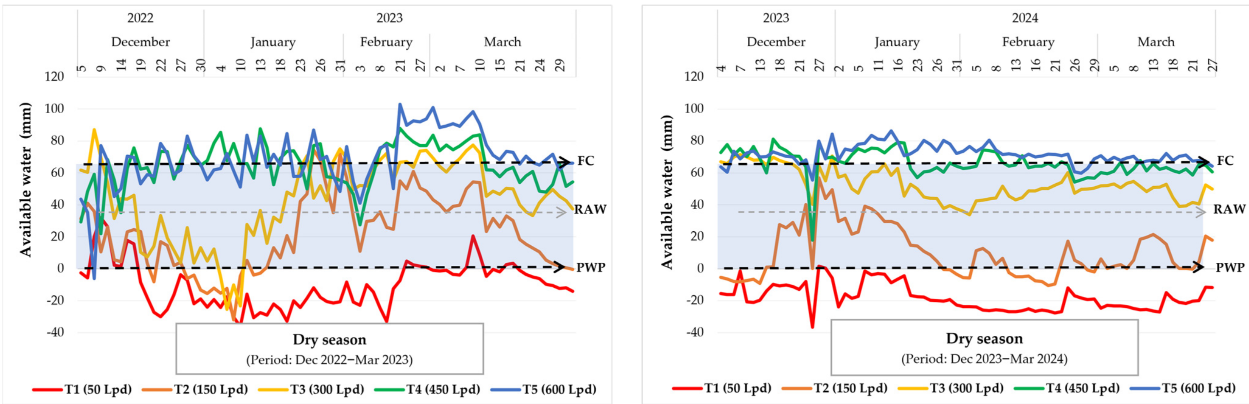
(**a**) (**b**)

Figure 3. Rainfall in the experimental areas during the trial for P1 (**a**) and P2 (**b**).

3.2. Measurement of Available Water in the Soil

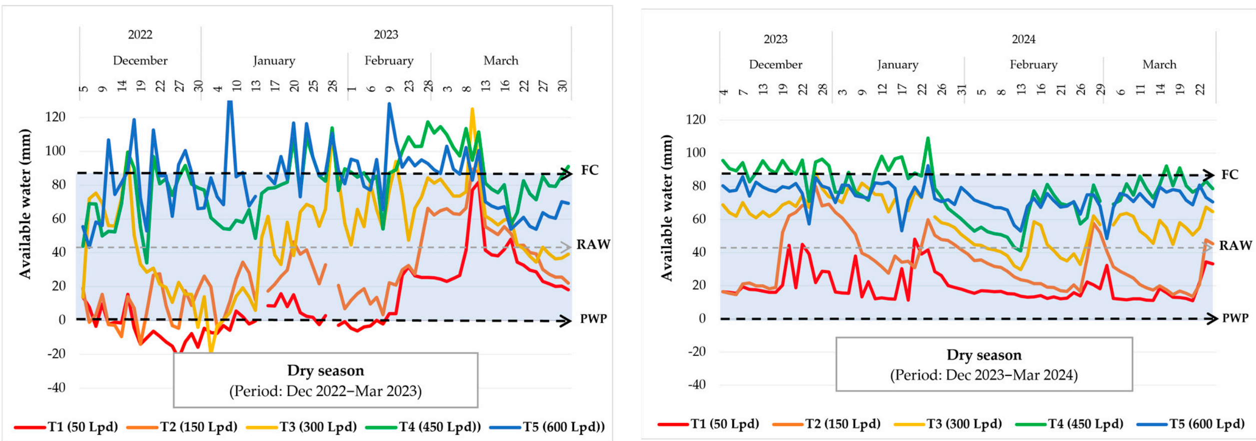
In order to comply with the treatments, a water balance was conducted for each of them. This allowed us to quantify that, in addition to precipitation events, treatments T1, T2, T3, T4, and T5 in the P1 plantation received an average of 130 mm, 319 mm, 761 mm, 1031 mm, and 1334 mm per year of water through irrigation, and 49 mm, 371 mm, 1248 mm, 1927 mm, and 2300 mm per year of water through rainfall, respectively. Meanwhile, in the P2 plantation, the amounts were higher due to lower occurrence of rainfall, with treatments T1, T2, T3, T4, and T5 receiving 1304 mm, 1031 mm, 239 mm, 77 mm, and 15 mm per year through irrigation, and 49 mm, 371 mm, 1248 mm, 1927 mm, and 2300 mm per year through rainfall. This resulted in an average annual deficit of 1132 mm, 1021 mm, 503 mm, 118 mm, and 54 mm per year in P1 and 1304 mm, 1031 mm, 239 mm, 77 mm, and 15 mm per year in P2 for treatments T1, T2, T3, T4, and T5, respectively.

Deficits were greater between December and March, coinciding with drought periods. Irrigation events were successfully scheduled using daily records of water balance and soil moisture. However, due to the rotation of irrigation shifts established by the plantations (night irrigation), applications were controlled by irrigation times and frequencies (adjusted to the plantation schedule), guaranteeing the volume of water stipulated in each treatment. Despite occasional pump and energy network failures, efforts were made to adjust the timing of subsequent irrigations to minimize these inconveniences and ensure that the available water values in the soil accurately represented each treatment (Figures 4 and 5).



(**a**) (**b**)

Figure 4. Available soil water in plantation 1 (P1) for the dry seasons during the study period: (**a**) December 2022 to March 2023 and (**b**) December 2023 to March 2024. FC: field capacity; RAW: readily available water; PWP: permanent wilting point.



(**a**) (**b**)

Figure 5. Available soil water in plantation 2 (P2) for the dry seasons during the study period: (**a**) December to March 2023 and (**b**) December to March 2024. FC: field capacity; RAW: readily available water; PWP: permanent wilting point.

According to the results, Figure 4 illustrates the significant fluctuations in soil moisture during the dry months in plantation 1, despite varying water availability. It was observed that the water status in T1 had a notable impact on soil moisture, leading to moisture levels below the permanent wilting point (PWP). In T2, a soil moisture deficit of up to 40 mm was recorded, although it fluctuated based on irrigation. Periodic rainfall brought the moisture levels close to field capacity at times; however, for 83% of days during the dry months, the soil moisture remained below the RAW. In T3, soil moisture stayed between RAW and FC for roughly 70% of the drought period. For T4 and T5, the soil moisture levels remained at or above field capacity for 85% and 94% of the time, respectively.

On the other hand, in the P2 plantation (Figure 5), as the soil had higher moisture retention, greater water availability was observed. This indicates that soil moisture levels in treatments T1 and T2 remained within the range of deficit stress for the crop, staying between RAW and PWP. Treatment T3 fluctuated between RAW and moisture at FC for 75% of the evaluation period. Finally, in treatments T4 and T5, the soil water content remained at or above FC for 79% and 88% of the dry period, respectively.

