

Article

Optimizing Irrigation Strategies in Black Pepper (*Piper nigrum* L.) for Enhanced Productivity and Essential Oil Yield

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Abstract

Black pepper (*Piper nigrum* L.) is an important crop in Pará, Brazil; however, irrigation management remains one of the main constraints to achieving stable productivity and high essential oil yield. By determining soil water tension for rational irrigation management that ensures high agronomic performance of black pepper, it is possible to optimize irrigation water use efficiency through monitoring critical soil moisture with the aid of tensiometers. This study evaluated yield, water use efficiency (WUE) and essential oil yield of two black pepper genotypes under five soil water tensions (15–55 kPa) using a split-plot experimental design. The Uthirankotta genotype showed higher yield and WUE, reaching maximum values at 35 kPa, whereas the highest essential oil extraction yield occurred at 15 kPa. Positive correlations were observed between essential oil yield and the main productive traits. Therefore, cultivation of the Uthirankotta genotype under tensiometer-based irrigation management is recommended under the edaphoclimatic conditions of Pará, using a critical tension of 35 kPa as a reference to increase productivity and optimize irrigation water use efficiency, considering the differential genotype response to irrigation management under humid tropical conditions.

Keywords: water use efficiency; genotype performance; tensiometry; irrigated agriculture



Academic Editors: Rosario Paolo Mauro, Xuewen Gong and Xianbo Zhang

Received: 28 October 2025

Revised: 27 December 2025

Accepted: 8 January 2026

Published: 20 January 2026

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1. Introduction

Currently, Brazil occupies the second position in world *Piper nigrum* production and export, with 128,331 tons [1], mainly in the form of black pepper. The main production centers are concentrated in Southeast Brazil and Pará (North Brazil) under different cultiva-

tion patterns; that is, in the Southeast, pepper cultivation is developed in a business-rural manner, while in the North region it is carried out through family farming [2].

Several factors contribute to the decline in production in the areas cultivated by pepper growers from Pará (North Brazil) compared to the systems practiced by producers from southeast Brazil, among which the low adoption of agronomic technologies and the decline in recent years of rural credit lines linked to the crop stand out [3,4].

In contrast, the cultivation of high-yielding black pepper genotypes, combined with the seasonality of harvest and the use of technologies in the production system, such as irrigation, contribute to the significant yields achieved by Espírito Santo (Southeast Brazil) producers in recent years [5,6]. Although irrigated agriculture is associated with a high technological level, inadequate technical management of irrigation in some regions of Brazil generates great water waste, with estimates that only 50% of all water withdrawn is effectively used by plants [7,8].

Through rational irrigation management, it is possible to reduce water use by up to 30% and achieve increases in crop productivity ranging from 10% to 30% [9]. In irrigation managed by tensiometry, measurements of soil water tension are used to indirectly determine the crop's water demand. The readings are obtained through the tensiometer, which establishes when and how much to irrigate, without the need for meteorological data, which are commonly unavailable and costly to farmers [10], and minimizes the risks of water stress, whether due to deficit or excess.

Water deficiency presents a direct correlation with the concentration of substances belonging to the secondary metabolism of plants [11]. The combination of these classes of substances (volatile and lipophilic) constitutes essential oils, which may have their composition and yield influenced by genetic, edaphic and climatic factors [12]. The essential oil obtained from black pepper is widely used in the food, cosmetics and perfume industries and contains several compounds, among which piperine stands out as the main compound responsible for pungency, while the characteristic aroma derives from volatile terpenes present in the essential oil [5,13].

Given the above, in aromatic plants, in addition to productive performance, essential oil production may also be influenced by biotic and abiotic factors. In this context, although new studies related to the use of tensiometers in the irrigation management of black pepper are emerging, the definition of the ideal soil water tension for applying the appropriate irrigation depth for each black pepper genotype under humid tropical conditions—by comparing and evaluating their different productive responses and fruit essential oil yields—remains poorly addressed, thereby limiting practical recommendations for the agronomic performance of the crop.

Thus, to analyze the influence of irrigation management in black pepper crops under the edaphoclimatic conditions of Pará, Brazil, the present study aimed to evaluate the productive performance and essential oil yield of black pepper genotypes subjected to different critical soil water tensions.

Therefore, this study was designed to evaluate how black pepper genotypes respond to different critical soil water tensions under tensiometer-based irrigation management. We hypothesized that genotype $\times$ tension interactions would significantly influence both productive performance and essential oil yield, allowing the identification of an optimal irrigation threshold for the edaphoclimatic conditions of Pará. By integrating agronomic and phytochemical responses, this work aims to provide a science-based recommendation for improving irrigation efficiency, maximizing yield and supporting sustainable water use in black pepper cultivation in the Brazilian Amazon region.

2. Materials and Methods

2.1. Location and Environmental Conditions of the Experiment

The experiment was carried out in situ from December 2022 to December 2023, in the experimental field of the company: Empresa de Produtos Tropicais de Castanhal LTDA—TROPOC, located in the municipality of Castanhal ($1^{\circ}17'50''$ S and $47^{\circ}55'20''$ W), Pará State, Brazil (Figure 1).

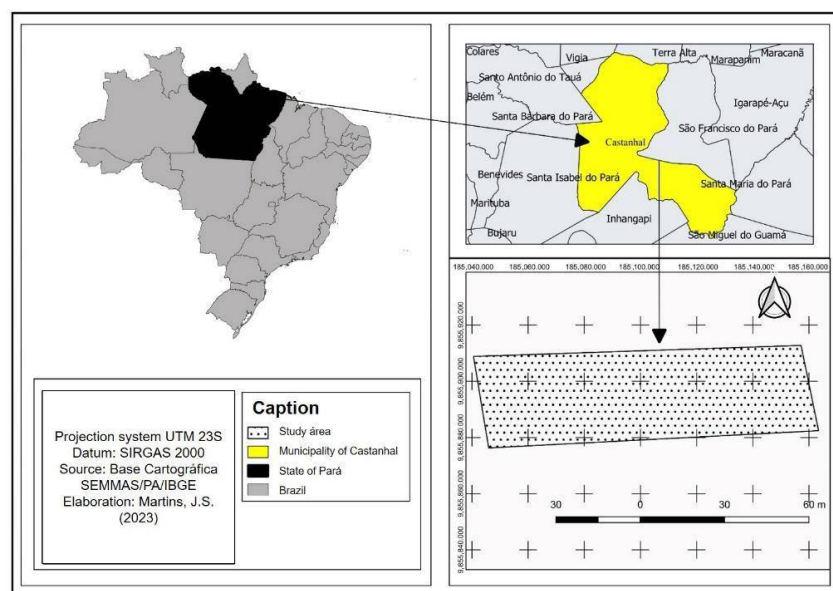


Figure 1. Location map of the area used for conducting the experiment in the state of Pará, Brazil. Source: The author (2024).

The climate of the region, according to the Köppen classification, is type Ami, with an average annual temperature of 26°C and annual rainfall of 2571.6 [14]. Figure 2 illustrates the behavior of the meteorological variables air temperature, global radiation, relative humidity and rainfall throughout the experiment, based on data from the automatic station A202 (Castanhal-PA) of the National Institute of Meteorology (INMET), located approximately 20 km from the experimental area.

