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Cashew Clones Water Productivity and Production Responses to Different Biochar Levels

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Abstract: The cashew peduncle, the so-called cashew apple, is frequently considered as waste generated by the cashew nut industries. It needs production quality improvements to achieve a more noble use. The objective of this research was to evaluate the application of biochar over irrigation water productivity, yield, and cashew apple quality of two clones ('BRS 226' and 'CCP 76') of an irrigated cashew orchard. This field experiment tested four treatments of biochar from tree pruning mixed hardwood as source material, corresponding to 0, 10, 20, and 40 g per kg of soil, equivalent to the amounts of 0.0, 1.0, 2.0, and 4.0 kg per plant, respectively. The evaluated production variables were irrigation water productivity in terms of cashew nuts and peduncles per cubic meter of irrigation water applied, cashew nuts, and apples' individual mean weight and yield. Cashew apple quality was also evaluated by soluble solids (SS), titratable acidity (TA), soluble solids/titratable acidity ratio (SS/TA), and firmness. The use of biochar had positive effects on the nut and cashew apple irrigation water productivity, on mean individual cashew apple weight only for 'BRS 226′ Clone and soluble solids for both clones ('BRS 226' and 'CCP 76'). The soluble solids/titratable acidity ratio also improved only for the BRS 226 cashew clone. There was no statistically significant positive effect of applied biochar in cashew nut and cashew apple yield and firmness. The optimal doses were 1.70 kg, 1.90 kg, 4.00 kg, 2.10 kg, and 2.25 kg per plant of biochar, respectively.

Keywords: *Anacardium occidentale* L.; cashew apple; yield; irrigation; climate change; adaptation

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1. Introduction

Cashew (*Anacardium occidentale* L.) is a native species of South America, possibly in the coastal zones of northeast Brazil. The industrial use of cashews around the world is basically aimed at the processing of the nut and, to a minor extent, the use of the peduncle, generating high losses due to the large quantity of cashew apple bagasse that is discarded [1]. Nutritious kernel, the edible part of the nut, is the main reason to grow cashew trees, while the so-called 'cashew apple', a pseudo-fruit formed by an enlarged peduncle, is another potentially valuable by-product, for example, as fresh fruit and source of juice [2,3]. Refs. [2,4] have reported the use of cashew apples for animal feeding. Ref. [5] as a source of organic fertilizer. The cashew apple is frequently considered as waste generated by the cashew nut industries since its commercial applications are restricted by the astringency and poor storability [6], which requires production quality improvements to achieve a more noble use, including the production of various foods such as juices and sweets [2].

Region climatic elements and variability between years of production, as well as the genotype, influence the quality and antioxidant activity of cashew apples, which may explain the rare market driven production. Some regions simply do not have a good quality of cashew apples despite the potential income value of the production, while

Brazil produces cashew apples with physical characteristics within commercialization standards [7].

The flowering and fruiting phases of cashew trees coincide with the dry season [8]. Moisture stress during these critical growth periods adversely affects flowering and fruit sets, leading to nut drop and yield reduction by affecting the relative number of male and hermaphrodite flowers [3]. Genotype, improved plant nutrition, water management, and conservation strategies, together, can potentially improve the yield and post-harvest quality of cashew apples.

In the Northeast region of Brazil, responsible for almost the total national production of cashew nuts, the main cultivated clones are 'CCP 76' and 'BRS 226' dwarf cashew trees.

Biochar application in sandy soils increases the water holding capacity (WHC) and allows water to become more time available in the root zone and plant to have water and nutrient uptake and increase water productivity (WP). Ref. [9] found that the addition of biochar significantly increased water retention and promoted the water use efficiency of tobacco (*Nicotiana tabacum* L.) in both Ferrosol and Anthrosol. Ref. [10] studied three dosages of biochar in a field cultivated with corn under an irrigation deficit. The results showed that growth, yield, and water productivity were higher in soil with high biochar content.

According to [11] redwood sawdust and wheat straw biochar's effects on silt loam soil hydraulic properties at 4% and 7% concentrations by mass found that biochar amended soils showed an increase in water retention and apparent reduction in unsaturated hydraulic conductivity as the soil approached saturated conditions.

The investigation by [12] in a pot experiment, the growth, biomass, and water use efficiency (WUE) in faba bean-ryegrass inter-cropping system amended with 550 °C-pyrolyzed wheat straw (WSBC) and 800 °C-pyrolyzed cleaning residues biochar (CRBC from residual products of a seed cleaning facility producing grain and forage/turf grass seeds) under different irrigation treatments. CRBC significantly increased soil water holding capacity (WHC) by 15.0%, while WSBC had a minor effect. Compared with the no biochar controls, CRBC decreased above-ground biomass and seed yield of intercropped faba bean despite improved soil water-holding capacity, leaf water potential, and leaf hydraulic conductance of faba bean. In contrast, CRBC significantly increased ryegrass above-ground biomass. These effects were not evident under WSBC. Other potential mechanisms are also involved in the adverse effects of biochar on plant growth [13]. The CRBC produced at a high temperature of 800 °C formed molecular weight (1.0 mg kg^{-1}) polycyclic aromatic hydrocarbons (PAHs) compared with WSBC (0.4 mg kg^{-1}) pyrolyzed at 550 °C, posing an ecotoxicology risk to the soil environment [14] and damaging the faba bean [15].

Biochar can release salt ions into the soil solution [13], eventually leading to a loss of yield. As reported by [16,17], some low molecular weight compounds in biochar can negatively affect cellular development and plant metabolism.

Ref. [18] evaluated root growth, soil water depletion, and water productivity of sweet corn under three deficit irrigation treatments (100%, 70%, and 40% crop evapotranspiration, ETc) and biochar application (hardwood and softwood). Biochar did not show any interactive effects with irrigation treatments within two years after application. Hardwood biochar increased the root growth in the 0–20 cm soil profile without altering the soil water depletion, yield, and water productivity of sweet corn. The hardwood biochar increased root length density over no biochar treatment without affecting the soil water status and water productivity. Crop response to biochar application depends on the source material and production process.

Cashew trees in the northeast of Brazil blossom is during the dry months, while trees need to export water from soil to cashew apples. Soil types in the production regions are mainly sandy soils characterized by low water holding capacity, which makes the increase in crop yield and production quality a challenging goal. This work aimed to evaluate the application of biochar over irrigation water productivity, crop yield, and cashew apple quality of two clones ('BRS 226' and 'CCP 76') of an irrigated cashew orchard.

2. Methodology

The field experiment was carried out at the Pacajus Experimental Station (4°11′16.59″ S; 38°29′59.13″ W), belonging to Embrapa Agroindústria Tropical, located in the municipality of Pacajus, CE, Brazil, from January to December 2023. The region occupies a transition zone between the coast and the semiarid region, with an average altitude of 79 m, a mean annual temperature of around 26 °C, and 750 mm of annual rainfall. Tables 1 and 2 show the soil analysis results of the red-yellow argisol [19] of the physical-hydraulic (Table 1) and chemical (Table 2) soil attributes in the experimental area.

Table 1. Physical-hydraulic soil attributes of the experimental area at different soil depths, Pacajus-CE, Brazil.

Depth	θ_{fc}	θ_{pwp}	θ_s	ds	Sand	Silt	Clay
(m)	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})
0–0.3	0.085	0.043	0.407	1.62	932	38	30
0.3–0.6	0.101	0.045	0.416	1.58	920	39	41

θfc—field capacity soil moisture; θpwp—moisture at permanent wilting point; θs—saturation moisture; ds—soil density.

