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Survival and initial growth in the field of eucalyptus seedlings produced in different substrates

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Abstract – The objective of this work was to evaluate the survival and initial growth, in the field, of eucalyptus seedlings produced in different substrates. *Eucalyptus benthamii* seedlings produced in 36 substrates were evaluated in the field. The substrates consisted of mixtures, at different volumetric proportions, of: carbonized rice husk, charcoal with granulometry between 1.0–3.0 mm, charcoal with granulometry between 3.0–5.0 mm, coconut fiber, semi-decomposed pine bark, fine vermiculite, sewage sludge, and peat moss. At 1, 2, 3, 6, 12, 18, and 24 months after planting, survival, height, and diameter were determined. At 24 months after planting, height increment, diameter increment, transversal area, and basal area were also measured. The seedlings that showed 100% survival after 24 months under field conditions were those grown in the nursery in substrates with a higher proportion of fine vermiculite, sewage sludge, and peat moss, that is, in substrates with a higher microporosity. However, there is no effect of substrate characteristics on seedling initial growth in the field. A significant correlation is observed between the survival of seedlings at 6 months and their diameter at the end of the nursery period, evidencing the importance of this characteristic for the establishment of the plant in the field, regardless of the used substrate.

Index terms: *Eucalyptus benthamii*, agricultural residues, forest seedling quality, seedling production, silviculture.

Sobrevivência e crescimento inicial no campo de mudas de eucalipto produzidas em diferentes substratos

Resumo – O objetivo deste trabalho foi avaliar a sobrevivência e o crescimento inicial, no campo, de mudas de eucalipto produzidas em diferentes substratos. Mudas de *Eucalyptus benthamii* produzidas em 36 substratos foram avaliadas em campo. Os substratos consistiram em misturas, em diferentes proporções volumétricas, de: casca de arroz carbonizada, carvão com granulometria entre 1,0–3,0 mm, carvão com granulometria entre 3,0–5,0 mm, fibra de coco, casca de pinheiro semidecomposta, vermiculita fina, lodo de esgoto e turfa. Aos 1, 2, 3, 6, 12, 18 e 24 meses após o plantio, foram determinados sobrevivência, altura e diâmetro. Aos 24 meses após o plantio, também foram medidos incremento em altura, incremento em diâmetro, área transversal e área basal. As plântulas que apresentaram sobrevivência de 100% após 24 meses em condições de campo foram aquelas cultivadas, no viveiro, em substratos com maior proporção de vermiculita fina, lodo de esgoto e turfa, ou seja, em substratos com maior microporosidade. No entanto, não há efeito das características do substrato no crescimento inicial das plântulas. Há correlação significativa entre a sobrevivência da plântula aos 6 meses de idade e seu diâmetro no final da fase de viveiro, o que ressalta a importância desta característica para o estabelecimento da planta em campo, independentemente do substrato utilizado.

Termos para indexação: *Eucalyptus benthamii*, resíduos agrícolas, qualidade de mudas florestais, produção de mudas, silvicultura.

Introduction

Brazil is known worldwide for its excellence in the production of wood biomass, which is the result of favorable environmental conditions (Eufrade Junior et al., 2016) and a management capable of boosting forest research, based on a broad genetic base and breeding programs (Menucelli et al., 2019). The industry that drives the country's bioenergetic production focuses on a set of genetic materials of the genus *Eucalyptus* (Cavalett et al., 2018). This genus, due to its rapid growth, adaptability, and wood quality, is also widely planted to obtain wood products (Dias Júnior et al., 2016). For this reason, the commercial plantations of *Eucalyptus* spp. have expanded beyond the traditional producing regions, especially to Southern and Southeastern Brazil. In these two regions, the expansion is attributed to the advance in the selection and consequent recommendation of *Eucalyptus* species resistant to climatic variations (Elli et al., 2019) and also with a higher productivity than the genus *Pinus*.