3.3. Effect of Soil Water Conditions on the Crop

3.3.1. Effect on Growth Measures

Based on the gathered data, significant responses to water conditions at the vegetative level were observed after 12 months, notably impacting variables such as LAI, MLE, NL, and B. Table 3 presents the results of the assessment conducted in the first quarter of 2024, at which point treatments had been applied for 24 and 18 months in plantations P1 and P2, respectively.

Table 3. Effect of water conditions on oil palm growth for the last 12 months: leaf area index (LAI), emitted leaves (EL), number of leaves (NL), and dry weight of the fronds (FDW) for P1 (with two years of application of the treatments) and P2 (with 1.5 years of application of the treatments).

Plantation	Treatment	LAI		EL Emitted Leaves Year^{-1}		NL		FDW kg Palm^{-1} Year^{-1}	
P1	T1 (50 Lpd)	4.2 ± 0.3	c	22.4 ± 1.1	c	30.9 ± 1.2	b	84.8 ± 5.9	a
	T2 (150 Lpd)	4.5 ± 0.3	bc	23.1 ± 0.8	bc	33.6 ± 1.2	b	93.2 ± 4.8	a
	T3 (300 Lpd)	4.8 ± 0.2	abc	25.3 ± 0.6	ab	37.5 ± 0.9	a	99.5 ± 4.8	a
	T4 (450 Lpd)	5.1 ± 0.3	ab	27.0 ± 0.6	a	38.3 ± 1.0	a	102.8 ± 5.6	a
	T5 (600 Lpd)	5.3 ± 0.2	a	27.1 ± 0.6	a	38.9 ± 1.0	a	110.9 ± 5.5	a
P2	T1 (50 Lpd)	4.1 ± 0.2	a	22.3 ± 1.2	b	26.3 ± 0.9	b	101.6 ± 6.9	b
	T2 (150 Lpd)	4.2 ± 0.2	a	22.5 ± 1.1	ab	27.0 ± 1.0	b	100.2 ± 8.1	b
	T3 (300 Lpd)	4.6 ± 0.2	a	25.5 ± 0.8	ab	31.7 ± 1.0	a	120.0 ± 6.6	ab
	T4 (450 Lpd)	4.8 ± 0.2	a	26.3 ± 0.9	a	31.9 ± 1.1	a	124.8 ± 6.2	a
	T5 (600 Lpd)	4.5 ± 0.2	a	26.2 ± 0.8	a	32.1 ± 1.0	a	114.1 ± 6.1	ab

Means followed by the same letter are not significantly different from one another, based on Tukey's multiple test at $p < 0.05$.

It was observed that the average Leaf Area Index (LAI) values in both plantations varied between 4.0 and 5.5. These values decreased under treatments with lower soil water availability. Specifically, in P1, there was a significant reduction in LAI in treatments T1 and T2 compared to treatments T4 and T5 of up to 20% at 24 months of application. In the case of P2, although no statistical differences were observed between treatments ($p < 0.05$), there was a reduction in leaf area (of about 15%) in T1 and T2 at 18 months, indicating a decrease in the leaf area of adult palms under higher levels of soil drought.

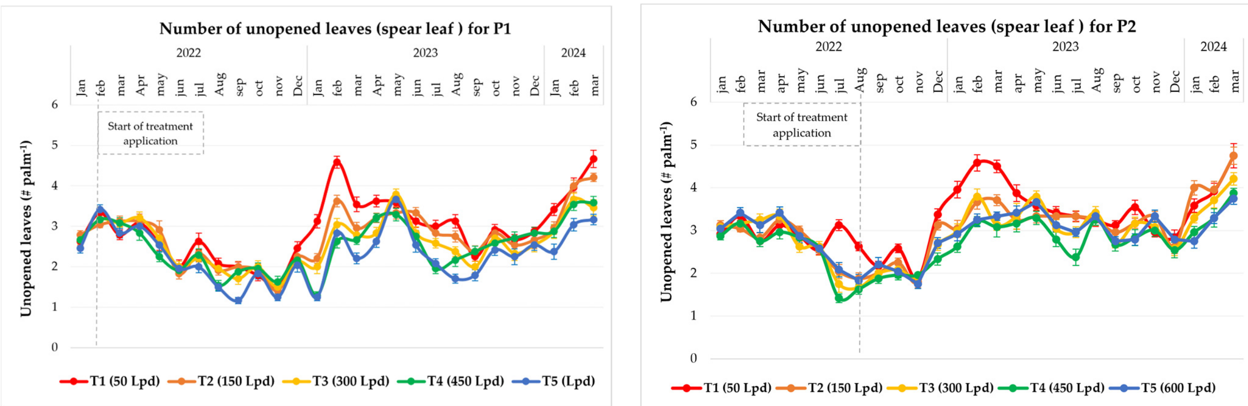
The EL in both plantations also exhibited a trend of decreasing under moisture deficit conditions. Treatments T1 and T2 demonstrated a significant reduction in this factor of up to five leaves per year (16%) compared to treatments T4 (450 Lpd) and T5 (600 Lpd). This indicates that the oil palm responds quickly to drought by lowering the rate of leaf opening, leading to an increased accumulation of leaves. Under prolonged deficit conditions, this may even result in a decrease in leaf initiation rates.

In relation to the number of leaves (NL), significant differences were observed in the two study sites for water deficit conditions (equal to or less than 150 Lpd), resulting in a reduction of 13% to 20% (five to nine leaves) for prolonged water deficits between 12 and 24 months. This reduction was a result of decreased leaf emission and the accumulation of non-functional leaves in the crop. These non-functional leaves were observed in the treatments and were characterized by subsequent drying and rachis breakage.

Finally, the dry weight of the fronds (FDW) of the crop (calculated as the product of the leaf dry weight of leaf 17 and the NL emitted in 12 months) exhibited a similar trend to the other variables. However, for plantation P1, no significant differences were observed. In plantation P2, a significant difference was observed between T1, T2, and T4, with the latter being 25 kg (five to six leaves) higher.

3.3.2. Effect on the Accumulation of Spears Leaf

The accumulation of spear leaves is a physiological symptom related to water stress caused by soil moisture deficit [33]. As shown in Figure 6a,b, during the experiment, the accumulation of unopened leaves ranged from 1.5 to 5 spears per palm on average across all treatments. Throughout the study period, during dry seasons, the crop showed an increase in this variable in direct response to delayed leaf opening under water deficit conditions. Conversely, with the onset of the rainy season, there was a notable increase in leaf opening, leading to a reduction in the number of spear leaves present on the palms. Although fluctuations in this variable were observed generally across the evaluated conditions, treatments T4 and T5 showed smaller fluctuations, reaching a maximum of 3.5 spears per month during the dry season in both plantations and a maximum of 2 and 3 spears per month during the rainy season.



(**a**) (**b**)

Figure 6. Monthly behavior of the accumulation of unopened leaves (spear leaf) per palm in the treatments for P1 (**a**) and P2 (**b**).

Based on the two-way ANOVA, no significant interaction between age and water application volume was found for all vegetative variables. The only notable difference was observed in crop age, indicating higher values for P2, which is logical considering the increased plant development at this stage (Figure A1).