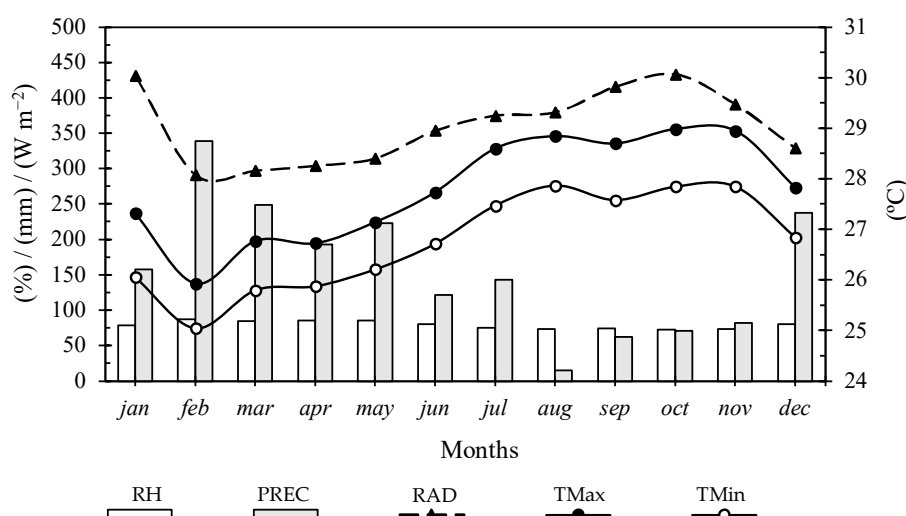


Figure 2. Monthly means of maximum (TMax) and minimum (TMin) temperatures, global radiation (RAD), relative humidity (RH) and precipitation (PREC) recorded during the experimental period. Adapted from INMET [15]. Source: The author (2024).

According to the climatological water balance of the municipality of Castanhal, conducted by Santos [16], it is observed that from February to May there is a water surplus in the region, while from July to November there is a water deficit. Between December and January, soil water replenishment occurs with the onset of the rainy season, whereas the maximum water deficiency, due to soil water withdrawal during the dry season, is recorded in August and September (Figure 3).

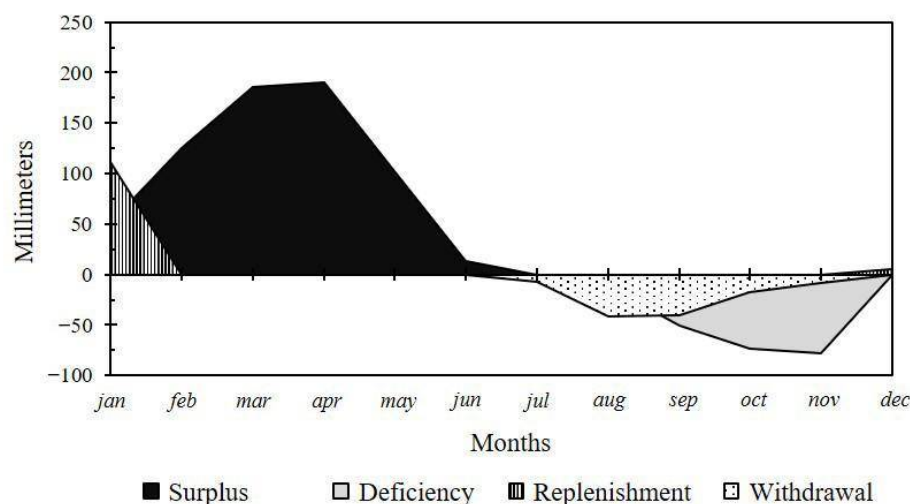


Figure 3. Periods of surplus, deficiency, withdrawal and replenishment of water in the municipality of Castanhal between 2003 and 2022.

The direct relationship between local climatic variability, shown in Figure 3, and the decision-making process of how much and when to irrigate, conditions the use of irrigation management methods based on monitoring the soil water status, rather than just relying on climatic averages, as in methods based on local evapotranspirative conditions, which are often used in the irrigation management of other Amazonian tropical crops.

According to the Brazilian Soil Classification System—SiBCS [17], the soil in the experimental area is classified as a dystrophic Yellow Latosol, with a medium textural class. Soil samples were collected annually from the 0–20 cm layer between the end of harvest and the beginning of the annual fertilization period, for chemical and physical analyses conducted at the Soil Laboratory of EMBRAPA Eastern Amazon. These evaluations correspond to the third productive year of the crop (fourth year after planting). The results of the soil physicochemical properties, presented in Table 1, were used to determine the fertilizer rates applied to the black pepper plants.

2.2. Agronomic Management of Black Pepper Plants

Wooden stakes are used as support structures for training black pepper vines in the field, since the crop requires a trellising system; in this case, the plants were supported by wooden stakes (non-living or “dead” tutors). The data presented in this study are part of a long-term research project initiated in 2019 and concluded with the execution of the present experiment.

The subplots (2.2 m × 8.8 m) consisted of eight plants of the Uthirankotta and Clonada genotypes, acquired from the ProMudas nursery (Castanhal-PA). The useful subplot area (4.84 m²) was composed of the four central plants, while two plants at the front and two at the end of each subplot were considered border plants and therefore excluded from the evaluations. The subdivision of the plots allowed the combination of the experimental factors—soil water tension and genotype—where each main plot contained 16 plants (8 of each genotype), forming two subplots per treatment. The experiment was arranged in

three blocks, with treatments distributed using the restricted randomization method within each block.

Table 1. Physical–chemical characterization of the soil used in experimental planting. Data collected EMBRAPA (2023).

Chemical properties													
Depth	pH	O.M.	N	P	K	Na	Ca	Ca + Mg	Al	H + Al	CEC	Saturation	
(cm)	(H ₂ O)	(g kg ^{−1})	(%)	(mg dm ^{−3})			(cmolc dm ^{−3})					Base	Al
												(V%)	(m%)
0–20	5.75	10	36	8	2.14	3.25	0.11	2.51	4.36	59.89	4.09	5.75	10
Physical properties													
Depth	Granulometry					Density			Porosity				
	Sand		Silt	Clay	Soil	Particle	Particle	Micro	Total				
	Thick	Fine											
	(cm)	(g kg ^{−1})			(g cm ^{−3})			(cm ³ cm ^{−3})					
0–20	291	442	127	140	1.54	2.6	0.078	0.286	0.364				

Source: The author (2024).

Production fertilization for the fourth year of planting (phenological stage during the experiment) was carried out according to the results of the soil chemical analysis and following the recommendations for liming and fertilization for the state of Pará [18]. In early January 2023, during the rainy season, organic and mineral fertilization was applied in a semicircle in front of the plant stems: 1.5 L plant^{−1} of castor cake; 109.8 g plant^{−1} of triple superphosphate—41% P₂O₅ and 10% Ca (equivalent to the total phosphorus dose); 148.1 g plant^{−1} of urea—45% N; and 161.1 g plant^{−1} of potassium chloride—60% K₂O (one-third of the total nitrogen (144.4 g plant^{−1}) and potassium (483.3 g plant^{−1}) doses, respectively). After application, the fertilizer mixture was covered with soil. According to Brasil et al. [18], at 45 and 90 days after the first fertilization, the remaining two-thirds of the total nitrogen and potassium doses were applied in a similar manner. Fifteen days after the first fertilization of the fourth planting year, 0.1 g L^{−1} of Complex 151 was applied via foliar fertilization to improve plant recovery and development [19].