Among the species of *Eucalyptus* with silviculture potential, *Eucalyptus benthamii* Maiden & Cambage stands out as one of the few with frost resistance (Arnold et al., 2015). Its performance has increased the demand for its seedlings, which has led to the emergence of new studies to improve seedling quality, involving the substrate component and its variations (Kratz et al., 2017; Gonzaga et al., 2018; Wang et al., 2018; Gabira et al., 2020). These goals may be achieved by using regional substrate components with low acquisition and transport costs (Stuepp et al., 2016; Mieth et al., 2019; Manca et al., 2020; Yasin et al., 2020). However, it is necessary to pay attention to variations in the physicochemical properties of the formulated substrates, which differ as to their origin, production method, and proportions of used materials (Kratz & Wendling, 2016; Mieth et al., 2019).

The quality of forest seedlings is closely linked to their survival and initial growth after field planting. Therefore, many studies have focused on determining which factors are most important when producing seedlings with adequate characteristics to be planted in the field (Gonzaga et al., 2018; Wang et al., 2018; Gabira et al., 2020). In general, nursery management – including substrates, irrigation, and nutrition – affects directly seedling morphological characteristics, which may result in different responses in the first months of the plantations. Besides seedling size, other factors, such as genetic potential, plant density, climatic conditions, and soil characteristics, may also interfere in plant survival and initial growth after planting (Resquin et al., 2018; Shalizi et al., 2019).

Although the efficiency of alternative substrates has been largely evaluated in nursery conditions (Kratz et al., 2012, 2013; Kratz & Wendling, 2016; Stuepp et al., 2016; Gabira et al., 2020; Manca et al., 2020), their influence on increasing the growth of forest species in the field has not (Stuepp et al., 2016), generating a gap in substrate recommendation for commercial plantations. The challenge, in this case, has been to produce quality seedlings at a reduced cost (Kratz & Wendling, 2016; Kratz et al., 2017), seeking a better performance in the field, with reduced mortality and weed competition.

The objective of this work was to evaluate the survival and initial growth, in the field, of *Eucalyptus benthamii* seedlings produced in different substrates.

Materials and Methods

Eucalyptus benthamii seedlings were produced in 36 substrates, according to Kratz et al. (2017), for 120 days. The used substrates consisted of mixtures, at different volumetric proportions (v:v), of: carbonized rice husk (CRH), charcoal with granulometry between 1.0–3.0 mm (C1), charcoal with granulometry between 3.0–5.0 mm (C2), coconut fiber (CF), semi-decomposed pine bark (PB), fine vermiculite (FV), sewage sludge (SS), and peat moss (PM). Two commercial substrates based on peat moss (CS1) and pine bark (CS2) were used as the control. The physical and chemical characteristics of the substrates were determined following the methodology described in Normative Instruction nº 17 (Brasil, 2007) (Table 1).

The experiment was carried out between June 2014 and June 2016 at Fazenda Canguiri, an experimental area of Universidade Federal do Paraná, located in the municipality of Pinhais, in the state of Paraná, Brazil (25°23'S, 49°07'W, at 900 m altitude). According to the classification of Köppen-Geiger (Alvares et al., 2013), the climate of the region is temperate, of the Cfb type, with temperature between -3 and 22°C, constant humidity, well-distributed rainfalls throughout the year, and average temperature of the warmest month lower than 22°C. The soil of the experimental area has a low fertility (Table 2) and was classified as a Cambissolo

Háplico according to the Brazilian classification system (Santos et al., 2013), i.e., as a Dystric Cambisol in the FAO world reference base for soils (IUSS Working Group WRB, 2015).