3.3.3. Effect on Production (FFB t ha^{-1})

The data analysis indicated that the yield (FFB t ha^{-1}) is influenced by varying water conditions, displaying a clear trend of reduction as the soil moisture deficit intensifies. These effects became evident six months after the application of the treatments in both experiments (Table 4, Figures A2 and A3).

For plantation 1 (cultivar Deli × Avros, 10 to 12 years old), the production results for each of the treatments during the period from October 2021 to March 2024 are shown in Table 4 and Figure A2. After 2 years of applying the treatments, statistically significant differences ($p < 0.05$) were observed. Particularly, treatment T1 exhibited the lowest accumulated yield at 48.8 t ha^{-1}, representing a 26% reduction compared to treatment T4, which showed the highest accumulated yield at 65.7 t ha^{-1}. Treatments T2 and T3 recorded cumulative yields of 61 t ha^{-1} and 56.4 t ha^{-1}, indicating reductions of 6% and 14%, respectively. Treatment T5, with a value of 64.9 t ha^{-1}, did not exhibit statistically significant differences compared to treatment T4. These reductions in production, mainly in treatments T1, T2, and T3, can mainly be attributed to a decrease in the NB per palm (Table 4), as no significant differences were observed in the average BW among them.

Table 4. Cumulative yield (FFB), cumulative number of bunches per palm (NB), and average bunch weight (BW) in each treatment (for P1 between February 2022 and March 2024, and for P2 between August 2022 and March 2024).

	P1			P2		
Treatments	**FFB (t ha^{-1})**	**NB**	**BW (kg)**	**FFB (t ha^{-1})**	**NB**	**BW (kg)**
T1 (50 Lpd)	48.8 ± 3.1 b	18.5 ± 1.2 b	18.4 ± 0.8	57.6 ± 2.8	19.9 ± 1.0	21 ± 0.8
T2 (150 Lpd)	61.0 ± 2.7 ab	23.4 ± 1.2 ab	17.5 ± 0.6	58.5 ± 3.1	20.5 ± 1.1	20.7 ± 0.7
T3 (300 Lpd)	56.4 ± 2.4 ab	22.6 ±1.0 ab	17.8 ± 0.7	61.8 ± 2.8	21.1 ± 0.8	21.8 ± 0.7
T4 (450 Lpd)	65.7 ± 3.4 a	25.1 ± 1.2 a	18.3 ± 0.7	61.3 ± 4.1	18.8 ± 1.3	23.6 ± 0.7
T5 (600 Lpd)	64.9 ± 3.6 a	24.7 ± 1.3 a	18.4 ± 0.9	72.2 ± 3.3	21.7 ± 1.1	24.0 ± 0.8

Means followed by the same letter are not significantly different from one another, based on Tukey's multiple test at $p < 0.05$.

In contrast, at the P2 plantation (Deli × Avros cultivar, aged 15 to 17 years), although there was a tendency for yields to decrease with the reduction of available water in the soil, no significant differences were observed within the short evaluation period after the treatments (Table 4 and Figure A3). Up to this point, treatments T1, T2, T3, T4, and T5 yielded 57.6, 58.5, 61.8, 61.3, and 72.2 t ha^{-1}, respectively.

In the two-way ANOVA, no significant interaction was found between age and treatments for the PMR and yield (t ha^{-1}). However, a significant interaction was observed for the NR variable ($p < 0.0001$), indicating that the increase in NR between the two ages is proportional to the volume of water applied, with the most evident differences seen at application rates of 450 and 600 Lpd (Figure A4).

3.3.4. Effect on Oil Content

The baseline corresponding to the dry season of 2022 presented an oil potential content for P1 and P2 that varied between 25% and 34%. In the records from the dry and rainy seasons of 2023, there were no significant differences in treatments between the two plantations (Table 5). However, a trend was observed after 12 months of application, with a reduction in oil potential by 3% to 8% for water conditions below 300 L per day. This reduction was associated with decreases in Mes/FN and Oil/Mes by up to 6.8% and 8% for P1 and 7% and 3% for P2, respectively (Figures A5 and A6). Additionally, a slight reduction in oil potential (Oil/FFB) of up to 9% was observed in the rainy season compared to the dry period of 2023.

Table 5. Impact of water conditions on the normal fruit to fresh fruit bunch (NF/FFB), mesocarp to normal fruit (Mes/NF), oil to mesocarp (Oil/Mes), and oil potential (Oil/FFB) ratios for P1 and P2 in the dry and rainy seasons of 2023.

Plantation	Treatment	NF/FFB (%)		Mes/NF (%)		Oil/Mes (%)		Oil/FFB (%)	
		Dry S.	Rainy S.	Dry S.	Rainy S.	Dry S.	Rainy S.	Dry S.	Rainy S.
P1	T1 (50 Lpd)	73.9 ± 1.1	61.7 ± 2.7	74.4 ± 1.7	72.7 ± 2.1	58.3 ± 1.8	51.6 ± 1.8	29.0 ± 0.8	21.0 ± 1.3
	T2 (150 Lpd)	73.3 ± 1.3	69.1 ± 2.4	77.9 ± 1.2	75.8 ± 1.5	57.6 ± 2.2	52.2 ± 2.2	29.9 ± 0.9	25.5 ± 1.9
	T3 (300 Lpd)	72.6 ± 1.3	65.1 ± 3.7	78.5 ± 1.3	78.4 ± 2.3	54.3 ± 1.8	57.6 ± 2.3	27.9 ± 0.9	26.5 ± 1.8
	T4 (450 Lpd)	72.9 ± 1.5	69.4 ± 2.2	75.1 ± 1.5	78.7 ± 0.9	57.3 ± 2.2	59.8 ± 1.6	28.6 ± 1.2	29.9 ± 1.5
	T5 (600 Lpd)	73.1 ± 1.4	64.7 ± 1.8	79.4 ± 1.2	79.5 ± 1.3	55.3 ± 1.6	56.5 ± 1.9	29.3 ± 0.7	26.1 ± 1.5
P2	T1 (50 Lpd)	76.0 ± 1.6	74.7 ± 1.1	74.6 ± 2.0	74.3 ± 1.8	71.9 ± 1.4	73.9 ± 1.1	25.6 ± 1.9	25.5 ± 1.2
	T2 (150 Lpd)	77.3 ± 1.6	78.4 ± 0.7	78.8 ± 1.8	75.3 ± 1.9	71.9 ± 1.5	74.4 ± 0.7	29.0 ± 1.8	27.6 ± 1.6
	T3 (300 Lpd)	76.2 ± 1.2	75.4 ± 1.2	79.9 ± 0.9	77.5 ± 1.3	74.3 ± 0.8	75.4 ± 0.6	32.0 ± 1.0	28.3 ± 0.8
	T4 (450 Lpd)	78.8 ± 0.9	77.7 ± 1.3	77.7 ± 1.5	77.7 ± 1.3	74.4 ± 0.5	75.0 ± 0.7	30.2 ± 1.0	30.3 ± 1.2
	T5 (600 Lpd)	75.4 ± 1.1	78.1 ± 1.2	80.9 ± 0.8	77.3 ± 1.0	74.3 ± 0.9	77.0 ± 0.7	29.0 ± 1.3	30.6 ± 1.5

3.3.5. Evapotranspiration of the Oil Palm Crop (ETc)

After analyzing the crop and water balance data, it was determined that the crop evapotranspiration value for the two age ranges is best represented by treatments T4 (450 Lpd) and T5 (600 Lpd) due to their favorable impact on development, yield, and oil content potential.