Crop protection practices consisted of applications of neem oil (20 mL L H₂O^{−1}) for the eventual control of insect pests [20], mowing between and along planting rows and manual weeding around the base of black pepper plants for weed control. Mulching was also applied around the plants using *Urochloa decumbens* biomass (also used as a live cover crop) removed from the inter-rows, to maintain soil moisture in the rhizosphere.

A drip micro-irrigation system was used for soil moisture and irrigation management. The system operated at a flow rate of 3.55 L h^{−1}, with emitters spaced at 30 cm intervals. The drip line, with a nominal diameter (DN) of 16 mm, contained pressure-compensating flat emitters (drip-tech PC/AS) and was installed on the soil surface of the experimental area with a service pressure of 10 m.w.c. (meters of water column) at the end of the drip tube. Seven emitters were used per plant, with two drip lines positioned within each experimental plot due to the double-row planting system of black pepper.

2.3. Irrigation Management by Tensiometry

Irrigation management was carried out through soil monitoring, based on the critical matric potential for the crop. For this purpose, sets of three puncture tensiometers were used to measure soil water tension, which determined when and how much to irrigate. Two tensiometers were installed at a depth of 20 cm and one at 40 cm from the soil surface

to monitor water percolation. The instruments were placed parallel to the crop rows at 15 cm from the emitters [21]. For reading the matric potential (tension) in the digital needle tensiometer, a digital puncture tensiometer was used. Measurements were taken daily at 08:30 a.m.

Irrigation events were performed when the average value of the tensions measured by the tensiometers installed at 20 cm depth reached the critical tension defined for each treatment, aiming to raise the soil moisture content to field capacity [22]. The volume of water applied per plant and the irrigation time for each treatment were calculated by first determining the soil water matric potential using Equation (1) [21]

$$\Psi_m = -L + 0.098 \times c \quad (1)$$

in which,

- Ψ_m —Soil water matric potential (kPa);
- L —Average tension measured in puncture tensiometers (kPa);
- 0.098—Moisture adjustment factor (dimensionless) and;
- c —Tensiometer length (cm).

Based on the soil water retention curve (Figure 4), fitted by the van Genuchten mathematical model [23] as proposed by Santos [16] for the 0–20 cm soil layer, the range of tensions used as treatments was defined according to the soil physical-hydric principles of the experimental area (sandy texture). In other words, the 15 to 55 kPa range encompasses the interval of greatest dynamic relevance for plant-available water in this type of soil.

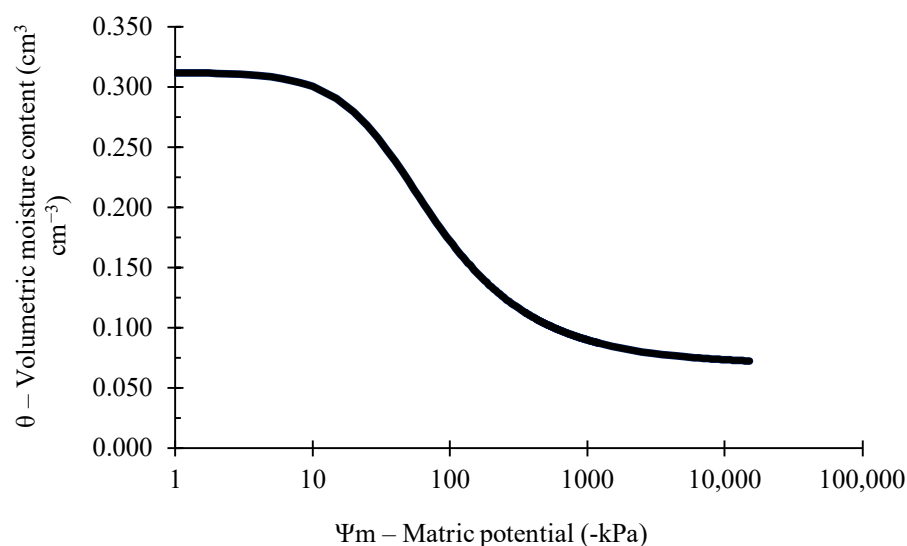


Figure 4. Soil water retention curve for the experimental area. Source: [16].

Based on the soil water retention curve, fitted by the mathematical model of van Genuchten [23] by Santos [16] for the 0–20 cm soil layer, the current soil moisture content (θ) was estimated as a function of soil water tension (Ψ_m), using Equation (2).

$$\theta = \left\{ \frac{(0.312 - 0.0696)}{\left[1 + (0.03 \times |\Psi_m|)^{1.73} \right]^{0.422}} \right\} + 0.0696 \quad (2)$$

in which,

- θ —Volume-based soil moisture ($\text{cm}^3 \text{cm}^{-3}$) and;
- Ψ_m —Soil water matric potential (kPa).

From the current soil moisture value (θ), estimated by Equation (2), the net irrigation depth for each treatment was calculated using Equation (3) [24], considering the effective rooting depth of black pepper plants as 20 cm [20] and the volumetric water content equivalent to field capacity at a tension of 10 kPa [25], which, according to the model fitted in Equation (3), corresponds to $0.3003 \text{ cm}^3 \text{ cm}^{-3}$

$$L_L = (\theta_{CC} - \theta) \times Z \quad (3)$$

in which,

L_L —Net irrigation depth (mm);
 θ_{CC} —Soil moisture at field capacity ($\text{cm}^3 \text{ cm}^{-3}$);
 θ —Current soil moisture ($\text{cm}^3 \text{ cm}^{-3}$) and;
 Z —Effective depth of the root system (mm).

Once the net irrigation depth was obtained, the gross irrigation depth was calculated using Equation (4), and finally, the operating time of the system for each irrigation event was determined using Equation (5) [24].

$$L_B = \frac{L_L}{(1 - k) \times \text{CUD}} \quad (4)$$

in which,

L_B —Gross irrigation depth (mm);
 L_L —Net irrigation depth (mm);
 CUD —Distribution Uniformity Coefficient (%) equal to 97% and;
 k —Efficient water application constant of the irrigation system [26].

$$T_i = \frac{L_B \times A}{e \times q_m} \quad (5)$$

in which,

T_i —Irrigation time for each treatment (hours);
 L_B —Gross irrigation depth (mm);
 A —Area occupied per plot (m^2);
 q_m —Average flow rate of emitters (L h^{-1}) and;
 e —Number of emitters per experimental plot (unit).

2.4. Data Processing and Collection

For the field plots, a randomized block design (RBD) was used, in a split-plot factorial scheme (5×2), totaling ten treatments and three blocks (replications). The factors that comprised the treatments were five critical soil water tensions (15, 25, 35, 45 and 55 kPa), evaluated in the main plots, and two black pepper genotypes (Clonada and Uthirankotta), analyzed in the subplots. Four repetitions per treatment were considered within each block. One sample was collected from each central plant, resulting in four replicate samples per treatment, and these same plants were used for all other evaluated parameters, including pepper grain analyses.

