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Growth and Energy Characteristics of Arboreal Wood Irrigated with Treated Effluent in Degraded Soil of Semi-Arid Regions †

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Abstract: The management of forest species in the recovery of degraded areas of semi-arid regions is mainly limited by the availability of water and nutrients. Thus, the objective of this research was to evaluate the growth, yield, and energy characteristics of the wood of two forest species of the Brazilian semi-arid region subjected to deficient irrigation with sewage effluent by drip in degraded soil. For this, a field experiment was conducted in an agroforestry system with two native species of the Caatinga biome: sabiá (*Mimosa caesalpiniifolia* Benth) and aroeira (*Myracrodruon urundeuva* Allemão), intercropped with forage palm (*Opuntia stricta* (Haw) Haw). The wastewater used was domestic, coming from kitchen and bathroom sinks, which underwent primary and secondary treatment. The irrigation treatments were applied in the first two years: in the first year, water supply in the volume of 0.5 L/plant/week ($WS_{0.5}$), treated effluent in the volume of 0.5 L/plant/week ($TE_{0.5}$), and treated effluent in the volume of 1 L/plant/week (TE_1). In the second year, all treatments were leveled at 0.5 L/plant/week, and in the following two years, all irrigation treatments were discontinued. Growth variables were monitored and, at the end of the study period, wood production was calculated and energetic analyses were performed. The Richards model adjusted satisfactorily to the growth variables for the species studied. The treated effluent at a volume of 1 L/week increased the yield in condensed liquid and decreased the volatile materials (VM) of sabiá, while in aroeira it increased the basic density and VM, with a decrease in the gravimetric yield.

Keywords: energy biomass; *Mimosa caesalpiniaefolia*; *Myracrodruon urundeuva* Allemão; deficient irrigation

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1. Introduction

The cultivation of forest species in degraded areas of semi-arid regions is a recommended practice in environmental restoration programs and agroecosystem management. However, the availability of water and nutrients in these environments are the most limiting factors for plant growth [1,2], necessitating strategies that facilitate species development without overburdening the available water resources.

The Brazilian semi-arid region is one of the most populous dry areas in the world [3,4] and recently experienced the worst water crisis ever recorded (2010–2016) [5]. Furthermore, environmental degradation processes result in severe economic and social impacts due to the decline in agricultural production and financial resource generation [6]. Therefore, there is a pressing need to shift exploitation models, particularly in agriculture, towards more sustainable practices that support the maintenance of tree vegetation, such as in silvopastoral and agrosilvopastoral systems [7]. Additionally, alternative technologies for the enrichment and/or recovery of degraded soils should be implemented.

Domestic effluents could serve as an alternative to reducing water scarcity and promoting the recovery of degraded soils. Furthermore, the use of these effluents can enhance forestry production. When properly managed, the application of sewage effluent has various effects, including the contribution and recycling of organic matter and nutrients, which generate chemical, physical, and biological benefits for the soil. Additionally, the use of effluent conserves available water and minimizes sewage discharges into water bodies, supporting environmental conservation [8,9]. The use of wastewater can improve plant growth and productivity, as it contains different nutrients for trees, which increases the accumulation of dry matter [10,11] and, consequently, the amount of energy per volume. Some studies estimate that irrigation with treated wastewater has the potential to save more than 50% of chemical fertilizers in some crops [12], with the contribution of nutrients, organic matter, and cation exchange capacity [13]. Effluents of domestic origin can be treated more easily compared to those of industrial origin [14], as they have a very low risk of contaminants, especially for use in agriculture, generally consisting of two basic stages, filtration and sedimentation tanks.

The sabiá (*Mimosa caesalpiniifolia* Benth) of the Fabaceae family is medium-sized (up to 5 m) and fast-growing, while the aroeira (*Myracrodruon urundeuva* Allemão) of the Anacardiaceae family is large (20 to 30 m) and slow to moderately growing. Both species are native to the Brazilian semi-arid region and are primarily valued for timber, but they have versatile uses, ranging from fodder to medicinal applications [15], and are therefore of economic interest. Despite this, it is observed in the literature that most research has focused on the study of seeds and propagation of native species in the semi-arid region [15]. The impacts of irrigation with treated sewage effluent on tree species are still poorly understood [16], especially regarding growth patterns, yield, and the energy characteristics of the wood.

This study aimed to evaluate the growth, yield, and energy characteristics of the wood of two forest species from the Brazilian semi-arid region when subjected to the application of sewage effluent in small quantities for the first two years and without irrigation in the subsequent two years.

2. Materials and Methods

2.1. Characterization of the Experimental Area

This study was conducted in the experimental area at the Instituto Nacional do Semiárido (INSA) headquarters in Campina Grande, PB. The region has a hot and dry semi-arid climate (AC), with a rainy season from March to July and significant annual fluctuations (Figure 1).