In these treatments for the 10- to 12-year-old crop, the mean values of ETc ranged between 5.4 and 5.7 mm per day, with minimum and maximum values of 2.1 and 12 mm per day, respectively. For the 15- to 17-year-old crop, the mean values ranged from 5.1 to 5.7 mm per day (2.0–12 mm day^{-1}). The highest values were observed during the dry season (December to March), ranging from 4 to 12 mm per day, with mean values between 6 and 6.7 mm per day (Table 6). These results are attributed to high temperatures, increased wind speed, solar radiation, and irrigation management during this period. Conversely, values between 4.0 and 4.7 mm per day were recorded during the rainy season for both plantations.

Table 6. ETc values of adult *Elaeis guineensis* palm trees (10–17 years old) according to season.

Treatments	P1: 10–12 Years		P2: 15–17 Years Old	
	ETc (mm per Day)		ETc (mm per Day)	
	Dry Season (Dec–Mar)	Rainy Season (Apr–Nov)	Dry Season (Dec–Mar)	Rainy Season (Apr–Nov)
T1 (50 Lpd)	3.7 (1.5–7.8) *	2.7 (1.8–7.8)	2.9 (2.0–5.6)	2.3 (1.2–5.5)
T2 (150 Lpd)	4.1 (1.5–7.7)	3.5 (1.5–7.8)	3.3 (2.0–7.1)	2.2 (1.5–5.0)
T3 (300 Lpd)	5.0 (2.2–10.0)	3.5 (1.9–10.0)	4.1 (1.8–8.0)	3.9 (2.4–9.1)
T4 (450 Lpd)	6.1 (4.5–12)	4.7 (2.1–9.7)	6.0 (4.0–12)	4.1 (2.0–10)
T5 (600 Lpd)	6.6 (4.0–12)	4.8 (2.0–10)	6.7 (3.7–12)	4.7 (2.0–12)

* Numbers in parentheses correspond to ranges (maximum and minimum values).

On the other hand, it is also evident that crop evapotranspiration was influenced by the treatments and decreased in situations where the crop experienced a soil moisture deficit, particularly under treatments T1 (50 Lpd) and T2 (150 Lpd). This outcome is predictable because, as soil moisture declines, plants transpire at a lower rate than their potential, given that they must exert greater effort to access water [34].

Under treatment T1 (50 Lpd), the average evapotranspiration (ETc) value was 3.0 mm per day, ranging from 1.5 to 7.8 mm per day, reflecting a reduction of approximately 47% compared to the potential ETc values. Under treatment T2 (150 Lpd), the evapotranspiration ranged between 1.5 and 7.8 mm per day, with an average value of 3.8 mm per day, representing a decrease of approximately 33%. For treatment T3, with an application volume of 300 Lpd, the average evapotranspiration value was 4.2 mm per day (ranging from 1.9 to 10 mm per day), signifying a 26% reduction compared to the crop evapotranspiration determined in the treatments with the best crop response.

In contrast, when examining the ETc data from treatments T4 and T5, we noticed that they both show similar values. This suggests that the higher water application in treatment T5 may be excessive. This is because the crop only absorbs the necessary amount of water for its functions, while the rest of the water is lost through deep percolation and runoff, impacting the storage capacity of the soil.

3.3.6. Crop Coefficient (Kc)

The crop coefficient, Kc, reflects the relationship between estimated crop evapotranspiration (ETc) and reference crop evapotranspiration (ETo) for both P1 and P2. Table 7 illustrates the Kc values for each treatment, categorized by their variations in the dry and rainy months. The average Kc value for the 10- to 12-year-old crop was 0.88, ranging from 0.7 to 1.1, with a higher value observed in the dry season (at 0.9). Similarly, the 15- to 17-year-old crop had an average Kc value of 0.9, varying between 0.7 and 1.0. Notably, there was a distinction in Kc values between dry and rainy seasons, with higher values during dry months, decreasing as soil water availability diminishes. On average, for palms aged between 10 and 12 years, the Kc values were 0.6, 0.54, and 0.46 under treatments T3, T2, and T1, respectively. For palms aged between 15 and 17 years, the mean Kc values were 0.65 for T3, 0.43 for T2, and 0.4 for T1.

Table 7. Crop coefficient (Kc) values for adult *Elaeis guineensis* palm trees (10–17 years old) according to season.

Treatments	P1: 10–12 Years Kc		P2: 15–17 Years Old Kc	
	Dry Season (Dec–Mar)	Rainy Season (Apr–Nov)	Dry Season (Dec–Mar)	Rainy Season (Apr–Nov)
T1 (50 Lpd)	0.5 (0.2–1.2) *	0.4 (0.2–1.2)	0.4 (0.2–0.9)	0.4 (0.2–0.9)
T2 (150 Lpd)	0.6 (0.2–1.1)	0.5 (0.2–1.2)	0.5 (0.2–1.0)	0.4 (0.2–0.7)
T3 (300 Lpd)	0.7 (0.3–1.3)	0.5 (0.3–1.4)	0.6 (0.3–1.7)	0.7 (0.3–1.3)
T4 (450 Lpd)	0.9 (0.5–1.4)	0.7 (0.4–1.8)	0.9 (0.5–1.4)	0.7 (0.4–1.2)
T5 (600 Lpd)	1.1 (0.5–1.5)	0.7 (0.4–1.7)	1.0 (0.5–1.7)	0.8 (0.4–1.7)

* Numbers in parentheses correspond to ranges (maximum and minimum values).

4. Discussion

Ensuring adequate soil moisture is essential for optimal oil palm growth, helping to mitigate the effects of climate change and climate variability [35]. For this, as a first step, the actual water requirements of the crop must be determined. In this context, the reference values for average crop evapotranspiration (ETc) for mature oil palm trees in Colombia are still set at 5 mm per day, based on studies conducted in Malaysia under different climatic conditions [16,21].

Globally, within the areas where oil palm cultivation is established, the Northern Zone of Colombia has the most adverse climatic conditions. This region experiences the highest temperatures (33.4 °C), the lowest annual rainfall, and the longest periods of consecutive months with less than 100 mm of rainfall [36]. Therefore, this study aimed to establish experimental areas with these specific agroclimatic conditions in order to strategically evaluate the response of the crop to different water conditions.