Harvests were carried out between July and November 2023, with fruits of the Clonada genotype harvested from July to September, and those of the Uthirankotta genotype from September to November. Berries were manually harvested when 1/3 of the fruits were at the mature stage (yellow and/or red coloration) from the four central plants of each cultivar analyzed in the experimental subplots. The fresh weight of the fruits per spike per plant was then measured using a digital scale, and subsequently, the spikes were threshed (separation of the Berries).

After threshing, the green fruits were weighed and subsequently subjected to natural drying in an oven for an average duration of three days, aiming to obtain a grain moisture content of approximately 13% [27]. The dried fruit samples were then placed in a manual blower to remove plant residues and separate empty grains (winnowing). Finally, the black peppers (dried) were weighed, packed in polypropylene bags and stored in the company's facilities.

2.5. Production Parameters Evaluated

The determination of the average green pepper yield, in kg per plant, was obtained through the ratio between the total weight of the fruits after harvest (fresh fruits) and the number of plants evaluated per cultivar (Equation (6)). The average yield of green pepper fruit was defined by the grain weight measured after threshing, following the same quantification method as for Ppv (Equation (7)).

$$P_{pv} = \frac{\sum_{i=1}^4 PF_F}{4} \quad (6)$$

in which

Ppv—Green pepper production (kg plant^{−1}) and;

PF_F—Weight of fresh fruit (kg).

$$PF_{pv} = \frac{\sum_{i=1}^4 PF_D}{4} \quad (7)$$

in which

PF_{pv}—Green pepper fruit production (kg plant^{−1}) and;

PF_D—Fruit weight after threshing (kg).

The average black pepper yield, in kg per plant, was obtained by the mathematical ratio between the total weight recorded after the winnowing process and the number of black pepper plants evaluated in each experimental subplot, using Equation (8).

$$P_{pp} = \frac{\sum_{i=1}^4 PF_V}{4} \quad (8)$$

in which

Ppp—Black pepper production (kg plant^{−1}) and;

PF_V—Fruit weight after ventilation (kg).

The average black pepper productivity obtained from the experiment was calculated by the ratio between the total weight of black pepper and the area occupied by the four plants evaluated for each cultivar, according to Equation (9):

$$PROD = \frac{\sum_{i=1}^4 PF_V}{A} \quad (9)$$

in which

PROD—Black pepper productivity (kg ha^{−1});

PF_V—Fruit weight after ventilation (kg);

A—Area (ha).

The productivity per unit of applied water depth, defined in irrigated agriculture as water use efficiency, was estimated according to Equation (10) [28]:

$$WUE = \frac{PROD}{w} \quad (10)$$

in which

WUE—Water use efficiency ($\text{kg ha}^{-1} \text{ mm}^{-1}$);
 PROD—Black pepper productivity (kg ha^{-1});
 w—Applied irrigation blade (mm).

2.6. Determination of Essential Oil Yield

The black pepper samples used for laboratory analyses were collected in September 2023, a period of greatest water deficit in Castanhal-PA. After the natural drying process of the grains (black pepper), 30 g of pepper were collected from each of the four plants evaluated in the productive subplot, to form a composite sample of 120 g of each treatment per subplot, with three repetitions (blocks).

The grains were ground using a knife mill, and then 100 g of each sample were weighed. The weighed portions were placed in 2000 mL round-bottom volumetric flasks and combined with 1000 mL of distilled water. The hydrodistillation method was employed for essential oil extraction using a Clevenger-type apparatus for 3 h at 100 °C. Afterwards, the volume of the extracted oil was quantified with the aid of a micropipette [21].

The essential oil contents extracted were calculated using the standardized moisture-free basis (MFB) method. For this purpose, during the natural drying process, a biomass moisture content of around 13% was adopted, according to the quality standard established for black pepper commercialization [27]. The extraction yields were determined using Equation (11) [29].

$$R_e = \frac{V_o}{B_m - \left(\frac{B_m \times U_{\%}}{100} \right)} \times 100 \quad (11)$$

in which

R_e —Extraction yield (%);
 V_o —Volume of oil extracted (mL);
 B_m —Plant biomass (g);
 $U_{\%}$ —Moisture content (%).

2.7. Statistical Analysis

After verifying the homoscedasticity and normality of the data, analysis of variance (Shapiro–Wilk test) was performed using the F-test ($p \leq 0.05$). When significant differences were observed among treatments, regression analysis was applied to the variables obtained, testing both linear and second-degree polynomial models [30]. The criteria for model selection were the significance of the regression coefficients at the 5% probability level (F-test) and the highest R^2 value. The means of the analyzed variables were also compared using Tukey's test at the 5% significance level. The analyses were performed using the SISVAR 5.8 statistical software [31].

In addition, Pearson correlation studies were carried out between essential oil yield and the following parameters: green and black pepper production, productivity and water use efficiency for the Clonada and Uthirankotta cultivars. The interpretation of the Pearson correlation coefficient (r) considered in this study followed the classification proposed by Hinkle et al. [32], as shown in Table 2.

Table 2. Interpretation of Pearson's correlation coefficients (r).

Pearson's r	Interpretation
± 0.90 to ± 1.00	Very high positive or negative correlation
± 0.70 to ± 0.90	High positive or negative correlation
± 0.50 to ± 0.70	Moderate positive or negative correlation
± 0.30 to ± 0.50	Low positive to negative correlation
± 0.00 to ± 0.30	Insignificant correlation

Source: Adapted from Hinkle et al. [32].

3. Results

3.1. Irrigation Management

Figure 5 shows the amounts of irrigation water applied as a function of the evaluated soil water tensions (15, 25, 35, 45 and 55 kPa) in black pepper cultivation during the year 2023, in the municipality of Castanhal, Pará, Brazil.

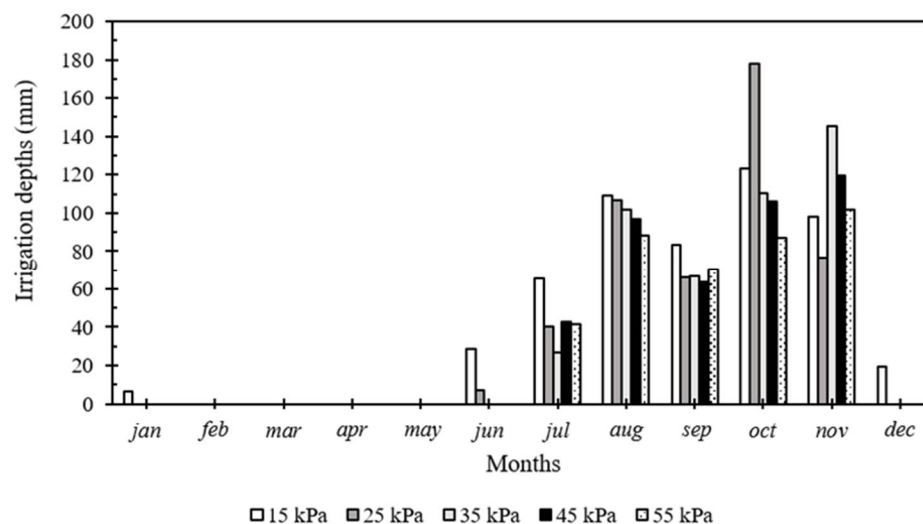


Figure 5. Irrigation depths applied as a function of critical soil water tensions.