Table 2. Soil chemical attributes.

Depth (m)	P (mg dm^{-3})	OM g kg^{-1}	pH H_2O	K^+	Ca^{2+}	Mg^{2+}	Na^+	H + Al	Al^{+3}	SB	CEC	BS	m
				mmol$_c$ dm^{-3}								%	
0–0.3	10.0	6.5	6.5	1.3	11	11	2	7	0	25	32	77	0
0.3–0.6	8.8	3.5	6.9	0.5	5	7	2	4	0	14	19	78	0

Depth (m)	Zn	Cu	Fe	Mn	B
	mg dm^{-3}				
0–0.3	3.5	0.2	1.6	5.7	NA
0.3–0.6	1.8	0.3	6.5	1.0	NA

OM: organic matter; H + Al: $Ca(CH_3COO)_2 \cdot H_2O$ 0.5 mol L^{-1} pH 7.1–7.2. SB: Sum of Bases (K^+ + Ca^{2+} + Mg^{2+} + Na^+). CEC: Cation Exchangeable Capacity (SB + (H+Al)). BS: base saturation. m: aluminum saturation. pH in H_2O: ratio soil/water: 1:2.5. Ca^{2+}; Mg^{2+} and Al^{3+}: KCl 1 mol L^{-1}. P, K^+, Na^+: Mehlich 1. Cu, Fe, Zn, and Mn: Mehlich 1. S-SO_4^{2-}: $Ca(H_2PO_4)_2$. B: hot water. NA: not analyzed.

The orchard installation occurred in March 2017 using a factorial statistical design with blocks, consisting of eight treatments and four replications in a 2 × 4 factorial scheme: two dwarf cashew clones ('BRS 226' and 'CCP 76') spaced 8 m × 6 m (208 plants ha^{-1}). Each repetition occupied an area of 180 m × 40 m, and it consisted of three plants per repetition, totaling 96 plants evaluated. In 2023, each plant received 1300 g of urea (45% of N), 133 g of KCl (60% of K_2O), 1100 g of N-P-K 10-28-20 mixture, and 32.4 kg $plant^{-1}$ of organic compost (0.76% of N, 3.77% of P, 0.96% of K, 0.63% of Mg, and 8.31% of total organic carbon (TOC)).

Four treatments of biochar prepared using a rustic brick kiln with no oxygen made from a mix of tree pruning hardwood and particles of 2 mm to 4 mm diameter were tested. Biochar levels were 0, 10, 20, and 40 g per kg of soil, equivalent to the amounts of 0.0, 1.0, 2.0, and 4.0 kg per plant, respectively. The application of biochar to the pit was performed manually using plastic containers with a previously known weight of content.

Intergovernmental Panel on Climate Change [20] methodology for estimating biochar Carbon (C) additions into soils considers the fraction of biochar carbon remaining (un-mineralized) after 100 years for each production type (high or low technology). There are default carbon decay values when biochar is destined for soil applications. The value was determined using production temperatures reported in the literature. Smallholder and farm-level biochar production settings may adopt values from [20] for different feedstocks and production types with a lack of emissions controls during production, but an important role in carbon removal is associated with its production and use. According to [20], a default value of 0.56 must be used where pyrolysis temperature is unknown (like in this experiment), as the fraction of carbon in the biochar remains after 100 years.

The chemical characterization of the biochar (Table 3) followed the methodological standards by [21], and it was conducted at Embrapa Agroindústria Tropical Soil Laboratory. Results indicate lower nitrogen (N) (2.2 g kg^{-1}), potassium (K) (0.9 g kg^{-1}), magnesium (Mg) (1.3 g kg^{-1}), and phosphorus (P) (0.3 g kg^{-1}) but higher micronutrients, that is, copper (Cu) (14 mg kg^{-1}), iron (Fe) (364 mg kg^{-1}), zinc (Zn) (48 mg kg^{-1}), and manganese (Mn) (44 mg kg^{-1}), when compared to other biochar, such as coconut husk [22].

Table 3. Chemical attributes of the biochar.

Macronutrients (g kg^{-1})						Micronutrients (mg kg^{-1})				(%)
N	**P**	**Mg**	**Ca**	**S**	**K**	**Cu**	**Fe**	**Zn**	**Mn**	**TC**
2.2	0.3	0.5	7.5	ND **	3.4	2	419	33	54	35.6

pH and EC on water biochar/water ratio 1:10. ** ND—not detected.

Iron and manganese exist in several organic forms in the biomass and are largely retained during biochar formation, as [23] reported; these differences in composition are explained by the raw material and process conditions that control the mineral content of biochar, which may vary significantly between different types. According to [24], large ranges of biochar content may be observed, ranging from pH (4 to 12), carbon (C) (172 g kg^{-1} to 905 g kg^{-1}), nitrogen (N) (1.8 g kg^{-1} to 56.4 g kg^{-1}), phosphorus (P) (2.7 g kg^{-1} to 480 g kg^{-1}), and potassium (K) (1.0 g kg^{-1} to 58 g kg^{-1}). The total carbon content (TC) of tree pruning mix hardwood biochar (35.61%) is considered low according to the classification of [25]: <60% (low), 60% to 80% (medium), and above 80% (high).

The monthly rainfall in 2023 and average Penman–Monteith reference evapotranspiration (ETo) in the experimental area (total annual rainfall of 833 mm and ETo of 1629 mm) are shown in Figure 1. The rainy season is normally concentrated from January to May, the dry season occurs in the second semester of the year, when blossoming, and fruiting happens on cashew plants.

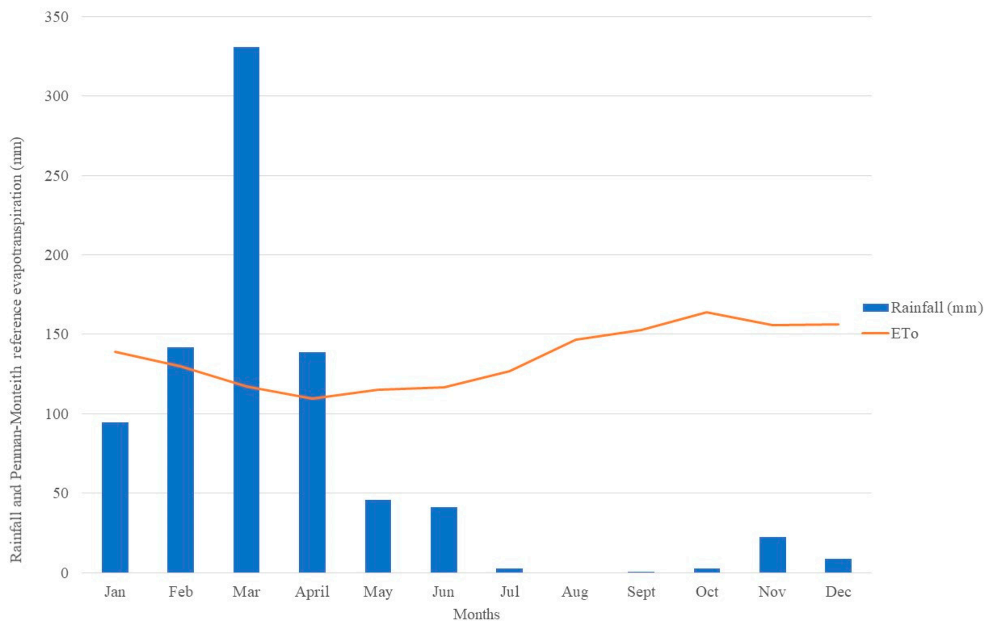

Figure 1. Monthly rainfall in 2023 and average Penman–Monteith reference evapotranspiration (mm) in the experimental area, Pacajus-CE, Brazil.