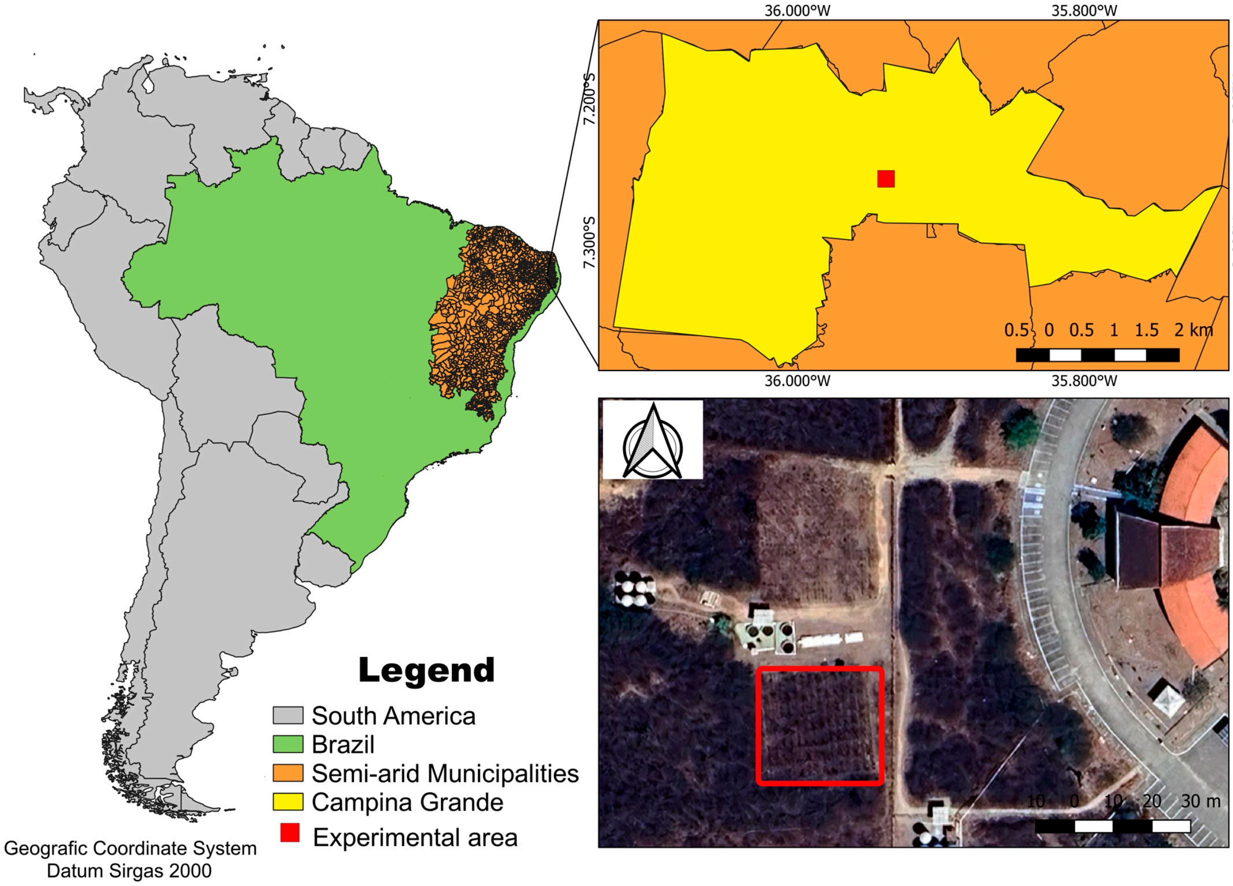

Figure 1. Location of the experimental area, Campina Grande, Paraíba, Brazil.

The local geology is represented by a peraluminous granite-migmatite suite, mainly consisting of orthogneiss and granodioritic to monzogranitic migmatite (1037 Ma U-Pb) [17]. Their weathering originates Dystric Gleiyc Planosol (Loamic, Ochric) [17,18], which presents a sequence of horizons A1-A2-Btg1-Btg2-Cr. These Planosols have high runoff potential, presenting very low infiltration, especially in the more clayey subsurface layers with the occurrence of expandable phyllosilicates, such as smectites and vermiculites. In addition, this area presents high soil density, a small volume of macropores, and low permeability, characterized by an infiltration rate of <1.27 mm/h [17]. In the experimental area, the surface horizons were removed by civil construction, resulting in a "truncation" process that exposed the subsurface horizons (Cr). The main characteristics of the soil are stoniness and shallowness. Soil granulometry was conducted according to Teixeira et al. (2017) [19], and the texture was classified as "sandy loam", with its chemical characteristics described in Table 1.

Table 1. Chemical characterization of the degraded soil before applying treated sewage effluent treatments in the 0–15 and 15–30 cm layers in the semi-arid region of Paraíba, Brazil.

Depth	pH 1:2.5	P	Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	EB	CEC	CECe	BS	AS
	H_2O	$mg \cdot kg^{-1}$					$cmol_c \cdot kg^{-1}$					%	
0–15	6.07	8.14	0.1	3.29	0.27	0.23	0.21	0.02	0.74	4.0	0.84	19.05	12.45
15–30	6.37	4.07	0.1	2.87	0.28	0.18	0.16	0.01	0.64	3.5	0.74	18.60	16.04

EB: exchangeable bases: CEC: cation exchange capacity; CECe: effective cation exchange capacity; BS: base saturation; AS: aluminium saturation.

2.2. Description and Experimental Design

The experiment was conducted over an area of 780 m^2, in which 195 seedlings of 2 native Caatinga species with timber potential were planted: sabiá (*Mimosa caesalpiniaefolia* Benth) and aroeira (*Myracrodruon urundeuva* Allemão). The seedlings were planted level, with one seedling per hole measuring 30 × 30 × 30 cm and spaced 2.0 × 2.0 m. The foundation was fertilized with 1 kg of organic matter per hole. The experiment was set up as an agroforestry system intercropped with 1560 forage palm plants, erect prickly pear (*Opuntia stricta* (Haw) Haw), planted in a double row.