The differentiation of treatments related to soil water tensions began at the end of June and extended until the end of November, totaling 157 days. The highest irrigation depths were applied in October and November under soil water tensions of 25 kPa (177.9 mm) and 35 kPa (145.45 mm), respectively. In the remaining months, treatments subjected to the 15 kPa tension received the highest irrigation depths.

Table 3 presents the gross (L_B) applied during the experiment (157 days) as a function of critical soil water tensions, as well as the mean depths (L_m) and the total applied in each tension treatment (w), rainfall during the evaluation period (PREC), the number of irrigation events per control tension (NI), the irrigation interval (TR) and the daily water demand (DH).

Table 3. Gross water depth (L_B), average water depth (L_m), irrigation volume per plant (VI), total water depth applied (w), rainfall (PREC), number of irrigations (NI), irrigation shift (TR) and water demand (DH) of irrigation management in black pepper crops in Castanhal, PA.

Tension (kPa)	L_B (mm)	L_m (mm)	V_I (L Plant ⁻¹)	w	PREC (mm)	Total	NI (Unit)	TR (Days)	DH (mm Day ⁻¹)
15	2.2	6.4	5.0	508.49	493.6	1002.09	80	2	3.24
25	7.0	14.0	11.0	474.48	493.6	968.08	34	5	3.02
35	11.5	15.0	11.9	450.88	493.6	944.48	30	5	2.87
45	15.4	18.7	14.7	429.38	493.6	922.98	23	7	2.73
55	18.6	19.5	15.4	389.53	493.6	883.13	20	8	2.48

As the percentage of wetted area was 11.6% of the total area occupied by each plant (6.8 m²), the conversion of L_m values from millimeters to liters per plant (VI) was performed by multiplying the value in mm by the effective wetted area per plant [32–34]. The irrigation management information shows that black pepper plants subjected to 15 kPa tension received more than 23.4% more irrigation water (w) than plants cultivated under 55 kPa tension (349.53 mm) and 11.3% more than plants subjected to 35 kPa tension (450.88 mm).

At 15 kPa, a shorter irrigation interval (TR = 2 days) was associated with 2 days. At 15 kPa tension, higher irrigation frequency (80 events) and greater daily water demand (3.24 mm day^{-1}) were observed for this critical soil water tension during the 157 days of treatment differentiation. In contrast, black pepper plants subjected to 35 kPa tension with a TR of 5 days and 55 kPa tension with a TR of 8 days received, respectively, 62.5% and 75% fewer irrigation events (NI) than plants under 15 kPa water conditions.

3.2. Productive Performance

Table 4 presents the F-test values at the 5% significance level for the productive variables (Ppv, PFpv, Ppp, PROD and WUE) and the essential oil extraction yield of black pepper (R_e). It can be observed that all the evaluated parameters were influenced both by the black pepper genotype factor (Clonada and Uthirankotta) and by the soil water tension factor (15, 25, 35, 45 and 55 kPa), as well as by the interaction between both factors.

Table 4. Summary of analysis of variance for green pepper production (Ppv), green pepper fruit production (PFpv), black pepper production (Ppp), productivity (PROD), water use efficiency (WUE) and essential oil extraction yield (R_e) in black pepper genotypes subjected to soil water tensions in Castanhal, Pará, Brazil.

Variation Factor	F Values					
	Ppv	PFpv	Ppp	PROD	WUE	R_e
Block	0.13 ^{ns}	0.18 ^{ns}	0.12 ^{ns}	0.13 ^{ns}	0.05 ^{ns}	0.09 ^{ns}
Genotype (G)	6560.31 *	4170.38 *	9670.80 *	8984.78 *	7824.38 *	638.76 *
Tension (T)	161.69 *	160.77 *	137.44 *	137.81 *	152.82 *	47.06 *
G × T	1302.78 *	807.10 *	869.61 *	805.80 *	740.73 *	5.55 *
CV (G) (%)	3.70	4.73	2.74	2.85	3.08	6.16
CV (T) (%)	13.01	13.15	10.78	10.76	10.38	6.19

* significant at 5% probability. ^{ns}: not significant. CV (%) = coefficient of variation.

The result of the interaction between soil water tensions and black pepper genotypes for the variable green pepper production is graphically shown in Figure 6.

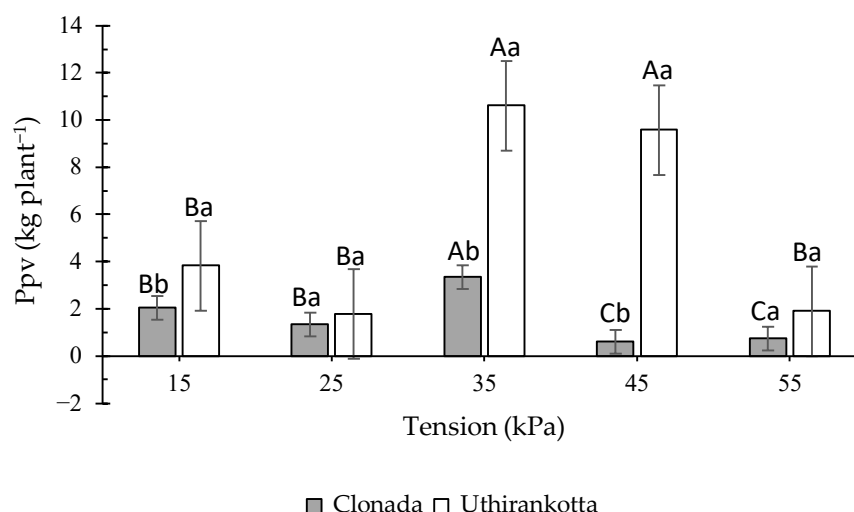


Figure 6. Green pepper (Ppv) production between Clonada and Uthirankotta genotypes under different critical soil water tensions. Note: Mean values followed by the same letter do not differ from each other in the Tukey test ($p \leq 0.05$). Capital letters compare the effect of stress and lowercase letters compare the effect of genotypes.

The highest average Ppv values for both genotypes were observed at the 35 kPa soil water tension, reaching 3.36 kg plant⁻¹ for Clonada and 10.62 kg plant⁻¹ for Uthirankotta. At this tension, Uthirankotta exceeded Clonada by approximately 68%. The lowest average Ppv for Clonada (0.61 kg plant⁻¹) was recorded at 45 kPa, not differing from values observed at 25 and 55 kPa. For Uthirankotta, the lowest Ppv values were observed at 25 and 55 kPa, with averages of 1.79 and 1.91 kg plant⁻¹, respectively.

As shown in Figure 7, the fruit production performance of green pepper by the two evaluated black pepper genotypes in relation to soil water tensions.