2.1. Irrigation and Water Productivity

The micro-sprinkler irrigation system (average flow of 71.2 L h^{-1}) used water distribution piping and valves to open the irrigation independently for each treatment, which allowed water application according to the water demand by the trees. The evaluation of the installed irrigation system resulted in a Coefficient of Uniformity Distribution of 80.95%, an application efficiency of 72.86%, an average wet diameter of 3.3 m, and a precipitation rate of 7.8 mm h^{-1}. Daily monitoring of soil water potential was carried out using tensiometers (two sets per treatment) installed at a depth of 0.15 m (0–0.30 m soil layer) and at 0.45 m (soil layer from 0.30 m to 0.60 m). Water potential from 80 kPa (22.9% of the total available soil water in the 0–0.30 m soil profile at field capacity) was the irrigation starting level. The amount of water supply was enough to return soil moisture to field capacity in the 0–0.6 m soil profile. Irrigation occurs during the reproductive phase. According to a report by [26], irrigation of established cashew plantations can be restricted to the period between flowerings and harvest without reducing yield.

The irrigation water productivity (kg m^{-3}) was the cashew nut and apple production per quantity of water applied per treatment.

2.2. Available Soil Moisture

The daily soil water potential data allowed the use of the retention curve and the [27] equation (Equation (1)) to obtain the average available daily soil moisture.

$$\theta = \theta_r + \frac{(\theta s - \theta r)}{\left[1 + \left(\alpha|\psi \mathrm{m}|^n\right)\right)^m\right]}, \quad (1)$$

where the following is true:

θ—soil water content (cm^3 cm^{-3});

θ_r—residual water content (cm^3 cm^{-3});

θ_s—saturation soil water (cm^3 cm^{-3});

Ψm—soil water matric potential (kPa);

α, n, and m—equation empirical parameters.

The determination of average available daily soil moisture (ADS) in the soil profile used Equation (2), which estimates the water content from actual soil water content (θ_a) to the permanent wilting point (θ_{pwp}). Water content above field capacity was considered percolating gravitational water and, therefore, not available to plants.

$$\mathrm{ADS} = (\theta_a - \theta_{pwp})\ z, \quad (2)$$

where the following is true:

ADS—available daily soil moisture (mm);

θ_a—actual soil moisture (cm^3 cm^{-3});

θ_{pwp}—moisture at permanent wilting point (cm^3 cm^{-3});

z—soil depth (mm).

2.3. Production Variables

The evaluated production variables were cashew nuts and apples individual mean weight and yield. Cashew apple quality was evaluated using total soluble solids (SS), titratable acidity (AT), soluble solids/titratable acidity ratio (SS/AT), and firmness.

Total soluble solids (SS) were evaluated after filtering the cashew apple juice with a paper filter. A digital refractometer ATAGO PR-101® was used with a measurable range from 0 to 45 °Brix, in accordance with the methodology recommended by [28]. Titratable acidity (TA) was measured using titration with NaOH solution (0.1 N). The results were expressed as a percentage of malic acid, according to the [29] methodology. The SS/TA ratio was obtained using the quotient between the two variables. Pulp firmness was performed on intact peduncles with a T011® manual penetrometer with 8 mm diameter tips and an average of two punctures made in the middle portion of the peduncle (cashew apple).

2.4. Statistical Analysis

Analysis of variance was carried out after checking the normality of the residuals using the Shapiro–Wilk test and the homogeneity of the variances using the Bartlett test. If there was a significant effect of the treatment factor (biochar rate) evaluated using ANOVA's F test, the regression models were adjusted. The effect of the biochar rate on the volume of water required for irrigation was adjusted using statistically significant regression models. All statistical analyses were performed using R version 4.2.2 statistical software by The R Foundation for Statistical Computing Platform [30]. All tables of analysis of variance and F test are available on Supplementary Materials.

3. Results and Discussion

3.1. Cashew Nut and Apple Yield

The analysis of variance of the mean raw cashew nut weight and yield demonstrated that there were significant differences only between clones. These differences reflect the natural genetic potential of each clone [31] and not the experiment sources of variation. The average weight per nut was higher for 'BRS 226' Clone (9.4 g) than for 'CCP 76' (8.0 g), while averages nut yields were 2866 kg ha^{-1} and 1111 kg ha^{-1} for 'BRS 226' and 'CCP 76', respectively. Ref. [32] reported an approximate mean cashew nut weight of 7.96 g for 'CCP 76' from rainfed production, while [33] reported for the same clone, from 7.53 to 7.63 g per raw nut when irrigated trees of the same age as this experiment (six years old).

Ref. [34] reported cashew nut yield ranging from 1184 to 1747 kg ha^{-1} of six years old (same age as this experiment) cashew trees of 'CCP 76', while [33] reported to the same clone, cashew nut yields from 1513 to 1704 kg ha^{-1} when irrigated trees of the same age as this experiment (six years old) from soil water potentials of 20 kPa. Ref. [31] reported a nut yield of 772.5 kg ha^{-1} for 'CCP 76' and 1584.2 kg ha^{-1} for 'BRS 226' of 4-year-old trees under seasonal irrigation. In this experiment, the irrigation from 80 kPa soil water potential submitted the cashew trees to a certain level of deficit irrigation, which may have led to a loss of nut yield as a response to less water applied when compared to that achieved by [33].

The mean cashew apple weight shows a statistically significant difference between clones (140.4 g for 'CCP 76' and 121.3 g for 'BRS 226') and in the interaction between clones and treatments (p = 0.0413). The breakdown of the interaction between each clone and the treatments demonstrates a statistically significant difference only for the 'BRS226' (p = 0.0319). There is a statistical significance of the linear effect (y = 6.73x + 109.5; R^2 = 0.89; p = 0.00559) of the average individual cashew apple weight (g) as a function of biochar dose for the 'BRS 226' (Figure 2). Ref. [32] reported a mean cashew apple weight of 140 g for 'CCP 76', which is the approximate value observed in this experiment. It is possible for cashew apples of 'BRS 226' to reach a similar mean weight as those of 'CCP 76' by applying 4 kg plant^{-1} of biochar (Figure 2). Soil moisture availability for trees improves cashew apple size, and the quality of 'BRS226' cashew apples is favorable to its market and improves farmers' income. A significant increase in mango fruit weight per plant validated the efficacy of 40 Mg ha^{1} acidified biochar, which was reported by [35]. Fruit quality improvement with application of biochar (control, 2, 4, 6, 8, 10, and 12 kg plant^{-1}, also, on old apple orchards [36]. The single fruit weight (g) increased and then decreased with a quadratic effect.