The results of this research revealed that, under the conditions of the Northern Zone (ZN) of Colombia, the best crop responses were under treatments T4 (450 Lpd) and T5 (600 Lpd), between which statistical differences were not registered; however, concerning treatments T3, T2, and T1, significant reductions in LAI, EL, and B were observed. These results corroborate the studies conducted by Maillard et al. [37] (cited by Corley and Tinker [36]), who showed that the accumulation of spear leaves and the drying and cracking of leaves are some of the negative impacts of a lack of water in the soil. In the study conducted by Ikhajiagbe et al. [38], similar results were obtained regarding the LAI. This reduction can be attributed to a decrease in soil water availability. Furthermore, our observation of the LE's response to varying water volumes reaffirmed that oil palm trees quickly adjust to drought by decreasing their leaf opening rates, as highlighted by Chang et al. [39].

Moreover, this adjustment leads to increased accumulation of arrows [40,41] and, under prolonged deficit conditions, it can even generate a reduction in the leaf initiation rate [11].

Likewise, there was a decrease in the cumulative yield by 6%, 14%, and 25% under treatments T3, T2, and T1, respectively, mainly due to a reduction in the number of bunches due to the water deficit conditions. These results contrast with those reported by different authors (Azlan et al. [42]; Corley and Tinker [36]; Woittiez et al. [11]; Rhebergen et al. [43]), who have reported that water deficit conditions in oil palm mainly lead to a decrease in the number of bunches due to inflorescence abortions occurring 8 to 10 months before harvest, changes in the sex ratio, and an increase in male inflorescences 21 to 24 months before harvest. In severe droughts, bunch failure can occur 4 to 5 months before harvest [44]. Considering the response times of the crop to the treatments, it can be inferred that the reduction in the number of bunches is primarily due to inflorescence abortion and bunch dieback. Furthermore, it was observed that moisture deficit conditions also affected oil content, with reductions of 3% and 8% under applications of 150 and 50 Lpd, respectively. Research conducted by Henson [44] supports these findings. Their studies indicated that during periods of low rainfall, the rate of oil extraction decreases due to the impact of water deficit on the oil synthesis capacity. Under water stress conditions, authors such as Foong [45] and Cornaire et al. [46] have observed a 25% reduction in dry matter production, leading to a 50% decrease in FFB yields and, consequently, oil production.

Considering the above, this study concluded that the average crop evapotranspiration rates under the climatic conditions of the ZN range from 5.4 to 5.7 mm per day for palms aged 10 to 12 years and from 5.1 to 5.7 mm per day for palms aged 15 to 17 years. These results suggest that the water requirements of the crop are not significantly impacted by age but are primarily influenced by climatic conditions and soil water availability. The water needs are higher during the dry season but decrease in the rainy months due to reduced solar radiation, wind speed, and increased air humidity. These findings are supported by the study of Goh et al. [47], who indicated that the optimal daily evapotranspiration value for the crop is between 5 and 6 mm per day. While lower values suggest a water deficit, a decrease during the rainy season does not necessarily indicate water stress in the plant.

The variation in evapotranspiration for each treatment was directly linked to the variations in water application rates, temperature, and soil moisture content. When the soil moisture content is high (T4 and T5), the palm tree evapotranspires at its maximum capacity, representing the crop's potential evapotranspiration. The peak values for both plantations were observed between December and March, as a result of the high temperatures and solar radiation, leading to higher evaporative demand. The findings contrast with those reported by Dufrené et al. [19] and Norizan [17], who observed a decrease in ETc values during the dry season. This disparity may be attributed to the lack of consideration for irrigation application in their studies, resulting in requirement values under water-deficit conditions. In the case of treatments with water deficit (especially T2 and T1), reductions in the evapotranspiration rate were observed, as the water consumption of the plants was limited by the cohesion and adhesion forces of the soil matrix. This means that the crop needs to work harder to extract the required water when the soil moisture content is lower [48].

As mentioned above, the assessment of crop water consumption under varying water conditions—such as excess and deficit of soil moisture—enabled the determination of potential evapotranspiration values. Despite the application of 600 L of water per palm per day in treatment T5, the crop consistently exhibited mean ETc values of 5.7 mm per day in both plantations. This indicates that 5.7 mm per day is the amount utilized by the oil palm for its essential functions, with the excess water being lost through deep percolation and runoff. From this, it can be inferred that excessive water application results in unnecessary expenses during irrigation and creates conditions conducive to the development of diseases such as bud rot [49].

Based on the ETc values and daily ETo monitoring, the crop coefficient (Kc) for mature oil palm *Elaeis guineensis* trees (10 to 17 years old) was calculated to be between 0.88 and

0.9. Similar to ETc, these values exhibited distinct variations throughout the evaluation years, with the highest values observed during the dry months (0.9–1.1) and decreasing (to 0.7) during the rainy months. Dufrené [19] observed similar variations using the water balance method. The average ETc/ETo ratio for the adult crop was 0.82 under favorable conditions; however, this value was reduced to 0.62 or even as low as 0.56 under moisture deficit conditions. Consequently, it is advisable to use the crop water requirement values determined for the dry season for irrigation scheduling in order to prevent the crop from experiencing stress conditions due to moisture deficit. Additionally, utilizing these crop coefficients on a daily basis alongside ETo values serves as a strategy for the adjustment of crop irrigation in response to varying climatic conditions, thereby minimizing the risk of under or over-estimating the crop's water needs and ensuring its proper development and production.

5. Conclusions

In the oil palm crop regions of Colombia, the impacts of climate change and variability are leading to water scarcity and a reduction in water resources. This affects the productivity of crops and poses challenges for meeting their water needs. Consequently, there is a growing demand in the oil palm sector to comprehensively understand crop water requirements under the existing climatic conditions. This understanding is essential for implementing efficient irrigation management practices and ensuring long-term sustainability.

Our study rigorously measured the crop's response, in terms of growth, production, and water requirements, under varying water conditions to establish effective management strategies for the experimental areas. Our analysis revealed that the most favorable outcomes in growth, production (FFB t ha^{-1}), and oil content for *Elaeis guineensis* Jac oil palm trees, aged 10 to 17 years, were achieved with water applications ranging between 420 and 450 L per palm per day. Crop yields were significantly negatively impacted with water applications of less than 300 Lpd. Furthermore, we recommend extending the duration of the experiments to fully evaluate their overall impact on production parameters, particularly those related to reductions due to sexual differentiation. Excessive humidity (resulting from the application of 600 L/palm/day) was deemed unnecessary and could create unfavorable conditions leading to fungal diseases in the crop.

The results of this study indicate that the average daily evapotranspiration of adult oil palm *Elaeis guineensis* Jac trees in the Northern Zone of Colombia ranges between 5.4 and 5.7 mm, increasing to 6.1 to 7 mm during the dry season (December–March) in irrigated areas. These findings can be utilized to mitigate water deficit risks during these periods. Additionally, the average crop coefficient (Kc) values for age ranges of 10–12 years and 15–17 years were found to be 0.88 and 0.9, respectively. This parameter exhibited variability during the evaluation period, suggesting its daily use in irrigation scheduling along with ETo data for more precise adjustment of irrigation requirements.