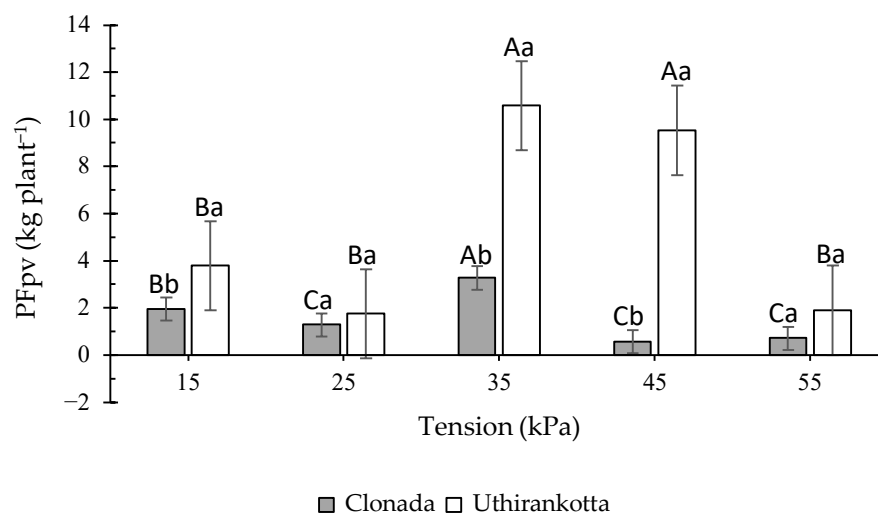


Figure 7. Green pepper fruit production (PFpv) between Clonada and Uthirankotta genotypes under different critical soil water tensions. Note: Mean values followed by the same letter do not differ from each other in the Tukey test ($p \leq 0.05$). Capital letters compare the effect of stress and lowercase letters compare the effect of genotypes.

The highest PFpv mean was recorded for the Uthirankotta genotype at the soil water tension of 35 kPa, reaching 10.58 kg plant⁻¹, which was approximately 69% higher than the value observed for Clonada under the same tension. The lowest PFpv values followed the same pattern observed for Ppv, with the lowest means recorded under the soil water tensions of 45 and 25 kPa for the evaluated genotypes, resulting in a difference of approximately 67% between the lowest values.

A significant interaction between soil water tension and genotype for green pepper fruit production, with a second-degree polynomial adjustment. These results are presented in Figure 8. To demonstrate the effects of the soil water tension factor on the black pepper production of the Clonada and Uthirankotta genotypes, regression analysis ($p \leq 0.05$) was performed, revealing a significant interaction between the evaluated factors, with a second-degree polynomial behavior (quadratic function). These results are presented in Figure 8.

An increase in Ppp was observed with increasing soil water tension, with the highest production values recorded at the 35 kPa tension for both genotypes. At this tension, black pepper production reached 4.76 kg plant⁻¹ for the Uthirankotta genotype and 1.57 kg plant⁻¹ for the Clonada genotype.

Regression analysis indicated a significant effect of soil water tension on Ppp, with a quadratic response for both genotypes. Based on the fitted models, the estimated maximum black pepper production for Clonada was 2.42 kg plant⁻¹ at a soil water tension of 31.0 kPa, whereas for Uthirankotta, the estimated maximum was 4.69 kg plant⁻¹ at 34.7 kPa, representing a difference of approximately 48% between genotypes under these conditions.

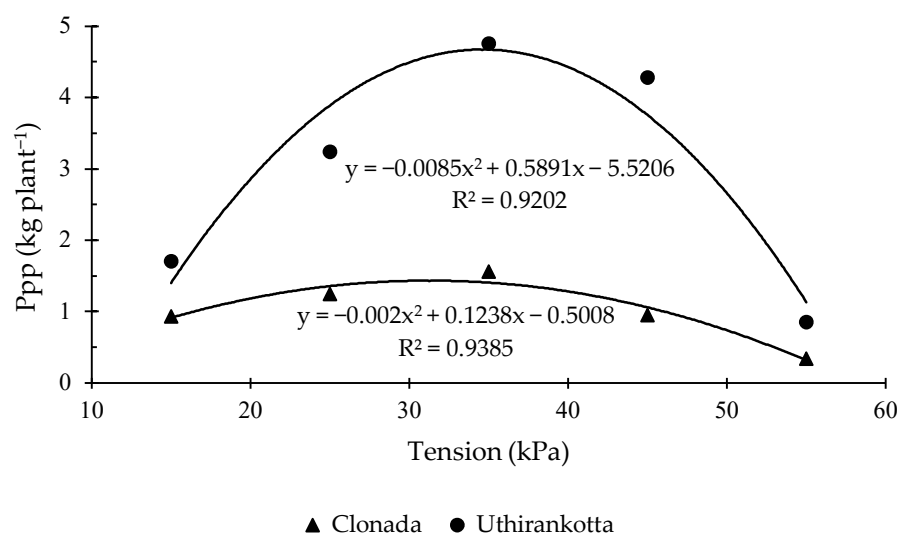


Figure 8. Black pepper (Ppp) production of Clonada and Uthirankotta genotypes as a function of critical soil water tensions.

Black pepper productivity as a function of soil water tension is shown in Figure 9. Regression analysis for the productivity variable was also significant, with a second-degree polynomial adjustment and coefficients of determination (R^2) above 0.90 for both Clonada and Uthirankotta.

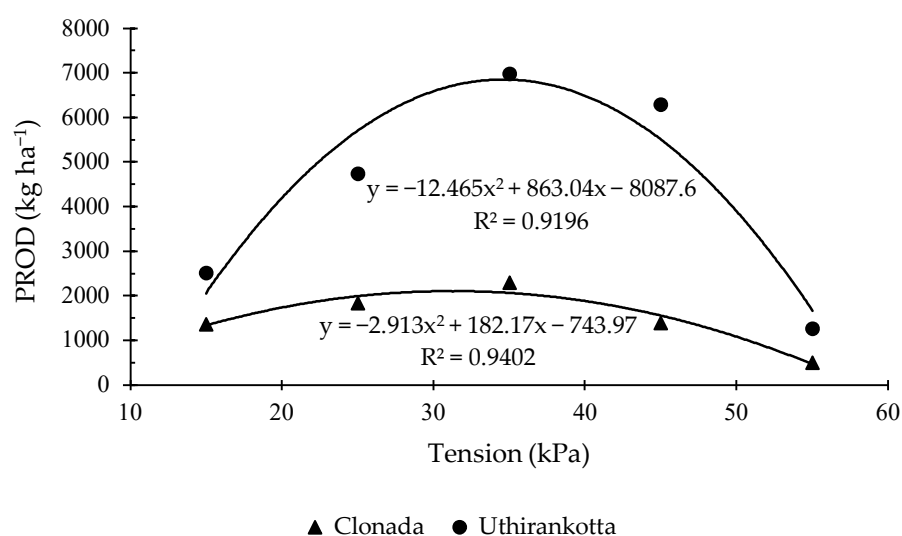


Figure 9. Productivity (PROD) of black pepper from the Clonada and Uthirankotta genotypes as a function of critical soil water tensions.

Figure 9 shows that black pepper productivity (PROD) increased with soil water tension up to 35 kPa for both genotypes. At this tension, maximum observed productivity values were 2296.76 kg ha⁻¹ for Clonada and 6979.29 kg ha⁻¹ for Uthirankotta.