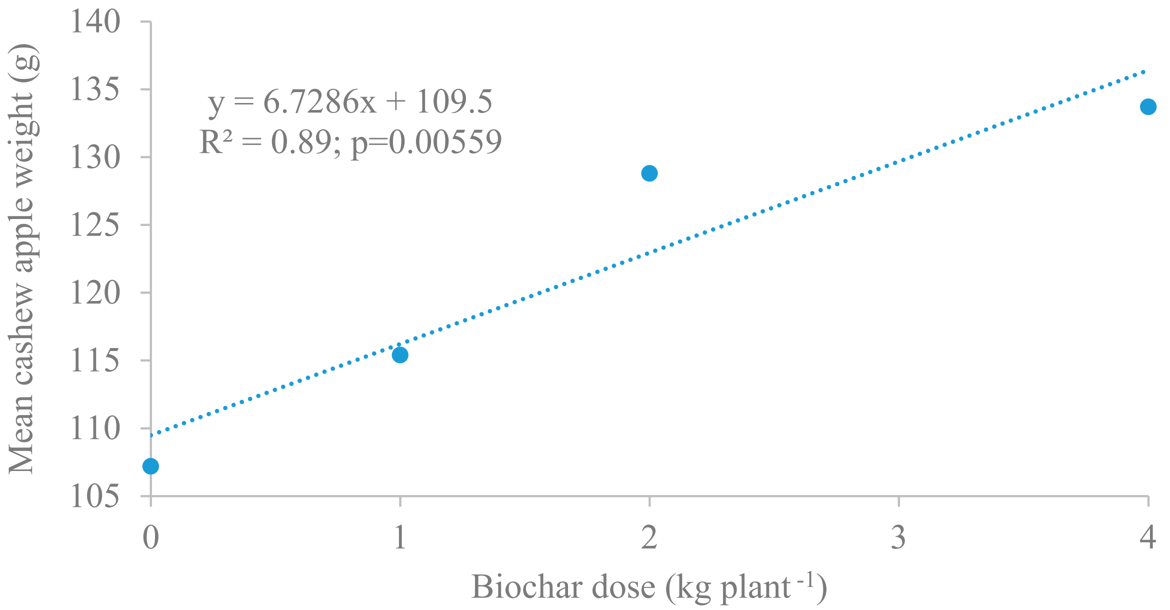

Figure 2. Linear regression (y = 6.7286 + 109.5; R^2 = 0.89; p = 0.00559) of the average cashew apple weight (g) as a function of biochar doses for 'BRS 226' Clone, Pacajus-CE, Brazil, 2023.

There was a cashew apple yield statistically significant difference between clones (averages of 34,477.29 kg ha^{-1} and 19,748.23 kg ha^{-1} for 'BRS 226' and 'CCP 76', respectively) but not between treatments of biochar doses. Ref. [31] reported a mean cashew apple yield of 10,217 kg ha^{-1} for 'CCP 76' and 15,156 kg ha^{-1} for 'BRS 226' of 4-year-old trees with seasonal irrigation strategy during flowering and harvest. In this experiment, a higher yield may be related to older trees (6-year-old trees).

3.2. Available Soil Moisture Content

Figure 3 shows the number of irrigation operations per treatment, as well as the average soil water potential (kPa) in the 0–0.3 m soil layer just before irrigation, which is carried out throughout the year, according to each cashew clone. It varied from 82.8 kPa to 90.6 kPa, and the number of irrigations varied from 54 to 88 among treatments and clones. The water potential in the irrigation day was planned to be 80 kPa, but in practice, it could surpass that level in the field within two days of data collection. The number of irrigation operations varied according to clone and biochar levels (Figure 3).

Table 4 shows the total annual hours of irrigation and respective water requirement per cashew tree (L plant^{-1}) in the year 2023 for each treatment. The reason 'BRS 226' trees required less irrigation than 'CCP 76' ones was due to the strategy to irrigate during flowering and harvest. 'CCP 76' trees started flowering on May 31st, while BRS 226 started on June 26th. The available daily soil moisture (ADS) content during the year ranged from 3.5 to 3.7 mm (37 to 39% of field capacity) to 2.4 to 2.6 mm (18 to 19% of field capacity) to 'BRS 226' and from 3.5 to 4.1 mm (37 to 44% of field capacity) to 2.4 to 3.6 mm (18 to 27% of field capacity) to 'CCP 76'in the 0–0.3 m and 0.3–0.6 m soil profile, respectively. These moisture percentages demonstrated only a few variabilities, especially in the most superficial soil layer (0–0.3 m), according to Table 4. This stable soil moisture content could be achieved with irrigation controlled by soil water sensors.

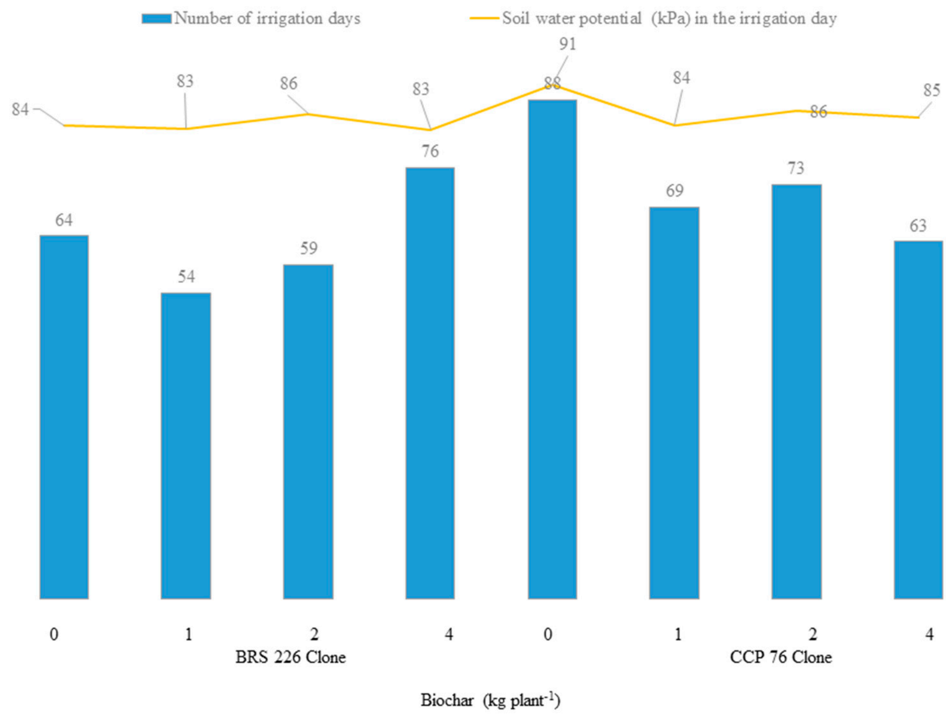

Figure 3. Number of irrigation and respective soil water potential (kPa) for each cashew tree clone ('BRS 226' or 'CCP 76') and biochar dose (0, 1, 2, and 4 kg plant^{-1}), Pacajus (CE), Brazil, 2023.

Table 4. Irrigation hours, total water applied (L plant^{-1} year^{-1}) and mean available daily soil moisture (ADS, mm) for 0–0.3 m and 0.3–0.6 m soil depths under different treatments (0, 1, 2, and 4 kg biochar plant^{-1}) in the year, Pacajus (CE), Brazil, 2023.