We used water from the INSA supply system, which comes from rainwater harvesting, and reused water from the sewage generated at the INSA administrative headquarters, which has toilets and pantries. The sewage underwent primary and secondary treatment at the INSA effluent treatment plant, consisting of a sequence of filtering tanks and a septic tank for sedimentation. The treated sewage was then pumped using a drip system with self-compensating drippers. The chemical characterization of the treated sewage is shown in Table 2. The production of reused water, from the treatment of sewage generated on INSA premises, remained in the range of 1280 L/day, resulting in 38.3 m^3/month of treated effluent used in the irrigation of the experimental area.

Table 2. Chemical characterization of the water supply and treated sewage effluent used to irrigate degraded soil in Campina Grande, PB.

Parameter	Unit	Water	
		Supply	Residual
pH	-	7.5	8.3
EC	$dS\ m^{-1}$	0.79	1.35
TOC	$mg\ L^{-1}$	1.72	3.7
N	$mg\ L^{-1}$	0.28	26.3
NH_4^+	$mg\ L^{-1}$	-	22.3
NO_2^{3-}	$mg\ L^{-1}$	-	4.5
P	$mg\ L^{-1}$	1.68	14
PO_4^{3-}	$mg\ L^{-1}$	-	9.4
K^+	$mg\ L^{-1}$	5.4	27.6
Ca^{+2}	$mg\ L^{-1}$	11.2	24.5
Mg^{+2}	$mg\ L^{-1}$	6.4	10.7
SO_4^{3-}	$mg\ L^{-1}$	-	51.9
Na^+	$mg\ L^{-1}$	9.1	22.3
Cl^-		178	270

EC—electrical conductivity; TOC—total organic carbon; N—total nitrogen; NH_4^+—ammoniacal nitrogen; NO_2^{3-}—nitrates; P—total phosphorus; PO_4^{3-}—phosphates; K^+—potassium; Ca^{+2}—calcium; Mg^{+2}—magnesium; SO_4^{3-}—sulphates; Na^+—sodium; and Cl^-—chlorine.

The experiment was set up in July 2013 and lasted four years, with irrigation treatments applied during the first two years (2013 to 2015). In the first year, the treatments were as follows: water supply at a volume of 0.5 L/plant/week ($WS_{0.5}$), treated effluent at a volume of 0.5 L/plant/week ($TE_{0.5}$), and treated effluent at a volume of 1 L/plant/week (TE_1). In the second year, all the treatments were standardized to a volume of 0.5 L/plant/week, as follows: $WS_{0.5}$ water supply at a volume of 0.5 L/plant/week; $TE_{0.5}$-treated effluent at a volume of 0.5 L/plant/week; and TE_1-treated effluent also at a volume of 0.5 L/plant/week. In the following years (2015 to 2017), all irrigation treatments were discontinued, and the crop was evaluated under a rainfed system, relying solely on rainfall to supply water to the cultivation system.

Rainfall and temperature were monitored during the experimental period using a weather station located 100 m from the experiment site (Figure 2). The experimental design was a randomized block arrangement with three treatments and ten replications.

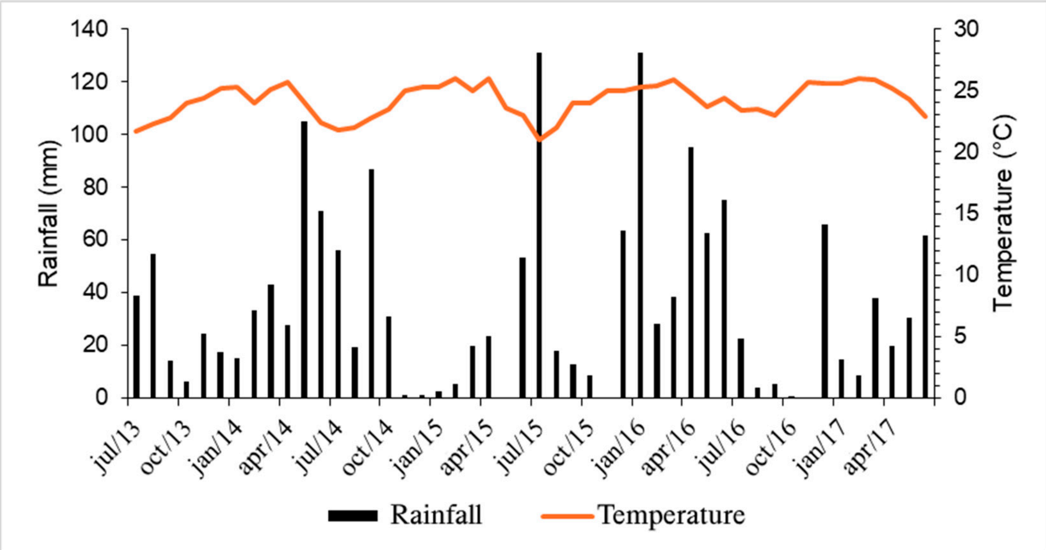

Figure 2. Rainfall and temperature during the experiment period in the semi-arid region of Paraíba BR.