Regression analysis revealed a significant quadratic response of productivity to soil water tension for both genotypes. Based on the fitted models, the estimated maximum productivity for Clonada was 3592.06 kg ha⁻¹ at a soil water tension of 31.3 kPa, whereas for Uthirankotta the estimated maximum was 6850.99 kg ha⁻¹ at 34.6 kPa.

Water use efficiency (WUE) also showed a significant quadratic adjustment in response to soil water tension. The dispersion of WUE values for the black pepper genotypes as a function of the evaluated soil water tensions is presented in Figure 10.

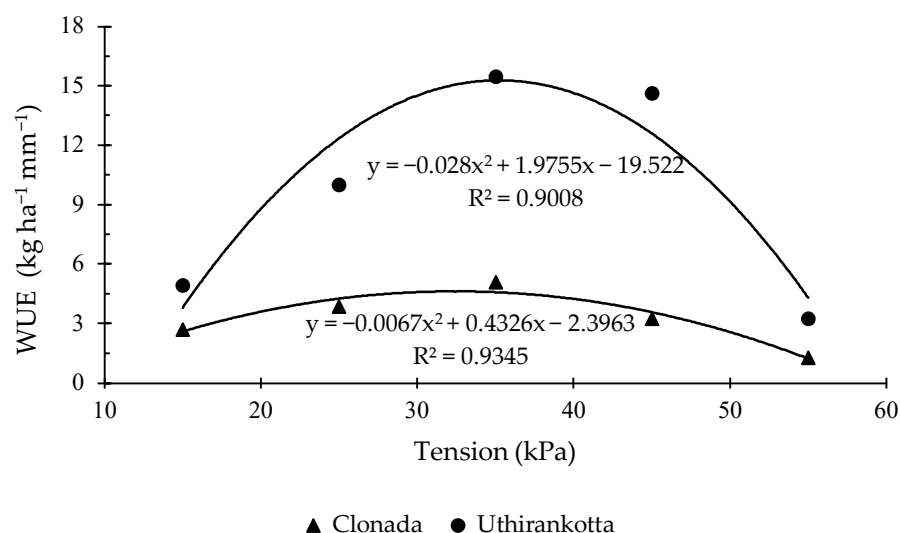


Figure 10. Water use efficiency (WUE) of the Clonada and Uthirankotta genotypes as a function of critical soil water tensions.

Figure 10 shows that water use efficiency (WUE) varied markedly among soil water tensions, with a range of approximately 67% between the maximum ($15.48 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and minimum ($5.09 \text{ kg ha}^{-1} \text{ mm}^{-1}$) values. The highest WUE values were observed at the soil water tension of 35 kPa for both genotypes.

When comparing soil water tensions, differences in WUE were observed between 35 kPa ($w = 450.88 \text{ mm}$) and the tensions of 15 kPa ($w = 508.49 \text{ mm}$) and 55 kPa ($w = 389.53 \text{ mm}$). For the Uthirankotta genotype, these differences were approximately 68% and 79%, respectively, whereas for the Clonada genotype the corresponding differences were 47% and 75%.

Regression analysis revealed a significant quadratic response of WUE to soil water tension for both genotypes. Based on the fitted second-degree polynomial models, the estimated maximum WUE was $9.38 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for Clonada at a soil water tension of 32.3 kPa and $15.32 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for Uthirankotta at 35.3 kPa, representing a difference of approximately 39% between genotypes under these conditions.

3.3. Essential Oil Yield and Pearson Correlation

Figure 11 graphically presents the result of the regression analysis of essential oil extraction yields (R_e) obtained from black pepper genotypes as a function of irrigation management by tensiometry, under the edaphoclimatic conditions of the municipality of Castanhal, Pará, Brazil.

Regression analysis for essential oil extraction yield (R_e) indicated that the linear model was significant at the 5% probability level for both genotypes. R_e values decreased with increasing soil water tension, with the lowest extraction yields observed at the 55 kPa tension.

At the soil water tension of 15 kPa ($w = 508.49 \text{ mm}$), the highest R_e value was recorded for the Uthirankotta genotype (5.09%), which was approximately 34% higher than the value observed for Clonada under the same condition. For Uthirankotta, R_e decreased from 5.09% at 15 kPa to 3.39% at 55 kPa, corresponding to a reduction of approximately 34%. The R_e value recorded for Clonada at 15 kPa (3.38%) was similar to that observed for Uthirankotta at 55 kPa (3.39%).

The Pearson linear correlation coefficients obtained from the association between essential oil extraction yield and the response variables—green pepper production (P_{pv}), black pepper production (P_{pp}), productivity (PROD) and water use efficiency (WUE)—are presented in Table 5.

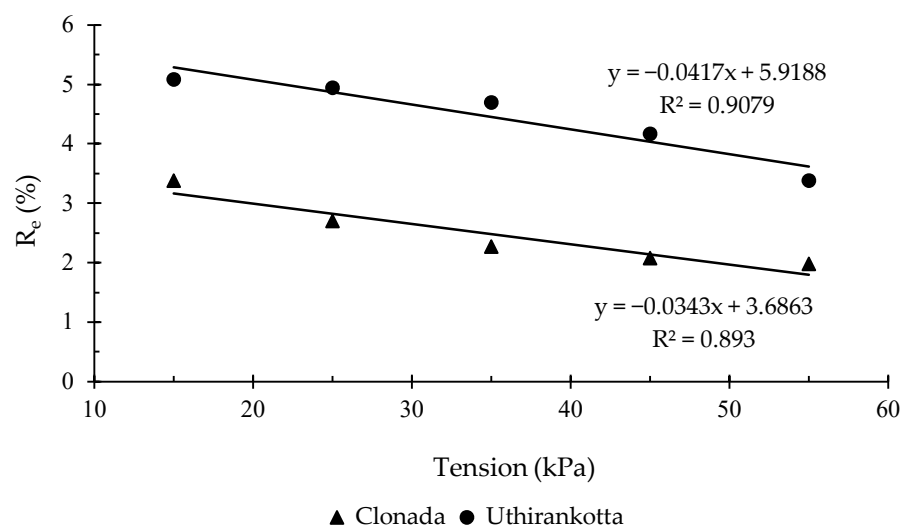


Figure 11. Extraction yield (R_e) of black pepper essential oil from Clonada and Uthirankotta genotypes as a function of critical soil water tensions.

Table 5. Pearson correlation coefficients (r) between the extraction yield (R_e) of essential oil and the production response variables (Ppv, Ppp and PROD) and water use efficiency (WUE) of black pepper under tensiometric irrigation management in Castanhal, PA.

Relation of R_e	Pearson's r	Interpretation of r	p Value
Ppv	0.547	Correlação positiva moderada	0.102 ^{ns}
Ppp	0.692	Correlação positiva moderada	0.027 *
PROD	0.691	Correlação positiva moderada	0.027 *
WUE	0.653	Correlação positiva moderada	0.041 *

* significant ($p < 0.05$) and positive r with a tendency for a directly proportional increase between the variables. ^{ns}, there are no significant relationships between any pair of variables ($p > 0.05$).