Author Contributions: Conceptualization, T.D.; methodology, T.D. and G.L.; formal analysis, T.D. and G.L.; investigation, G.L.; resources, N.A.; data curation, T.D. and G.L.; writing—original draft preparation, T.D. and G.L.; writing—review and editing, T.D. and G.L.; visualization, T.D. and G.L.; supervision, T.D. and N.A.; project administration, N.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data and materials supporting the results of this project are available upon request from the authors by mail because the data are part of the ongoing project "Water requirements by cultivar, production stage and agroecological zone" at the Oil Palm Research Center, Cenipalma.

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Conflicts of Interest: The authors declare that they have no conflicts of interest.

Appendix A

Type 3 Tests of Fixed Effects			
Variable	**Age**	**Treatment**	**Interaction (Age x Treatment)**
LA17	**	*	ns
DW17	**	ns	ns
LAI	ns	*	ns
FDW	*	ns	ns

(**) Very significant, (*) significant, and without significant statistical differences (ns).

Figure A1. Results of two-way ANOVA analysis for vegetative variable: leaf area of leaf 17 (LA17), dry weight of leaf 17 (DW17), leaf area index (LAI), and dry weight of the fronds (FDW).

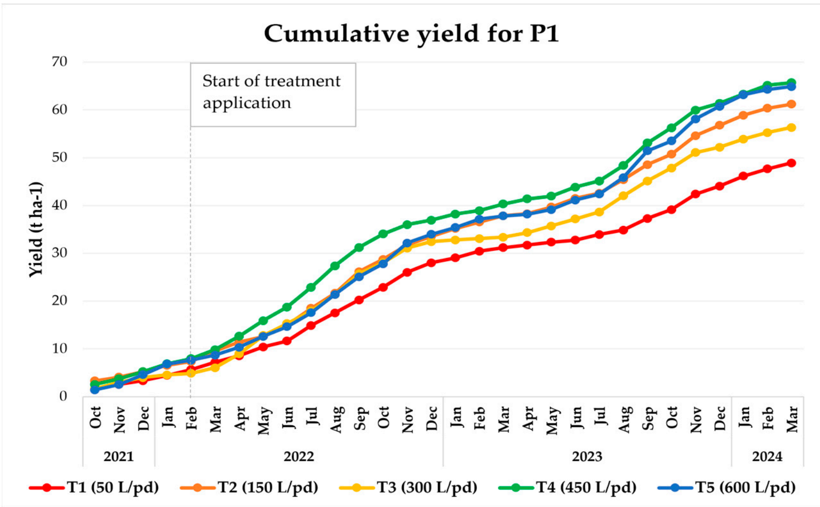

Figure A2. Cumulative yield FFB (October 2021–March 2024) for the cultivar Deli × Avros in planting P1.

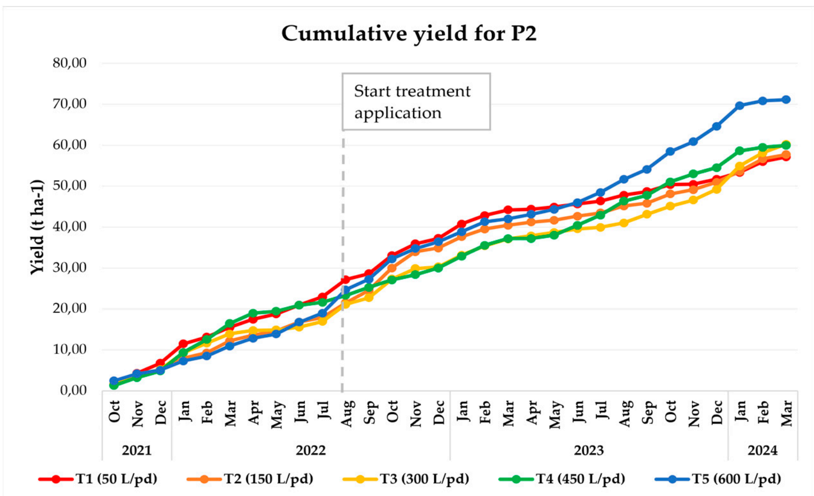

Figure A3. Cumulative yield FFB (October 2021–March 2024) for the cultivar Deli × Avros in planting P2.

Type 3 Tests of Fixed Effects			
Variable	**Age**	**Treatment**	**Interaction (Age x Treatment)**
FFB	ns	**	ns
NB	**	*	*
BW	**	*	ns

Very significant (**), significant (*), and without significant statistical differences (ns).

Figure A4. Results of two-way ANOVA analysis for crop production variables.

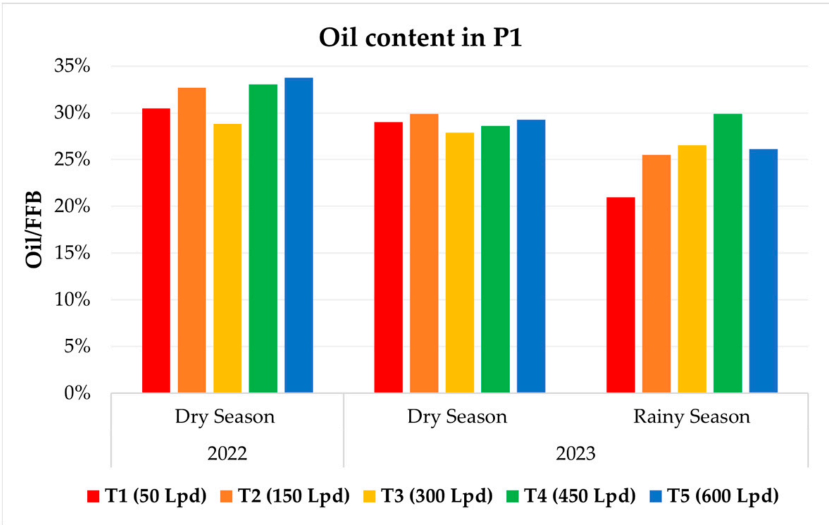

Figure A5. Oil potential content for P1 in the dry season of 2022 (baseline) and the dry and rainy season of 2023.