The following dendrometric characteristics were assessed for the tree species: total height, base diameter (5 cm from the ground), and diameter at breast height (DBH) for all the plants. The evaluations were conducted monthly until the third year, when growth over time was also modeled using the Richards equation for total height, base diameter, and diameter at breast height [20], according to Equation (1):

$$\frac{a}{1+\exp(b-c*x)}^{\left(\frac{1}{d}\right)} \quad (1)$$

Ultimately, all the trees in the experiment were felled, cut 30 cm from the ground, and measured at their commercial height. After this, 2.5 cm thick disks were removed from the stem at 0% (base), 50%, and 100% of the commercial height. These samples were duly identified and transported to the Forest Products Technology Sector (STPF) of the Forest Engineering Academic Unit (UAEF), the Federal University of Campina Grande (UFCG), Campus of Patos, PB. Part of the tree disks were used to determine basic density (Bd), and the rest were set aside for energy analysis.

The basic density of the wood was determined according to the method for disks using a hydrostatic balance (Bd, Equation (2)) under NBR 11941 [21].

$$Bd = \frac{m_3}{(m_2 - m_1)} \quad (2)$$

where *Bd* is the basic density of the wood, in grams per cubic centimeter (g/cm^3); m_3 is the mass of the sample dried in an oven at 105 °C ± 2 °C, in grams (g); m_2 is the mass of the container with water and the immersed disk, in grams (g); and m_1 is the mass of the container with water, in grams (g).

The carbonizations were conducted in an electric oven (muffle furnace) adapted for this operation, with temperature control. The heating was manually controlled in the following order: 100 °C for 30 min; 150 °C for 30 min; 200 °C for 30 min; 250 °C for 30 min; 300 °C for 30 min; 350 °C for 30 min; 400 °C for 30 min; and 450 °C for 30 min. Approximately 300 g of dry wood (moisture content of 0%) was charred. The vapors and gases were conducted to a tubular condenser, with the pyroligneous liquid collected in a Buchner flask.

After carbonization, the gravimetric yields in charcoal (CGY), pyroligneous liquid (PLY), and, by difference, the non-condensable gases (NCGY) were calculated using Equations (3), (4), and (5), respectively.

$$\text{CGY} = \frac{\text{Mc}}{\text{Mw}} \tag{3}$$

where CGY = charcoal gravimetric yield (%); Mc = mass of charcoal (g); and Mw = dry mass of wood (g).

$$\text{PLY} = \frac{\text{Mpl}}{\text{Mw}} \tag{4}$$

where PLY = pyroligneous liquid yield (%); Mpl = mass of pyroligneous liquid (g); and Mw = dry mass of wood (g).

$$\text{NCGY} = 100 - (\text{CGY} + \text{PLY}) \tag{5}$$

where NCGY = non-condensable gases yield (%); CGY = charcoal gravimetric yield (%); and PLY = pyroligneous liquid yield (%).

2.3. Statistical Analysis

The results were submitted to an analysis of variance according to the randomized block experiment model (F test), and the means were compared using orthogonal contrasts at the maximum significance level of 0.10 probability. SISVAR software version 5.6 [22] was used for the statistical analysis.

3. Results

The two trees species showed a satisfactory fit to the Richards model, with coefficients of determination (R^2) $\geq$ 0.90 for growth in height, diameter at breast height (DBH), and stem base diameter (SBD) under the three irrigation treatments evaluated during the first three years of growth (Figures 3–5).

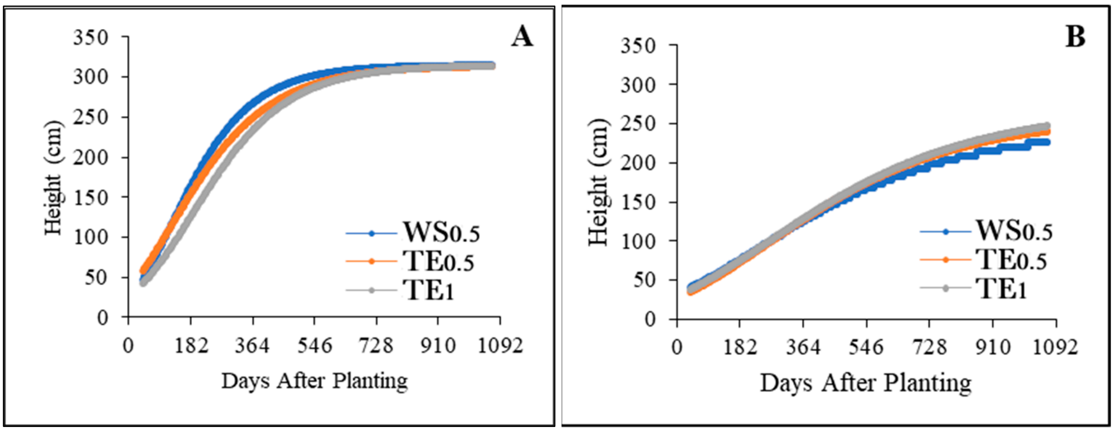

Figure 3. Height growth curve of sabiá (**A**) and aroeira (**B**) subjected to irrigation treatments with water supply ($WS_{0.5}$—0.5 L) and reuse water ($TE_{0.5}$—0.5 L and TE_1—1 L) in degraded soil in the Brazilian semi-arid region.

The height of the sabiá followed a similar trend among the treatments, with rapid exponential growth and a slight advantage for the $WS_{0.5}$ treatment during the first year. Subsequently, there was a slowdown in growth and stabilization before the end of the second year for all three irrigation treatments, a period in which irrigation treatments were leveled to 0.5 L/plant/week (Figure 3A).