Biochar (kg Plant^{-1})	Annual Hours of Irrigation	L Plant^{-1} Year^{-1}	ADS (mm)	
'BRS 226' Clone				
			0–0.3	0.3–0.6
0	198	14,098	3.5	2.5
1	168	11,962	3.7	2.4
2	186	13,243	3.6	2.6
4	239	17,017	3.6	2.5
'CCP 76' Clone				
0	273	19,438	4.1	3.5
1	215	15,308	4.1	3.6
2	224	15,949	3.5	2.4
4	194	13,813	3.7	2.7

The difference in water applied between treatments may be explained by different levels of biochar. Figure 4 shows quadratic models of the amount of irrigation water applied (L plant^{-1} year^{-1}) during the year in each treatment for 'BRS 226' trees. ($y_{226} = 365.71x^2 - 2743.8x + 13{,}851$; $R^2 = 0.81$) and 'CCP 76' trees ($y_{76} = 681.25x^2 - 1913x + 13{,}851$; $R^2 = 0.95$). Less water was required by the 'CCP 76' Clone when using 4 kg plant^{-1} of biochar when compared to control, while 'BRS 226' trees had the least water demand using 1 kg plant^{-1} of biochar and the highest level of biochar treatment (4 kg plant^{-1}) required more water than the control. The 'CCP 76' control required more water than 'BRS 226'. The latter is a drought-tolerant clone. When applying 4 kg plant^{-1} to 'BRS 226' cashew trees, part of the water fills biochar pores, which works as a driver to demand more water. The application of biochar helped to decrease the number of irrigation and the amount of water applied continuously with the biochar application level for 'CCP 76' cashew trees, which demanded more water than 'BRS 226' cashew trees.

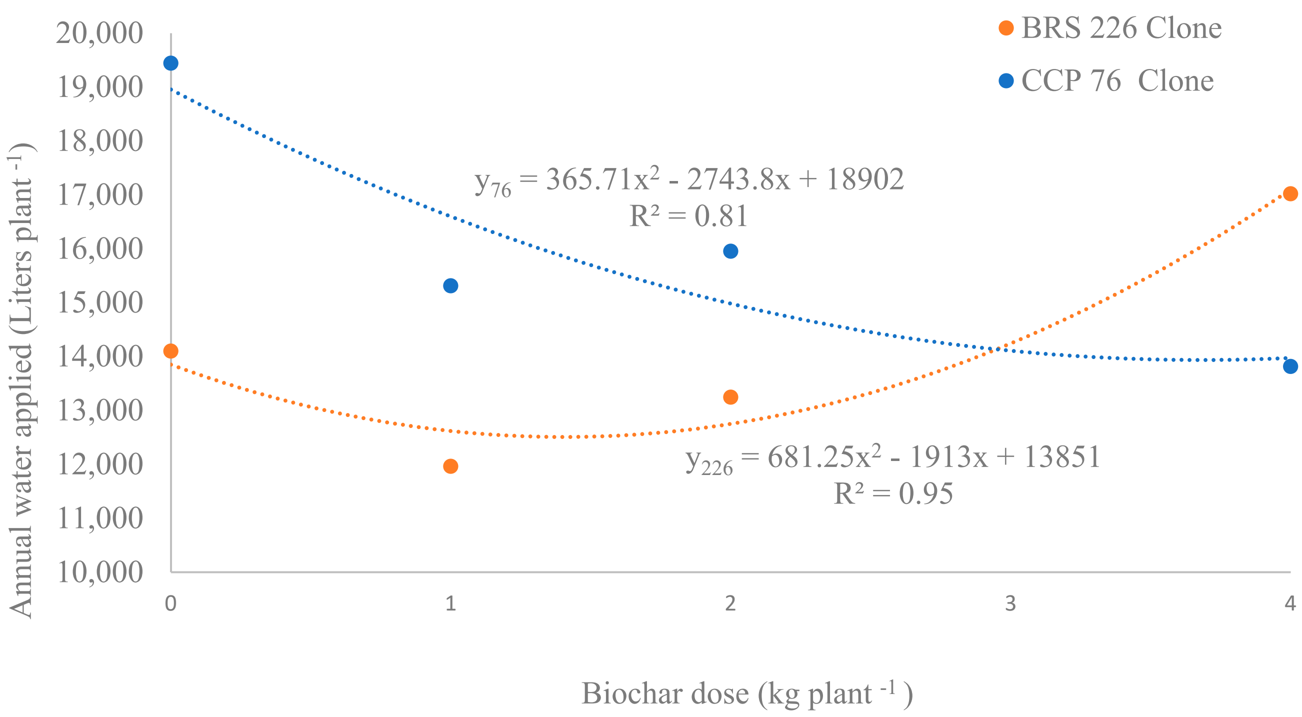

Figure 4. Volume of annual irrigation water (L plant^{-1} year^{-1}) applied to cashew clones 'BRS 226' (y_{226} = 681.25x^2 − 1913x + 13,851; R^2 = 0.95) and 'CCP 76' (y_{76} = 365.71x^2 − 2743.8x + 18,902; R^2 = 0.81), Pacajus-CE, Brazil, 2023.

Numerous studies have reported effect of biochar on soil moisture retention and available water content to plants: [9,37–41]. According to [41], biochar intrapores have the ability to increase water storage in sand-biochar mixtures. According to [42], water is generally stored and retained in the pores of biochar and an increase in biochar porosity will lead to an increase in soil water retention.

3.3. Irrigation Water Productivity

The productivity of irrigation water in terms of cashew nuts produced per volume of irrigation water applied (kg m^{-3}) demonstrated a significant effect between clones (averages of 1.0 kg m^{-3} and 0.3 kg m^{-3} for 'BRS 226' and 'CCP 76', respectively) and between treatments, as well as the interaction. Breaking down the interaction between clones and treatments, the analysis of variance demonstrated statistical significance only for the 'BRS 226' (p = 0.0001), with no treatment effect for the 'CCP 76'. Figure 5 presents the quadratic model (y = −0.092x^2 + 0.316x + 0.9345; R^2 = 0.80; p = 0.01374) referring to the productivity of irrigation water in terms of nuts produced per volume of irrigation water applied (kg m^{-3}) for 'BRS 226'. It is possible to estimate that the maximum productivity of irrigation water per nut produced (1.2 kg m^{-3}) is achieved with the application of 1.7 kg per plant of biochar (Figure 5). The amount of water per raw nut produced ranged from 0.43 kg m^{-3} to a maximum of 3.9 kg m^{-3} in India [8] when testing plant density and irrigation provided once every 15 days with 200 L plant^{-1} in the summer months compared with cumulative Class A pan evaporation of 20%, 40%, and 60%. The result in this experiment of water productivity is lower than that of [8], who reported a maximum of 3.9 kg m^{-3} with a lower plant density of cashew trees spaced 10 m × 5 m (200 plants ha^{-1}). The reason for higher irrigation water productivity in their work may be attributed to less water provided to plants (32 mm annually) than in this experiment (approximately

1500 mm annually), but they achieved a lower raw cashew nut yield (1601 kg ha^{-1}) than 'BRS 226' (2866 kg ha^{-1}) in this experiment.