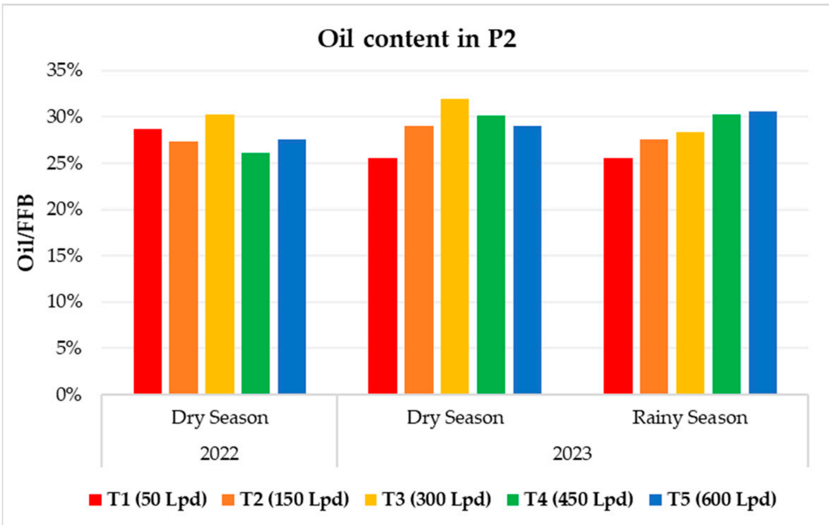

Figure A6. Oil potential content for P1 in the dry season of 2022 (baseline) and the dry and rainy season of 2023.

References

1. IDEAM. *Estudio Nacional Del Agua 2022*; Herrán, M.G., Martínez, M.O.V., Eds.; Instituto de Hidrología, Meteorología y Estudios Ambientales: Bogotá, Colombia, 2023; Volume 1.
2. IPCC. Sections. In Climate Change 2023: Synthesis Report. In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; Volume 1, pp. 35–115. [CrossRef]

3. Corley, R.H.V. Climate Change—What Does It Mean for Oil Palm. *Planter* **2016**, *92*, 631–654.
4. Watson-Hernández, F.; Serrano-Núñez, V.; Gómez-Calderón, N.; Pereira da Silva, R. Quantification and Evaluation of Water Requirements of Oil Palm Cultivation for Different Climate Change Scenarios in the Central Pacific of Costa Rica Using APSIM. *Agronomy* **2023**, *13*, 19. [CrossRef]
5. IDEAM; UNAL. *La Variabilidad Climática y El Cambio Climático En Colombia*, 1st ed.; Franco, J.M., Ruiz Murcia, F., Pabón Caicedo, J.D., Eds.; IDEAM: Bogotá, Colombia, 2018.
6. Fedepalma. Balance 2022 y Retos 2023. Available online: https://fedepalma.org/noticias/la-palmicultura-colombiana-en-cifras/ (accessed on 27 June 2024).
7. Almeida, J.; Ríos, A.R.; Prager, S.; Schiek, B.; González, C.E. Vulnerabilidad al Cambio Climático e Impactos Económicos En El Sector Agrícola En América Latina y El Caribe. In *Nota Técnica Del BID 1985*, 1st ed.; Cabrera, M., Ed.; Banco Interamericano de Desarrollo: Washington, DC, USA, 2020; Volume 1.
8. Brum, M.; Oliveira, R.S.; López, J.G.; Licata, J.; Pypker, T.; Chia, G.S.; Tinôco, R.S.; Asbjornsen, H. Effects of Irrigation on Oil Palm Transpiration during ENSO-Induced Drought in the Brazilian Eastern Amazon. *Agric. Water Manag.* **2021**, *245*, 106569. [CrossRef]
9. Culman, M.; de Farias, C.M.; Bayona, C.; Cabrera Cruz, J.D. Using Agrometeorological Data to Assist Irrigation Management in Oil Palm Crops: A Decision Support Method and Results from Crop Model Simulation. *Agric. Water Manag.* **2019**, *213*, 1047–1062. [CrossRef]
10. Álvarez, O.M.; Ruiz Álvarez, E.; Mosquera Montoya, M.; Silva, J.H. Evaluación Económica de Sistemas de Riego Para Plantaciones En La Zona Norte de Colombia. *Palmas* **2017**, *39*, 69–85.
11. Woittiez, L.S.; van Wijk, M.T.; Slingerland, M.; van Noordwijk, M.; Giller, K.E. Yield Gaps in Oil Palm: A Quantitative Review of Contributing Factors. *Eur. J. Agron.* **2017**, *83*, 57–77. [CrossRef]
12. Rey, H.; Quencez, P.; Dufrêne, É.; Dubos, B. Profils Hydriques et Alimentation En Eau Du Palmier à Huile En Côte d'Ivoire. *Plant. Rech. Dév.* **1998**, *5*, 47–57.
13. Mejía Sáenz, E.; Palacios Vélez, E.; Exebio García, A.; Santos Hernández, A.L. Problemas Operativos En El Manejo Del Agua En Distritos de Riego. *Terra* **2002**, *20*, 217–225.
14. Kallarackal, J.; Jeyakumar, P.; George, S.J. Water Use of Irrigated Oil Palm at Three Different Arid Locations in Peninsular India. *J. Oil Palm Res.* **2004**, *16*, 59–67.
15. Henson, I.E.; Roslan Noor, M.; Haniff Harun, M.; Yahya, Z.; Nor Aishah Mustakim, S. Stress Development and Its Detection in Young Oil Palms in North Kedah, Malaysia. *J. Oil Palm Res.* **2005**, *17*, 11–26.
16. Carr, M.K.V. The Water Relations and Irrigation Requirements of Oil Palm (*Elaeis guineensis*): A Review. *Exp. Agric.* **2011**, *47*, 629–652. [CrossRef]
17. Norizan, M.S.; Wayayok, A.; Karim, Y.A.; Abdullah, A.F.; Mahadi, M.R. Quantitative Approach for Irrigation Requirement of Oil Palm: Case Study in Chuping, Northern Malaysia. *J. Oil Palm Res.* **2021**, *33*, 278–288. [CrossRef]
18. Arshad, A.M. Crop Evapotranspiration and Crop Water Requirement for Oil Palm in Peninsular Malaysia. *J. Biol. Agric. Healthc.* **2014**, *4*, 23–28.
19. Dufrene, E.; Dubos, B.; Rey, H.; Quencez, P.; Saugier, B. Changes in Evapotranspiration from an Oil Palm Stand (*Elaeis guineensis* Jacq.) Exposed to Seasonal Soil Water Deficits. *Oléagineux* **1993**, *48*, 105–120.
20. Safitri, L.; Hermantoro, H.; Purboseno, S.; Kautsar, V.; Saptomo, S.K.; Kurniawan, A. Water Footprint and Crop Water Usage of Oil Palm (*Eleasis guineensis*) in Central Kalimantan: Environmental Sustainability Indicators for Different Crop Age and Soil Conditions. *Water* **2018**, *11*, 35. [CrossRef]
21. Foong, S.F. Potential Evapotranspiration, Potential Yield and Leaching Losses of Oil Palm. In Proceedings of the 1991 Porim International Palm Oil Conference, Kuala Lumpur, Malaysia, 9–14 September 1991; Palm Oil Research Institute of Malaysia: Kuala Lumpur, Malaysia, 1993; pp. 105–119.
22. Lee, C.T.; Arifin, I. Lysimeter Studies and Irrigation of Oil Plam in Some Inland Soils of Peninsular Malaysia-Felda's Experience. *Planter* **2013**, *89*, 15–29.
23. IGAC. Departamento Del Cesar. In *Estudio General de Suelos y Zonificación de Tierras: Escala: 1:100.000*, 1st ed.; Instituto Geográfico Agustín Codazzi, Subdirección de Agrología, Eds.; Imprenta Nacional de Colombia: Bogotá, Colombia, 2017.
24. USDA. Infiltración: Sección 2—Guía de Antecedentes e Interpretativas Para Ensayos Individuales. In *Guía para la Evaluación de la Calidad y Salud del Suelo*; Instituto de Calidad de Suelos, Departamento de Agricultura de los Estados Unidos: Washington, DC, USA, 1999; pp. 55–57.
25. Cenipalma. *Mejores Prácticas Agroindustriales Del Cultivo de La Palma de Aceite En Colombia*, 2nd ed.; Cenipalma: Bogotá, Colombia, 2017.
26. NRCS. Estimation of Direct Runoff from Storm Rainfall. In *National Engineering Handbook*; Part 630 Hydrology; Natural Resources Conservation Service, Ed.; NRCS: Washington, DC, USA, 2004; Volume 1, p. 51.
27. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Evapotranspiración Del Cultivo: Guías Para La Determinación de Los Requerimientos de Agua de Los Cultivos*, 1st ed.; Estudio FAO de Riego y Drenaje 56: Roma, Italy, 2006.
28. Corley, R.H.V.; Gray, B.S.; Kee, N.S. Productivity of the Oil Palm (*Elaeis guineensis* Jacq.) in Malaysia. *Exp. Agric.* **1971**, *7*, 129–136. [CrossRef]