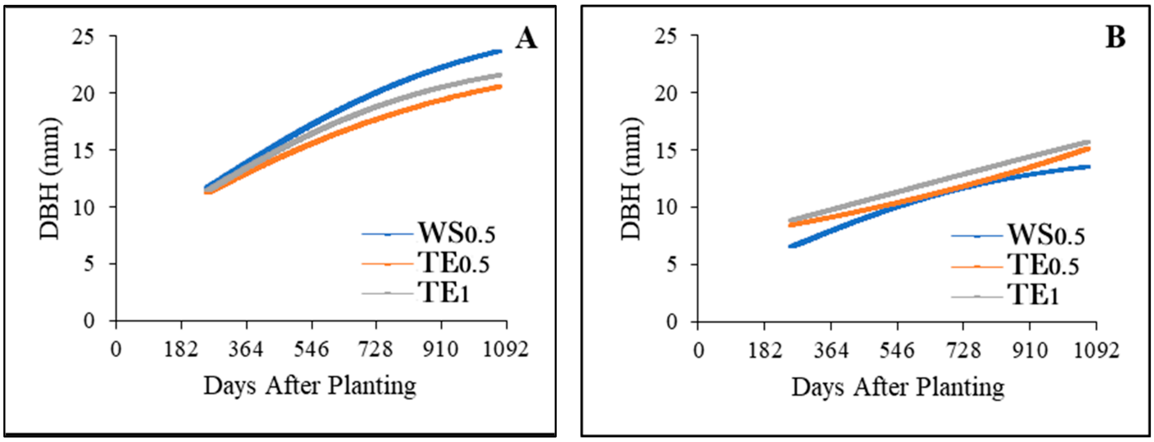

Figure 4. Growth curve of diameter at breast height (DBH) of sabiá (**A**) and aroeira (**B**) subjected to irrigation treatments with water supply ($WS_{0.5}$—0.5 L) and reuse water ($TE_{0.5}$—0.5 L and TE_1—1 L) in degraded soil in the Brazilian semi-arid region.

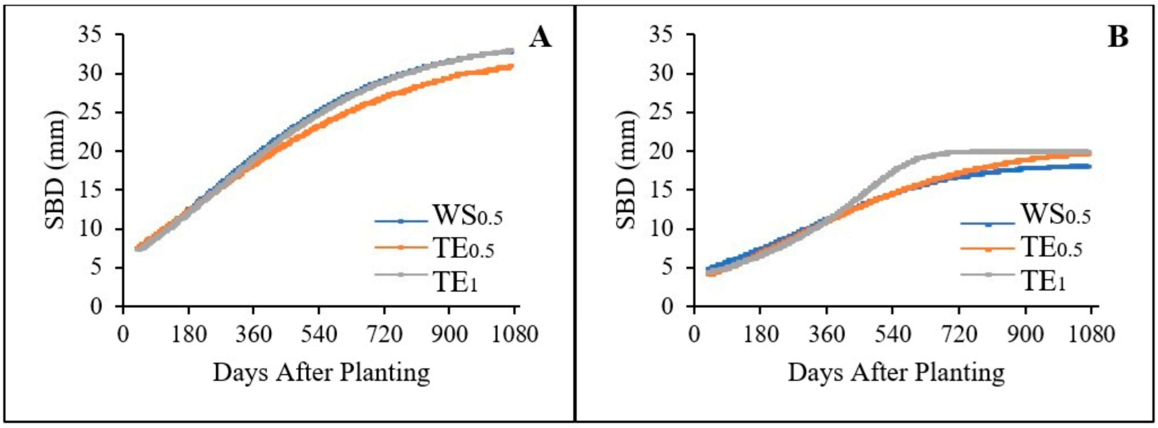

Figure 5. Growth curve of the stem base diameter (SBD) of sabiá (**A**) and aroeira (**B**) subjected to irrigation treatments with water supply ($WS_{0.5}$—0.5 L) and reuse water ($TE_{0.5}$—0.5 L and TE_1—1 L) in degraded soil in the Brazilian semi-arid region.

The aroeira showed slower growth than the sabiá, with similar growth curves among treatments. The decrease in growth up to the third year was not as evident as with the sabiá, indicating that the decrease and tendency to stabilize occurs later (Figure 3B). From the third year onwards, a period in which irrigation treatments had already been suspended, the TE_1 treatment was slightly superior to the other treatments.

The growth in DBH in sabiá showed a more obvious difference between the treatments, with greater growth in $WS_{0.5}$ from the second to the third year of evaluation (Figure 4A). However, unlike height, there was no decrease in growth rates or stabilization until the third year, showing that DBH continued to increase in the following years, with irrigation treatments already suspended. In aroeira, DBH showed exponential growth over time, especially in TE_1, which was also higher than the other treatments.

The SBD growth of sabiá increased gradually at the beginning and tended to decrease at the end of the evaluation period (Figure 5A). The $TE_{0.5}$ treatment showed a lower magnitude of growth from the first year onwards compared to the other treatments. There was greater variation between the treatments in the SBD curves of aroeira (Figure 5B). Initially, there was similar growth among the treatments; however, after the first year, TE_1 exhibited higher growth compared to the other treatments, with a tendency to stabilize from the second year onwards, when irrigation treatments were already suspended.