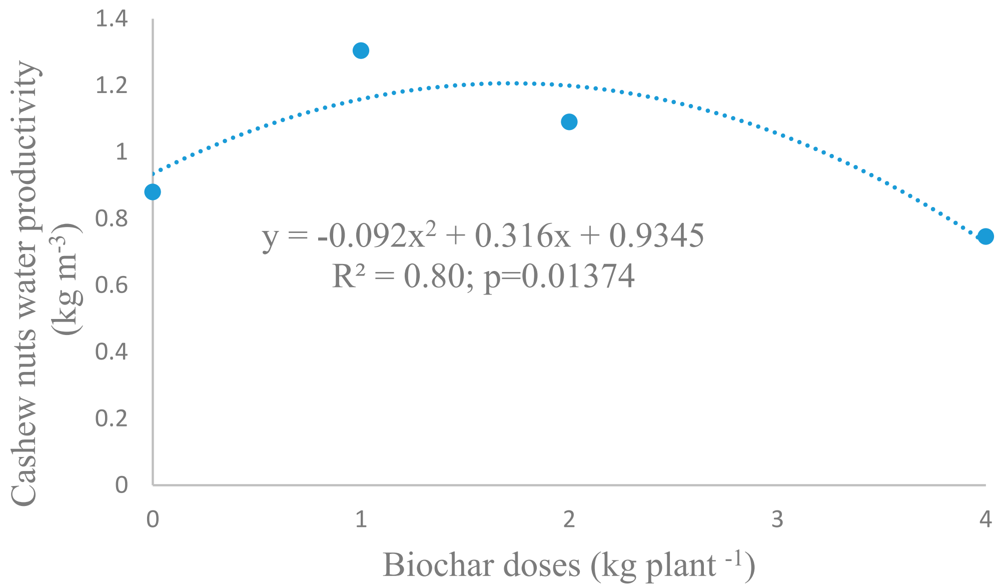

Figure 5. Quadratic model ($y = -0.092x^2 + 0.316x + 0.9345$; $R^2 = 0.80$; $p = 0.01374$) referring to the productivity of irrigation water per nuts produced (kg m^{-3}) for 'BRS 226' Clone, Pacajus-CE, Brazil, 2023.

The benefit of biochar on irrigation water productivity has also been reported by [10] on corn crops and by [40] on coconut tree orchards. One important aspect of achievement on water productivity is that it is the key for real water savings [43].

The productivity of irrigation water in terms of cashew apples produced per volume of irrigation water applied (kg m^{-3}) shows a significant effect between clones. The averages were 2245 kg m^{-3} and 1017 kg m^{-3} for 'BRS 226' and 'CCP 76', respectively; $p < 0.001$). The significant effect was also for the treatments ($p = 0.044556$) and the interaction between clones and treatments ($p = 0.009294$) in a similar way to that observed with cashew nuts. The analysis of variance of the split for each clone, in which statistical significance is demonstrated only for the BRS 226 Clone ($p = 0.0016$). Figure 6 presents the quadratic model ($y = -282.68x^2 + 1073.77x + 2328.86$; $R^2 = 0.93$; $p = 0.00029$) referring to the productivity of irrigation water in terms of cashew apples produced per volume of irrigation water applied (kg m^{-3}), depending on the treatments (quantities of biochar applied) for the 'BRS 226'. The application of 1.9 kg per plant of biochar results in the maximum productivity of irrigation water related to cashew apple production and the maximum peduncle estimated irrigation water productivity of 2382.52 kg m^{-3}.

The right amount of biochar could not only increase soil water content and effectively improve soil nutrients but also promote the development of the root system of fruit trees and improve the effective absorption of soil nutrients, which in turn improves fruit quality and weight, which results in higher irrigation water productivity in terms of fruit production per water applied (kg m^{-3}), as reported by [36].

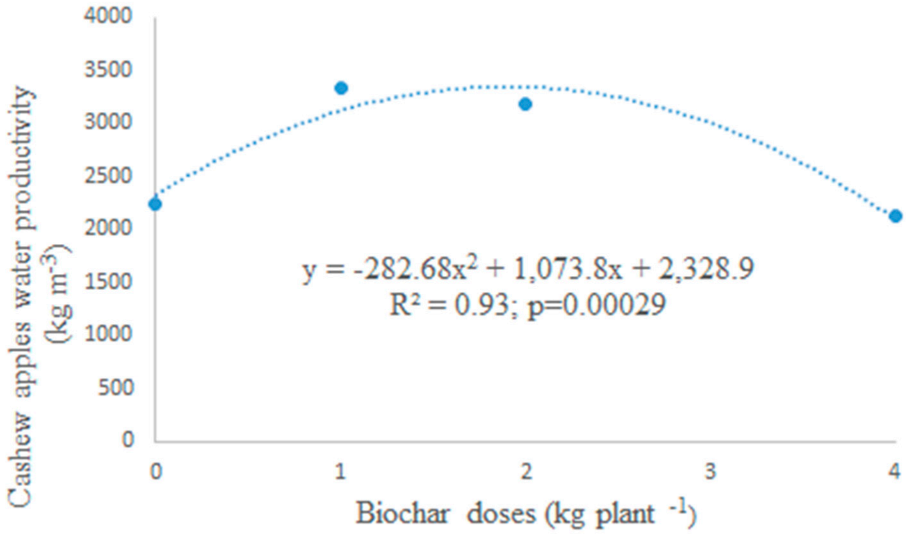

Figure 6. Quadratic model ($y = -282.68x^2 + 1073.77x + 2328.86$; $R^2 = 0.93$; $p = 0.00029$) referring to the productivity of irrigation water per cashew apples produced (kg m^{-3}) for the 'BRS 226' Clone, Pacajus-CE, Brazil, 2023.

3.4. Cashew Apple Post-Harvest Quality

3.4.1. Soluble Solids

Regarding cashew apple quality, the evaluation of soluble solids (°Brix) demonstrates the effect of clones and treatments, with the average content of soluble solids being higher for the 'CCP 76' (12.69 °Brix) than for the 'BRS 226' (10.97 °Brix). This is also a natural genetic difference between clones. Regarding treatments, the levels of biochar applied demonstrated statistical significance ($p = 0.0058$) with a quadratic effect ($y = -0.2855x^2 + 1.2168x + 11.204$; $R^2 = 0.99$; $p = 0.00059$), as Figure 7 shows. The application of 2.1 kg per plant of biochar for both clones results in the maximum soluble solids content, according to the quadratic model. An increase in soluble solids for apple fruits in all treatments compared with control has also been reported by [36].

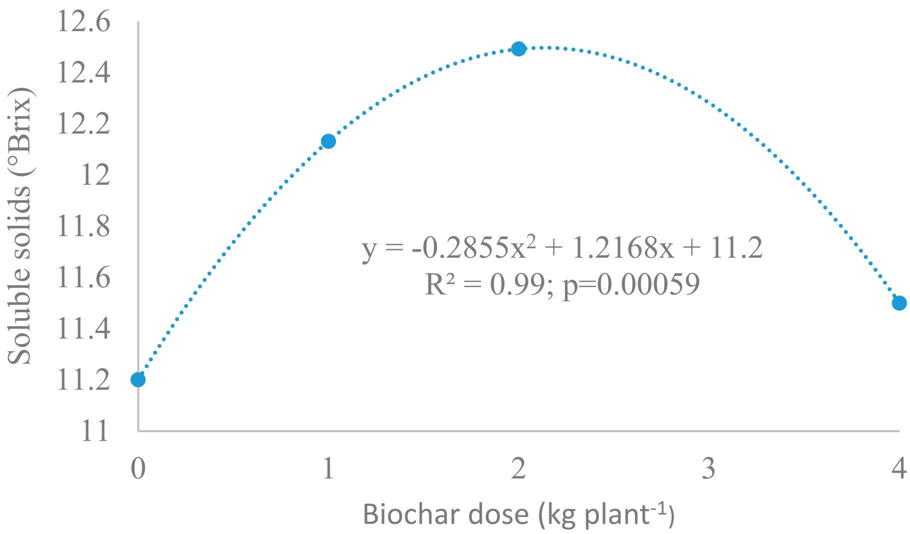

Figure 7. Quadratic model ($y = -0.2855x^2 + 1.2168x + 11.204$; $R^2 = 0.99$; $p = 0.00059$) referring to cashew apples soluble solids (°Brix) per amount of biochar applied to dwarf cashew plants, 'BRS 226' and 'CCP 76', Pacajus-CE, Brazil, 2023.