Eucalyptus benthamii seeds from a seed production area established in the municipality of Guarapuava, in the state of Paraná, were directly sown in 55-cm^3 plastic tubes. After sowing, the trays with the tubes were placed, during 120 days, in a greenhouse where irrigation was supplied four times a day for 10 min, at a flow rate of 144 L h^{-1}. Fertilization consisted of 4.0 g L^{-1} CH_4N_2O, 3.0 g L^{-1} simple superphosphate, 0.25 g L^{-1} of the FTE BR 10 fertilizer (7.0% Zn, 4.0% Fe, 4.0% Mn, 0.1% Mo, 2.5% B, and 0.8% Cu), and 3.0 g L^{-1} KCl, applied every 7 days. After 120 days, seedling height, stem diameter, and shoot and root dry biomass were evaluated, as well as the Dickson quality index (Table 3).

Table 1. Physicochemical characteristics of the substrates used for *Eucalyptus benthamii* seedling production(1).

Substrate (v:v)(2)	AD (kg m^{-3})	TP	Microporosity	Macroporosity	pH	EC (dS cm^{-1})
		-------(%)-------				
10 CRH / 90 PM	282.24	75.53	55.16	20.37	4.12	0.57
90 SS / 10 PB	547.31	71.38	52.47	18.91	9.00	4,08
10 C1 / 90 PM	250.01	63.08	51.53	11.55	4.32	0.61
10 CRH / 90 SS	542.33	74.19	50.78	23.42	9.09	4.26
CS1	315.34	77.29	50.37	26.93	5.86	0.57
50 SS / 50 PB	470.84	71.59	48.99	22.60	8.77	3.38
90 CF / 10 PB	118.85	72.74	48.32	24.43	6.51	0.13
50 PB / 50 PM	336.09	73.80	47.46	26.33	5.07	0.39
CS2	193.09	69.06	45.06	24.00	5.26	0.93
50 CF / 50 PB	234.72	75.28	44.84	30.46	6.42	0.14
50 C1 / 50 SS	492.70	61.74	43.67	18.07	9.22	2.88
50 C2 / 50 PM	312.03	58.87	43.28	15.60	5.03	0.62
10 CF / 90 FV	150.87	68.70	43.10	25.60	7.03	0.02
10 CRH / 90 FV	172.30	69.57	41.80	27.19	7.39	0.02
50 PB / 50 FV	283.45	70.10	41.71	28.40	6.72	0.10
90 PB / 10 PM	355.06	78.04	41.18	36.86	6.36	0.19
50 CF / 50 FV	120.26	67.50	40.98	26.52	6.55	0.06
10 C2 / 90 PB	353.94	75.23	40.63	34.60	6.62	0.23
90 PB / 10 FV	297.15	76.88	40.24	36.64	6.49	0.19
10 CRH / 90 PB	339.57	79.33	39.70	39.63	6.53	0.17
50 CRH / 50 PM	208.29	73.61	39.41	38.34	4.49	0.32
50 C1 / 50 PM	197.470	63.77	38.88	24.89	5.60	0.59
50 CRH / 50 SS	387.65	72.16	37.41	34.75	9.12	3.62
50 C2 / 50 FV	228.91	55.85	35.45	20.40	8.53	0.22
50 C1 / 50 FV	208.86	59.92	35.07	24.85	9.13	0.40
50 C2 / 50 PB	341.56	59.70	34.11	25.58	7.43	0.23
50 CRH / 50 FV	160.60	69.00	33.38	33.44	7.49	0.04
50 C1 / 50 PB	311.50	66.54	32.81	33.73	7.56	0.29
90 C2 / 10 PM	298.85	49.41	31.80	17.61	7.38	0.45
90 C1 / 10 FV	280.38	59.29	30.69	27.77	9.49	0.60
90 C2 / 10 SS	349.37	44.95	28.42	16.53	9.32	0.94
90 C1 / 10 PB	284.22	58.39	28.33	30.06	8.87	0.55
90 C1 / 10 SS	322.84	57.29	28.16	29.13	9.18	1.99
50 CRH / 50 PB	204.45	73.08	26.49	46.59	6.69	0.13
90 C2 / 10 FV	273.38	41.17	24.98	16.19	8.81	0.38
90 CRH / 10 CF	86.30	69.48	16.31	53.17	7.21	0.09