At four years of age, the sabiá species showed no significant difference ($p > 0.10$) between the treatments assessed for total plant height (TPH), stem base diameter (SBD), and total volume (TV). However, there was a significant difference in diameter at breast height (DBH), where $WS_{0.5}$ was higher than TE_1 at the 10% probability level (Table 3). In aroeira, a significant effect ($p < 0.10$) was observed for plant height (PLH), where TE_1 was superior to $WS_{0.5}$, and for total volume (TV), with TE_1 being superior to both $WS_{0.5}$ and $TE_{0.5}$. There was no significant difference in DBH and SBD for aroeira.

Table 3. Total plant height (TPH), diameter at breast height (DBH), stem base diameter (SBD), and total volume (TV) of sabiá and aroeira at four years of age irrigated with reuse water (TE_1 and $TE_{0.5}$) and water supply ($WS_{0.5}$) in degraded soil in the Brazilian semi-arid region.

Contrast	TPH m	DBH mm	SBD mm	TV m^3/ha
Sabiá (*Mimosa caesalpiniaefolia* Benth)				
$WS_{0.5}$–$TE_{0.5}$	3.33–3.16 ^{ns}	25.91–23.75 ^{ns}	40.19–37.11 ^{ns}	9.9–8.2 ^{ns}
$WS_{0.5}$–TE_1	3.33–3.10 ^{ns}	25.91–22.26 $^{\circ}$	40.19–39.06 ^{ns}	9.9–7.6 ^{ns}
$TE_{0.5}$–TE_1	3.16–3.10 ^{ns}	23.75–22.26 ^{ns}	37.11–39.06 ^{ns}	8.2–7.6 ^{ns}
Aroeira (*Myracrodruon urundeuva* Allemão)				
$WS_{0.5}$–$TE_{0.5}$	2.23–2.35 ^{ns}	12.85–14.08 ^{ns}	19.89–21.56 ^{ns}	1.9–2.0 ^{ns}
$WS_{0.5}$–TE_1	2.23–2.60 $^{\circ}$	12.85–13.18 ^{ns}	19.89–20.95 ^{ns}	1.9–2.9 $^{\circ}$
$TE_{0.5}$–TE_1	2.35–2.60 ^{ns}	14.08–13.18 ^{ns}	19.89–20.95 ^{ns}	2.0–2.9 $^{\circ}$

($^{\circ}$) are significant at 10% probability; (ns) is not significant.

These results indicate that the species under study responded differently to the application of treated effluent. The growth and production variables showed that the sabiá tended to have higher values when treated with water supply ($WS_{0.5}$), demonstrating the poor response of this species to reuse water, even though it was applied during the first two years of growth.

Aroeira, on the other hand, had a significant and positive response to sewage effluent, as the treatment with the largest volume of treated effluent (TE_1) increased TPH and TV. However, when comparing the timber potential of the two species at four years of age in terms of average TV values in the treatments with the highest results, sabiá had approximately 3.4 times greater timber volume production than aroeira.

The mean annual increment (MAI) of sabiá reached its maximum value in the third year of growth, with $WS_{0.5}$ being superior (Figure 6A). There was a downward trend in both treatments during the fourth year, when irrigation treatments were already suspended.

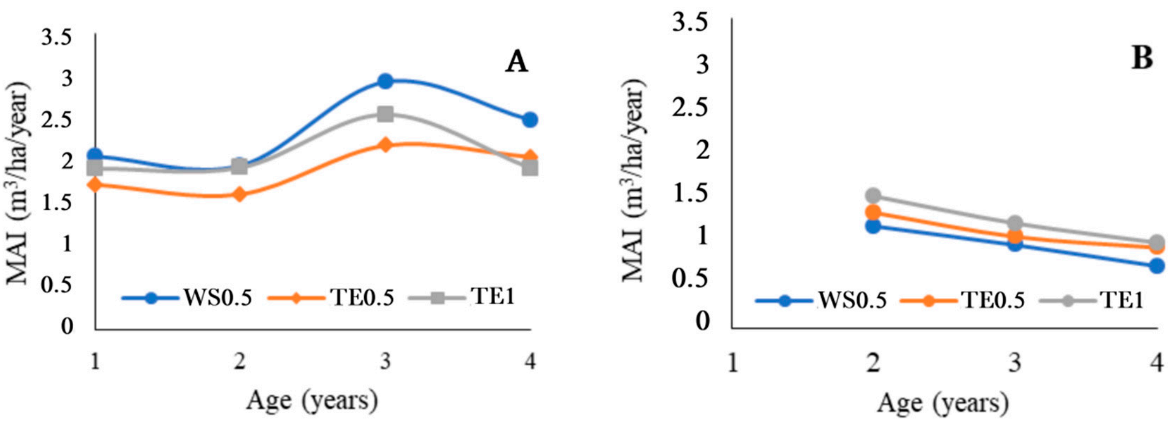

Figure 6. Mean annual increment (MAI) of sabiá (**A**) and aroeira (**B**) subjected to irrigation treatments with reuse water and water supply in degraded soil in the Brazilian semi-arid region.

The volume of the aroeira was only obtained after the first year due to its slow growth, allowing the calculation of only three years of MAI (Figure 6B). The MAI of the aroeira decreased linearly each year.