Higher SS for 'BRS226' cashew apples (12.84 °Brix) and lower for 'CCP76' (11.62 °Brix) was reported by [44]. As a matter of fact, CCP76 is a reference for the fresh cashew fruit market [45]. Higher levels of soluble solids of cashew apples were also detected (12.97 to 17.92 °Brix) by [7] for other cashew genotypes (CCP 09, BRS 265, and PRO 555.1 Clones). The highest levels were observed in the semiarid region when compared to coastal zones. This was attributed to the smaller size of the cashew apples (107 g) observed in this region since the soluble solids reflect the dry matter content, and it is inversely proportional to the size of the cashew apple. The factors that may have interfered with the smaller size of the cashew apples produced in the semiarid are probably due to the nutritional state of the plants, together with low water supply under high average temperatures and solar radiation.

In this study, the mean cashew apple weight varied from 121.3 g to 140.4 g, which may be attributed to irrigation management practices and soil moisture availability maintenance by biochar application. According to [46], biochar application substantially reduces damage to plants by promoting antioxidant activity, protein, and amino and organic acids and reducing reactive oxygen and methylglyoxal content that causes cell injury. They reported that in plants under drought stress, the uptake of nutrients is limited due to lower water supply, which ultimately affects metabolites including amino, organic acids, and soluble sugars, but biochar improved plant growth and development by mediating metabolites and soil physio-chemical status and reduced oxidative damage to plants under water stress.

3.4.2. Titratable Acidity (TA) (%)

The evaluation of titratable acidity (TA) (%) demonstrated the expected clone effect, as well as treatments and interaction between clones and treatments. 'BRS 226' presented a slightly higher level (0.23%) than 'CCP 76' (0.18%). These percentages are lower than those reported by [44], which are 0.40 for 'BRS226' and 0.30 for 'CCP76'. It becomes statistically equal when 2 kg per plant of biochar is applied. The interaction between clones and treatments demonstrates an effect for both clones. Figure 8 represents the phenomenon for each clone. The quadratic effect is concave (acidity reduces to a minimum and increases again) for the 'BRS 226' ($y_{226} = 0.0119x^2 - 0.0562x + 0.264$; $R^2 = 0.94$; $p = 0.0039$) and convex (acidity increases up to a maximum and then it is reduced) for the 'CCP 76' ($y_{76} = -00195x^2 + 0.0803x + 0.1436$; $R^2 = 0.57$; $p = 0.00003$). The statistical difference is not observed with the application of 2 kg plant^{-1} of biochar ($p = 0.5099$).

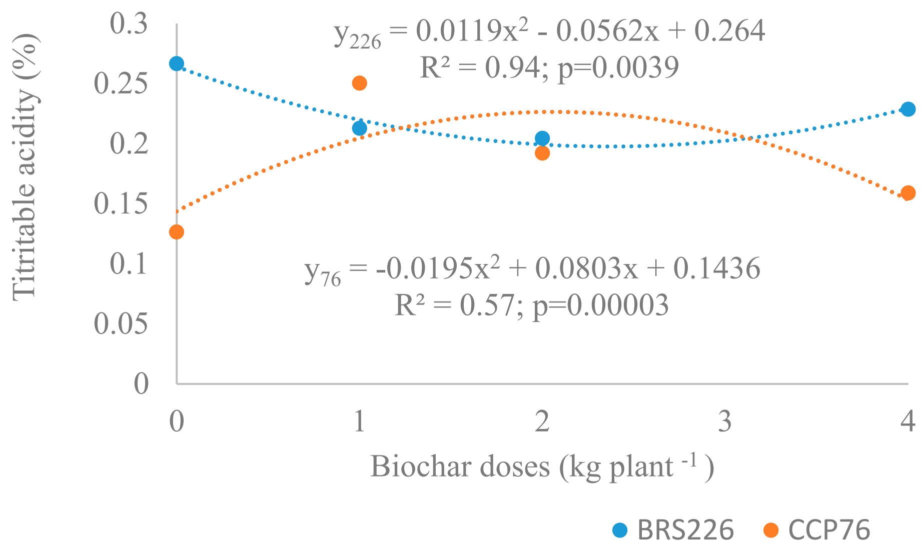

Figure 8. Titratable acidity (%) quadratic models according to biochar level (0, 1, 2, and 4 kg plant^{-1}) and cashew trees of clones 'BRS 226' ($y_{226} = 0.0119x^2 - 0.0562x + 0.264$ $R^2 = 0.94$; $p = 0.0039$) and 'CCP 76' ($y_{76} = -0.0195x^2 + 0.0803x + 0.1436$ $R^2 = 0.57$; $p = 0.00003$), Pacajus-CE, Brazil, 2023.

A decrease in fruit acidity in mango fruits caused by biochar, which is compatible with what happens to 'CCP76' cashew apples, was reported by [35].

Higher titratable acidity (0.26% to 0.48%) in cashew apples was detected by [7] for other cashew genotypes ('CCP 09', 'BRS 265' and 'PRO 555.1' Clones). According to [7], the titratable acidity had a similar performance to that of the SS, in which the highest levels were observed in the semiarid region when compared to coastal zones due to levels of annual rainfall (485.3 and 584.5 mm in the semiarid compared with 703 and 825 mm in the coastal zone). Cashew apples did not have favorable moisture retention conditions for their growth, causing higher concentrations of the compounds' SSs, TA, and soluble sugars for the semiarid zone [7]. In this study, soil moisture was not a restriction factor because water was supplied to trees by irrigation, but biochar contributed to different genotype responses. It reduced titrable acidity for 'BRS 226' (to a minimum with the application of 2.5 kg plant^{-1} of biochar) but increased it for 'CCP 76'.

3.4.3. Soluble Solids/Titratable Acidity Ratio

The soluble solids/titratable acidity ratio, which measures the sweet flavor of the cashew apples (the higher the ratio, the sweeter they are), in a similar way to titratable acidity, demonstrated a natural clone effect and interaction between clones and treatments, and it is higher for the 'CCP76' (74.20) than for the 'BRS 226' (49.52). Ref. [35] reported 32.34 for the 'BRS226' and 38.56 for the 'CCP76'. The interaction between clones and treatments demonstrates an effect for both clones. It becomes statistically equal when applying 1 kg plant^{-1} of biochar (p = 0.6356). Figure 9 represents the phenomenon for each clone. This time, the quadratic effect is convex (increases to a maximum and then reduces) for the 'BRS 226' ($y_{226} = -3.90x^2 + 17.52x + 39.35$; $R^2 = 0.96$; $p = 0.002$) and concave (it reduces to a minimum and then it increases again) for the 'CCP 76' ($y_{76} = 6.38x^2 - 27.98x + 89.66$; $R^2 = 0.56$; $p = 0.00001$). There is no statistical difference with the application of 1 kg plant^{-1} of biochar. This is due to the biochar improvement of this variable for the 'BRS 226' up to a maximum result with the application of 2.25 kg plant^{-1} of biochar.