29. España-Guechá, M.S.; Cayón-Salinas, D.G.; Darghan-Contreras, A.E.; Ochoa-Cadavid, I. Área Foliar, Contenido de Clorofila, y Masa Seca de Raíces En Palmas de Aceite (*Elaeis guineensis* Jacq.) Afectadas Por El Disturbio Del Plumero. *Agron. Colomb.* **2020**, *38*, 335–341. [CrossRef]
30. Cayón Salinas, D.G. Apuntes Sobre Fisiología Del Crecimiento y Desarrollo de La Palma de Aceite (*Elaeis guineensis* Jacq.). *Palmas* **1999**, *20*, 43–54.
31. Prada Chaparro, F.; Romero Angulo, H.M. Muestreo y Análisis de Racimos En El Cultivo de La Palma de Aceite. In *Tecnologías Para La Agroindustria de La Palma de Aceite: Guia Para Facilitadores*, 1st ed.; Cenipalma: Bogotá, Colombia, 2012.
32. NOAA. Cold & Warm Episodes by Season. Available online: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php (accessed on 4 August 2024).
33. Narsimha Rao, B.; Suresh, K.; Behera, S.K.; Ramachandrudu, K.; Manorama, K. *Technical Bulletin—Irrigation Management in Oil Palm*, 1st ed.; Institute of Oil Palm Research: Pedavegi, India, 2016; Volume 1.
34. Torres, J.; Cruz, R.; Villegas, F. *Avances Técnicos Para La Programación y El Manejo Del Riego En Caña de Azúcar. (Serie Técnica N° 33)*, 2nd ed.; Cenicaña: Cali, Colombia, 2004.
35. Ruiz-Romero, R.; Delgado, T.; Zapata, A.; Romero, H.M. Manejo y Uso Del Agua En Cultivares Híbridos Interespecíficos OxG. In *Los Híbridos Interespecíficos OxG de Palma de Aceite*; Romero, H.M., Ed.; Centro de Investigación en Palma de aceite, Cenipalma: Bogotá, Colombia, 2023; pp. 219–250.
36. Corley, R.H.V.; Tinker, P.B. *The Oil Palm*, 5th ed.; Wiley Blackwell: Hoboken, NJ, USA, 2016. [CrossRef]
37. Maillard, G.; Claude, D.; Ochs, R. Analyse Des Effets de La Sécheresse Sur Le Palmier a' Huile. *Oléagineux* **1974**, *29*, 397–404.
38. Ikhajiagbe, B.; Aituae, W.; Ogwu, M.C. Morpho-Physiological Assessment of Oil Palm (*Elaeis guineensis* Jacq.) Seedlings Exposed to Simulated Drought Conditions. *J. Oil Palm Res.* **2022**, *34*, 26–34. [CrossRef]
39. Chang, K.C.; Foster, H.L.; Abas, Z. Monthly Frond Production of Oil Palm in Malaysia. *Oléagineux* **1988**, *43*, 439–444.
40. Broekmans, A.F.M. Growth, Flowering and Yield of the Oil Palm in Nigeria. *J. West Afr. Inst. Oil Palm Res.* **1957**, *2*, 187–220.
41. Nouy, B.; Baudouin, L.; Djégui, N.; Omoré, A. Le Palmier à Huile En Conditions Hydriques Limitantes. *Plant. Rech. Dév.* **1999**, *6*, 31–45.
42. Azlan, A.H.; LeeChin, T.; SohKim, Y.; Selvaraja, S.; Rohan, R.; Ariffin, I.; Palaniappan, S. Impact of El Niño on Palm Oil Production. *Planter* **2016**, *92*, 789–806. [CrossRef]
43. Rhebergen, T.; Fairhurst, T.; Giller, K.E.; Zingore, S. The Influence of Water and Nutrient Management on Oil Palm Yield Trends on a Large-Scale Plantation in Ghana. *Agric. Water Manag.* **2019**, *221*, 377–387. [CrossRef]
44. Henson, I.E. Limitations to Gas Exchange, Growth and Yield of Young Oil Palm. *Trans. Malays. Soc. Plant Physiol.* **1991**, *1*, 165–171.
45. Foong, S.F. Impact of Moisture on Potential Evapotranspiration, Growth and Yield of Oil Palm. In Proceedings of the 1999 PORIM International Palm Oil Conference, Kuala Lumpur, Malaysia, 9–14 September 1991; Palm Oil Research Institute of Malaysia: Kuala Lumpur, Malaysia, 1999; p. 6486.
46. Cornaire, B.; Daniel, C.; Zuily-Fodil, Y.; Lamade, E. Oil Palm Performance under Water Stress. *Oleagineaux* **1994**, *49*, 1–11.
47. Goh, K.J.; Chiu, S.B.; Paramananthan, S. *Agronomic Principles and Practices of Oil Palm Cultivation*; Agricultural Crop Trust (ACT): Petaling Jaya, Malaysia, 2011.
48. Eisenhauer, D.E.; Martin, D.L.; Heeren, D.M.; Hoffman, G.J. *Irrigation Systems Management*, 1st ed.; McCann, P., Ed.; the American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 2021. [CrossRef]
49. Torres, G.A.; Sarria, G.A.; Martinez, G.; Varon, F.; Drenth, A.; Guest, D.I. Bud Rot Caused by Phytophthora Palmivora: A Destructive Emerging Disease of Oil Palm. *Phytopathology* **2016**, *106*, 320–329. [CrossRef]