Regarding the wood characteristics, there was no significant effect on basic density (Bd) and gravimetric yield in charcoal (CGY) for sabiá, although there was a significant effect on pyroligneous liquid yield (PLY) and non-condensable gases yield (NCGY) ($p < 0.01$) (Table 4). The TE_1 treatment increased PLY values compared to $WS_{0.5}$ and $TE_{0.5.}$ Conversely, NCGY values were higher in $WS_{0.5}$ and $TE_{0.5}$ compared to TE_1. In the aroeira, there was a significant difference ($p < 0.10$) for Bd and NCGY, with TE_1 obtaining the highest values compared to $WS_{0.5}$ and $TE_{0.5}$, respectively (Table 4). CGY had a higher value in the $WS_{0.5}$ treatment than TE_1, with no significant difference in any of the contrasts tested for PLY in the aroeira. The highest basic density value was observed for the TE_1 treatment (0.835 g/cm^3) of *M. caesalpiniaefolia* wood, with the lowest result for the $WS_{0.5}$ treatment (0.632 g/cm^3). *M. caesalpiniaefolia* wood showed the highest CGY value in the $TE_{0.5}$ treatment (38.11%), with the lowest value for $WS_{0.5}$ (37.01%). For the *M. urundeuva* species, the $WS_{0.5}$ treatment stood out with the highest result (35.83%). Regarding LP and NCGY, *M. caesalpiniaefolia* wood exhibited the lowest values for the $TE_{0.5}$ treatment (16.24%) and TE_1 treatment (30.55%), respectively.

Table 4. Orthogonal contrasts and mean values of the wood energy characteristics: basic density (Bd), gravimetric yield (CGY), condensed liquid yield (PLY), and non-condensable gases yield (NCGY) of two tree species irrigated with reuse water and water supply in a degraded soil in the Brazilian semi-arid region.

Contrast	Bd (g/cm^3)	CGY (%)	PLY (%)	NCGY (%)
		Sabiá		
$WS_{0.5}$–$TE_{0.5}$	0.824–0.802 ^{ns}	37.01–38.11 ^{ns}	20.18–16.24 ^{ns}	42.81–45.82 ^{ns}
$WS_{0.5}$–TE_1	0.824–0.835 ^{ns}	37.01–37.74 ^{ns}	20.18–31.77 **	42.81–30.55 **
$TE_{0.5}$–TE_1	0.802–0.835 ^{ns}	38.11–37.74 ^{ns}	16.24–31.77 **	45.82–30.55 **
		Aroeira		
$WS_{0.5}$–$TE_{0.5}$	0.632–0.637 ^{ns}	35.83–35.62 ^{ns}	27.47–29.71 ^{ns}	36.70–34.79 ^{ns}
$WS_{0.5}$–TE_1	0.632–0.661 °	35.83–34.23 °	27.47–25.28 ^{ns}	36.70–48.70 ^{ns}
$TE_{0.5}$–TE_1	0.637–0.661 ^{ns}	35.62–34.23 ^{ns}	29.71–25.28 ^{ns}	34.79–48.70 °

(°) and (**) are significant at 10 and 1% probability, respectively; (ns) is not significant.

4. Discussion

Detecting tree growth patterns is not simple and varies depending on the measured dimension [23]. A sigmoidal curve typically represents biological behavior; however, three years is considered too short to represent the growth of forest species. Therefore, only the initial behavior of these curves was observed in this research.

According to Machado [24], the sabiá tree is characterized by rapid development, reaching a height of 4 m at two years of age. This was also reported by Silva [25], who found that sabiá reached 4.85 m in 2 years when cultivated with a fertilized system. The exponential growth of sabiá in the first year (Figure 3A) likely occurred until lithic contact impeded root development, as the effective depth of the stripped soil was no more than 40 cm. The growth curve then stabilized at a height of around 3 m, remaining so until the third year of growth. Nascimento et al. [26] state that sabiá prefers deep, well-drained, and fertile soils. However, it can also grow in shallow, stony soils such as those in the crystalline basement of the Caatinga [27]. In addition to the shallow soil, planting density may have influenced sabiá development, as the recommended spacing for the species is at least 3×3 m.

In general, for tree height, the juvenile phase is identified up to the inflection point of the growth curve, where the growth rate decreases, marking the beginning of the maturity period, which continues up to the point of maximum tangency. Beyond this point, the tree enters the senescence phase [28].

The behavior of the aroeira growth curve reflects the inherent characteristics of the species, which is considered long-lived and slow to moderate growing, with an estimated harvesting age for the production of fence posts at 20 years [15,29].

Unlike height growth, which stabilizes when the tree reaches maturity, the increase in DBH is constant throughout the species' lifespan [30]. This was evident in this study, as both species did not show a tendency to stabilize or decrease in growth until the evaluation ended. Additionally, according to Bawman [23], the increase in DBH varies less than height, biomass, and volume in small and medium-sized trees. This study also observed this behavior, especially in the aroeira curves.

In general, the growth curves for height, DBH, and SBD reflected the intrinsic differences of each species, with sabiá showing a rapid growth in the first few years and aroeira, which has macrobiotic characteristics, exhibiting slower growth. Although the effluent did not change the overall trends in the curves, it slightly improved the curves for aroeira, while they were generally lower for sabiá. Discontinuing the treatments after the second year did not alter the growth trends for either species or treatments.

Sabiá's lower performance with the application of reuse water was probably due to its sensitivity to the salts present in higher concentrations in the sewage effluent (Table 2), which in turn increased the soil Na+ and ESP (exchangeable sodium percentage) levels. A study by Bessa et al. [31] classified aroeira as highly resistant and sabiá as the most sensitive to soil salinity levels among the native species grown in the Brazilian semi-arid region. The sensitivity of sabiá to salinity has been reported in several studies on young plants [32] and seedling production [33,34], all under greenhouse conditions.