Pearson correlation analysis revealed a significant positive linear correlation between essential oil extraction yield (R_e) and black pepper production (Ppp), productivity (PROD) and water use efficiency (WUE). No significant correlation was observed between R_e and green pepper production (Ppv). The Pearson correlation coefficients obtained for R_e in relation to Ppp, PROD and WUE ranged between 0.5 and 0.7, indicating moderate correlation strength.

4. Discussion

Black pepper cultivation plays a strategic role in Brazilian agriculture, particularly in the state of Pará, which concentrates a substantial share of national production but still exhibits marked productivity gaps when compared with more technologically advanced regions [1,2,6]. These gaps are largely associated with climatic seasonality, limited adoption of irrigation technologies and insufficient technical management of water resources, especially under humid tropical conditions [4,13].

The results obtained in this study demonstrate that irrigation management based on soil water tension plays a key role in optimizing black pepper productivity and water use efficiency. The superior agronomic performance observed under intermediate soil water tensions, particularly around 35 kPa, indicates that this threshold provides a favorable balance between soil water availability and soil aeration in medium-textured Amazonian soils [8,9,17]. Such balance is essential to sustain root metabolic activity and nutrient uptake without inducing hypoxic stress, which may occur under excessively frequent irrigation events [8,35], as evidenced by the quadratic responses observed for yield, productivity and water use efficiency.

The climatic context of Castanhal, characterized by pronounced intra-annual variability in rainfall distribution and a well-defined dry season during the second semester, reinforces the importance of soil-based irrigation scheduling [14,15]. Under these conditions, tensiometry emerges as an efficient and practical tool for irrigation control, as it directly reflects soil water status and reduces dependence on meteorological indicators that may not adequately represent field-scale variability [9,21]. The consistency between the optimal soil water tension identified in this study and thresholds reported for other irrigated crops supports the broader applicability of tensiometer-based irrigation management to improve agricultural water use efficiency [24,25].

The quadratic response of yield and productivity to increasing soil water tension highlights the sensitivity of black pepper to both water deficit and excess. Under low soil water tensions (15 kPa), higher irrigation frequency resulted in increased water application without proportional yield gains, indicating diminishing returns associated with excessive soil moisture. Such conditions may impair gas exchange in the root zone and compromise root functionality, limiting biomass accumulation despite adequate water supply [8,35]. Conversely, higher soil water tensions (45–55 kPa) imposed water stress conditions that restricted vegetative growth and reproductive development, a response commonly observed in perennial crops subjected to prolonged reductions in soil moisture [36,37].

Genotypic differences in response to irrigation management were evident throughout the study, with the Uthirankotta genotype consistently outperforming Clonada in terms of yield, productivity and water use efficiency. This behavior corroborates previous evaluations conducted in Pará, which reported superior agronomic performance of Uthirankotta under favorable management conditions [16,19,38]. These differences reflect intrinsic genetic variability related to traits such as root system efficiency, water uptake capacity and physiological regulation under fluctuating soil moisture conditions [3,20]. From a practical standpoint, these results reinforce the importance of integrating genotype selection with irrigation management strategies to maximize production efficiency in black pepper cultivation systems.

Water use efficiency followed a pattern closely associated with productivity, reaching maximum values at intermediate soil water tensions. This response aligns with the conceptual framework that defines water use efficiency as a function of biomass accumulation relative to water consumption, in which excessive irrigation reduces efficiency by increasing water input without proportional yield gains [35,39,40]. Similar responses have been reported for other irrigated crops, where optimal irrigation thresholds maximize carbon assimilation while minimizing non-productive water losses [41–43]. The consistently higher water use efficiency observed for the Uthirankotta genotype further emphasizes its suitability for irrigated systems aiming at sustainable water use.

In contrast to productive variables, essential oil extraction yield exhibited a distinct response pattern to soil water tension, with higher yields observed under lower tension levels. This behavior reflects the influence of water availability on secondary metabolism, whereby changes in plant water status alter the synthesis and accumulation of volatile compounds [44–46]. However, severe water stress tends to reduce essential oil yield due to limitations in biomass production, as reported for aromatic and medicinal plants [47]. This pattern is consistent with the linear decrease in essential oil extraction yield observed with increasing soil water tension in the present study, in contrast to the quadratic responses observed for productive variables.

The higher essential oil yields obtained for the Uthirankotta genotype across irrigation treatments suggest a genetic predisposition for greater accumulation or extraction efficiency of volatile compounds, consistent with reports on variability in essential oil yield among *Piper nigrum* genotypes [29,48]. Nevertheless, the inverse relationship between optimal

conditions for productivity and essential oil extraction highlights a trade-off that must be considered when defining irrigation strategies, particularly when production goals differ between grain yield and phytochemical exploitation [49,50].

The positive correlations observed between essential oil extraction yield and black pepper production, productivity and water use efficiency indicate that, within the range of conditions evaluated, improved agronomic performance tends to favor oil extraction yield. It is important to emphasize that these relationships are based on correlation analysis and do not imply causality, as essential oil yield may also be influenced by unmeasured physiological and biochemical factors [51,52]. However, the absence of correlation between essential oil extraction yield and green pepper production suggests that post-harvest processing, moisture content and extraction methodology also play a critical role in determining oil extraction efficiency [49,53].

Because only essential oil extraction yield was evaluated, without chemical compositional analysis, conclusions regarding oil quality or specific industrial applications should be interpreted with caution. Overall, the findings of this study provide robust evidence that tensiometer-based irrigation management is an effective strategy for optimizing black pepper production under humid tropical conditions. By integrating soil water monitoring with genotype-specific responses, it is possible to define irrigation thresholds that maximize productivity and water use efficiency while maintaining satisfactory essential oil yields. These results advance irrigation management practices for black pepper cultivation in the Brazilian Amazon and provide a science-based irrigation threshold that integrates productivity, water use efficiency and essential oil yield, contributing to greater sustainability and resilience of regional production systems.

5. Conclusions

The highest black pepper production and productivity for both Clonada and Uthirankotta genotypes were obtained at a soil water tension of 35 kPa, indicating this value as an appropriate reference for irrigation management under the edaphoclimatic conditions of northern Pará, Brazil. The Uthirankotta genotype showed superior productive performance and higher water use efficiency compared to Clonada under tensiometer-based irrigation management. The highest essential oil extraction yield was observed for Uthirankotta at 15 kPa. Positive correlations were identified between essential oil yield and production-related variables; however, these relationships are based on correlation analysis and do not imply causality. Furthermore, as only extraction yield was evaluated, without chemical compositional analysis, conclusions regarding essential oil quality should be interpreted with caution.

Author Contributions: Conceptualization, J.d.S.M., J.A.D.L.J. and O.F.d.L.; methodology, M.D.d.A.G., H.C.A.S. and J.A.D.L.J.; statistical analysis O.F.d.L., H.L.M., A.N.C. and M.C.P.; writing—original draft preparation, J.d.S.M., M.A.d.S.G. and J.A.D.L.J.; writing—review and editing, H.C.A.S., A.N.C., H.L.M. and M.C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Oriel Filgueira de Lemos was employed by the company Brazilian Agricultural Research Corporation (EMBRAPA). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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