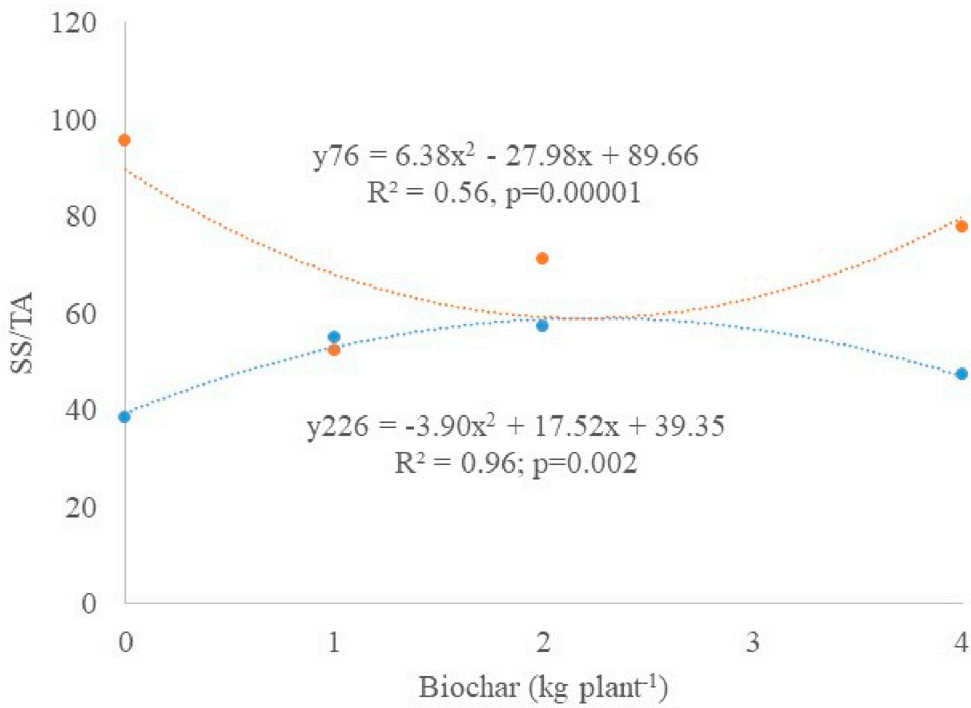

Figure 9. Soluble solids/titratable acidity ratio quadratic models according to biochar level (0, 1, 2, and 4 kg plant^{-1}) and the cashew tree clones 'BRS 226' ($y_{226} = -3.90x^2 + 17.52x + 39.35$ $R^2 = 0.96$; $p = 0.002$) and 'CCP 76' ($y_{76} = 6.38x^2 - 27.98x + 89.66$; $R^2 = 0.56$; $p = 0.00001$), Pacajus-CE, Brazil, 2023.

According to [36], compared with 'BRS 226' cashew apples, fruit sweetness increase by biochar on apple fruits was observed on three levels of application (4, 6, and 8 kg plant^{-1})

compared with control and decrease was observed in the highest levels of biochar application (10 and 12 kg plant^{-1}).

The soluble solids/titratable acidity ratio of cashew apples ranged from 35.72 to 50.00 in the semiarid region and from 53.46 to 57.91 in coastal zones for two observation years and different cashew genetic sources (CCP 09, BRS 265, and PRO 555.1 Clones) was found by [7]. There was a difference between the regions only in the first evaluation year, with the highest values obtained in cashew apples coming from the coast. The lowest level was observed in the semiarid region with less annual rainfall (485.3 and 584.5 mm compared with 703 and 825 mm in the coastal zone). The higher soluble solids/titratable acidity ratio is due to the lower titratable acidity identified in the cashew apples, while the highest levels of titratable acidity were observed in the semiarid region when compared to the coastal zones, which contributed to a lower SS/TA ratio.

The 'BRS 226' cashew clone has been demonstrated to be more drought-tolerant than the 'CCP 76'. Actually, the abiotic stress control processes of the 'CCP 76' have a greater burden on the enzymatic system, which somehow shows that the molecules present in the metabolome of this clone are not efficient in containing the damage caused by oxidative stress caused by drought. Six possible biomarkers responsible for drought tolerance in *A. occidentale* L. ('BRS 226') were cataloged. Anacardic acids are notable molecules in susceptible clones, having little importance in the composition of tolerant clones. Meanwhile, tolerant clones showed low metabolite variation [47].

In this study, cashew plants were irrigated under light water deficit conditions (from soil water potential of 80 kPa to field capacity). Biochar contributed to increasing SS for both clones but reduced TA only for the 'BRS 226', which is a drought-tolerant one. This fact resulted in a higher SS/TA ratio response only for the 'BRS 226'. Biochar helped to increase soil water availability for plants and to reduce TA in the same way it has been reported to happen in the coastal zone, where rainfall is higher [7].

The worsening of the SS/TA ratio observed for the 'CCP 76' makes it possible to conclude that the application of biochar could not be recommendable for this clone (R^2 = 0.56; Figure 9) when cashew apple quality is important. The 'CCP 76' is known as the best cashew apple quality for table consumption and the juice industry, while the 'BRS 226' plants are known as drought-tolerant, and their cashew apples are of lower quality when compared to 'CCP 76' ones. In the absence of strong water stress caused by irrigation, biochar helped 'BRS 226' trees improve cashew apple quality. The increase in SS, the decrease in TA, and the application of biochar favored the SS/TA ratio for BRS 226 cashew apples. The increase of SS, together with a reduction in titratable acidity, favors the SS/TA ratio.

For this reason, this study results demonstrate that the application of biochar is recommendable for the 'BRS 226' as a way to improve cashew apple quality, but it is not suggestable for the 'CCP76', for which SS/TA ratio response was unfavorable despite the increase of SS, while TA also increased, which resulted on lower SS/TA ratio. 'BRS 226' plants are known as drought-tolerant. In the absence of deep-water stress, biochar helped trees to improve cashew apple quality.

3.4.4. Firmness

Analysis of variance of the firmness (kgf) of the cashew apples demonstrated that there were significant statistical differences only between clones. The average was higher for the 'CCP 76' (2.3059 kgf) than for the 'BRS 226' (2.0778 kgf). Firmness descriptions report an average of 1.6509 for 'CCP76' [35]. Despite our results, fruit hardness reduction was observed in all treatments of biochar application for apple fruits [36].

4. Conclusions

The use of biochar had positive effects on irrigation water productivity in terms of cashew nuts and peduncles per cubic meter of irrigation water applied and mean individual cashew apple weight for the 'BRS 226'. Regarding cashew apples, soluble solids had positive effects for both clones ('BRS 226' and 'CCP76'), while the soluble solids/titratable acidity ratio improved only for the 'BRS 226' cashew clone. The optimal doses were 1.70 kg, 1.90 kg, 4.00 kg, 2.10 kg, and 2.25 kg per plant of biochar, respectively.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriengineering6040215/s1, Tables S1–S19: Analysis of variance.

Author Contributions: Conceptualization, L.A.L.S., R.S.G. and C.A.K.T.; methodology, R.S.G., C.A.K.T., L.A.L.S. and C.F.H.M.; software, R.S.G.; validation, R.S.G., C.A.K.T., L.A.L.S. and C.F.H.M.; formal analysis, R.S.G.; investigation C.F.H.M.; resources, C.F.H.M.; data curation, R.S.G.; writing—original draft preparation, R.S.G.; writing—review and editing, R.S.G., C.A.K.T., L.A.L.S. and C.F.H.M.; visualization, R.S.G.; C.A.K.T., L.A.L.S. and C.F.H.M.; supervision, R.S.G., C.A.K.T., L.A.L.S. and C.F.H.M.; project administration, C.A.K.T.; funding acquisition, C.A.K.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data availability under formal request to Brazilian Corporation of Agriculture Research.

Conflicts of Interest: The authors declare no conflicts of interest, the company had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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