In a sabiá plantation under two cultivation systems, less intensive (S0: no fertilization and cultural treatments) and more intensive (S1: phosphate fertilization, soil correction, and cultural treatments), Silva [25] reported higher values of height and wood volume (4.61 m and 12.5 m^3/ha, respectively) in S1 at four years of growth. By way of comparison with the values in this study, it should be noted that the planting in the above experiment was in Latossolo Amarelo, with a depth of more than 100 cm, and not very densely planted, with a 3 × 3 m spacing, which is considered ideal for timber purposes [35]. In this context, we can consider the relatively satisfactory development of sabiá in the severely degraded area it was subjected to in this research, with stripped, shallow, stony soil and dense planting.

For the sabiá and aroeira species, only research using wastewater for seedling production has been published [36–38]. These studies show that 100% wastewater promotes better performance in the growth and initial development of the species when grown in pots and in a protected environment. Evaluating the growth of shoots and yield of *Olea europaea* L. trees in the field for four consecutive years, Ayoub et al. [39] found equal efficiency between reuse water and fresh water in a semi-arid environment in Jordan. In a study of 11 species irrigated with wastewater for four years in different locations and soils in southeastern Australia, Stewart and Flinn [40] concluded that good growth rates were generally obtained, with similar results between irrigation with fresh and wastewater, highlighting its viability in the establishment of forest species.

Maximum values for the mean annual increment (MAI) of sabiá in the third year and a decrease in the fourth year were also reported by Silva [25] in fertilized cultivation and a rainfed system. This indicates that the experimental conditions in this study did not alter the trends in the growth rates of sabiá. On the other hand, despite showing a linear decrease in MAI throughout its growth cycle, aroeira can reach a maximum yield of up to 5.50 m^3/ha/year according to Coradin et al. [15].

The treated effluent affected the wood quality of the two species differently. In sabiá, the sewage effluent increased the PLY and decreased the NCGY, while in aroeira, it promoted higher Bd and NCGY and decreased the CGY. Basic density (Bd) is considered an important indicator of wood quality [41] and wood density ≤ 0.500 g/cm^{-3} is not recommended for energy purposes [42], and its interpretation depends on the intended use. For example, in the pulp industry, higher Bd values, such as those of sabiá, are not desirable [43,44], but for charcoal production and energy purposes, woods with higher densities are preferable. In this sense, with Bd values of 0.66 g/cm^3 in aroeira compared to 0.83 g/cm^3 in sabiá, the latter is more suitable for energy purposes. Both values are higher than those reported for *Eucalyptus* hybrids at seven years of age, with an average of 0.54 g/cm^3 [45]. Gonçalves et al. [44] characterized the basic density of sabiá, obtaining a value of 0.78 g/cm^3. For sabiá wood obtained from a 4-year-old plantation with fertilization and a rainfed regime, a basic density value of 0.81 g/cm^3 was reported [46]. These values are lower than those obtained in this study, which ranged from 0.80 to 0.83 g/cm^3 in $TE_{0.5}$ and TE_1, respectively. Thus, species with a higher CGY content are intended for later implementation of energy forests in Brazil, and the carbonization of wood with Bd ≥ 0.500 g/cm^{-3} results in denser charcoals [42].

Despite the increase in Bd with the effluent application, the decrease in charcoal CGY is likely due to a reduction in lignin and extractive content, as these are carbon-rich chemical constituents [47]. The high NCGY values in TE_1 support this, as the increase in NCGY is inversely proportional to the yields in Bd, CGY, lignin content, extractives, and fixed carbon [45,48].

The NCGY released can be undesirable in some cases because they promote impregnation, stench, etc. [48]. According to the National Biomass Reference Center [49], the best quality charcoal has high density and strength, and low NCGY and ash content. In an analysis of wood from adult plants of aroeira, using a carbonization process similar to that of this study, Silva et al. [50] obtained a value of 41.22% in CGY. It is evident that the sewage effluent promoted an increase in the NCGY content of aroeira; however, such differences in NCGY and CGY compared to those found by Silva et al. [50] are probably also due to the difference in the ages of the trees analyzed. A tendency for the basic density of wood to increase with age was observed for *Eucalyptus* [45].

5. Conclusions

- The Richards model fitted the growth variables satisfactorily for sabiá and aroeira.
- The shallow depth of the stripped soil affected the exponential growth of sabiá in the first few years, while aroeira showed slower growth rates regardless of treatment during the three years.
- The salts in the sewage effluent applied in the first two years reduced the growth and wood yield of sabiá.
- The application of treated sewage effluent increased the height, total volume, and MAI of aroeira at four years of age.
- The highest basic density value was observed for the TE_1 treatment (0.835 g/cm^3) of *M. caesalpiniaefolia* wood.
- The treated effluent at a volume of 1 L/week increased the condensed liquid yield (PLY) and non-condensable gases yield (NCGY) of sabiá, while in aroeira, the basic density (BD) and non-condensable gases yield (NCGY) increased, with a decrease in the gravimetric yield (CGY).
- Sewage effluent should be used cautiously to prevent damage to the species, and further studies are needed to establish the best management practices. The use of effluent is recommended for aroeira in degraded areas of the Brazilian semi-arid region.

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