(1)AD, apparent density; TP, total porosity; and EC, electric conductivity of the substrates. (2)CRH, carbonized rice husk; PM, peat moss; SS, sewage sludge; PB, semi-decomposed pine bark; C1, charcoal with granulometry between 1.0–3.0 mm; CS1, commercial substrate based on peat moss; CF, coconut fiber; CS2, commercial substrate based on pine bark; C2, charcoal with granulometry between 3.0–5.0 mm; and FV, fine vermiculite.

Table 2. Clay content and chemical properties of the Haplic Cambisol of the experimental area in the municipality of Pinhais, in the state of Paraná, Brazil[1].

Depth (cm)	pH H_2O	Ca	Mg	Al	H+Al	CEC	V	m	C (g dm^{-3})	P	K	Clay (g kg^{-1})
		----(cmol$_c$ dm^{-3})----					---- (%) ----			(mg dm^{-3})		
0–30	5.70	8.73	3.66	0.13	4.71	17.18	73	1	39.9	1.98	0.09	480
50–80	4.96	3.41	1.69	0.75	7.19	12.36	42	13	34.0	1.20	0.07	514

[1]Used extractors: Mehlich 1 for P and K; and KCl for Ca, Mg, and Al. CEC, cation exchange capacity at pH 7.0; V, base saturation; and m, aluminum saturation.

Table 3. Stem diameter (D), height (H), H/D ratio, shoot dry biomass (SDB), root dry biomass (RDB), and Dickson quality index (DQI) of *Eucalyptus benthamii* seedlings at 120 days after sowing in 36 substrates, in greenhouse conditions, in the municipality of Pinhais, in the state of Paraná, Brazil[1].

Substrate[2]	Stem diameter (mm)	Height (cm)	H/D ratio	SDB (g)	RDBc (g)	DQI
10 C1 / 90 PM	3.59a	34.50a	9.61b	1.68a	0.68a	0.20a
CS1	3.54a	31.84a	8.99b	1.53a	0.63a	0.19a
10 CRH / 90 PM	3.38a	34.36a	10.16a	1.62a	0.65a	0.18a
50 PB / 50 PM	3.34a	33.55a	10.04b	1.57a	0.63a	0.18a
50 C1 / 50 PM	3.18b	31.63a	9.95b	1.42a	0.58a	0.16b
50 CRH / 50 PM	3.13b	31.42a	10.03a	1.40a	0.57a	0.16b
50 CRH / 50 SS	2.80b	28.22b	10.08b	1.15b	0.47b	0.13b
10 CRH / 90 FV	2.80b	24.68c	8.81a	0.97c	0.41b	0.12c
10 CF / 90 FV	2.61c	26.26b	10.07b	0.99c	0.41b	0.11c
CS2	2.60c	23.82c	9.15b	0.87c	0.40b	0.11c
50 CRH / 50 PB	2.55c	26.83b	10.54a	1.01c	0.41b	0.11c
90 CRH / 10 CF	2.54c	26.05b	10.27a	0.96c	0.40b	0.11c
50 C2 / 50 PM	2.46c	27.16b	11.02b	1.00c	0.41b	0.11c
50 SS / 50 PB	2.39c	25.80b	10.81b	0.91c	0.38b	0.10c
50 CRH / 50 FV	2.38c	27.27b	11.46a	0.98c	0.40b	0.10c
10 CRH / 90 SS	2.37c	29.78a	12.56b	1.15b	0.47b	0.11c
50 C2 / 50 FV	2.32c	27.45b	11.81a	0.98c	0.40b	0.10c
50 C1 / 50 SS	2.31c	28.39b	12.31a	1.02c	0.41b	0.10c
50 CF / 50 FV	2.24c	25.74b	11.47b	0.87c	0.42b	0.09c
50 C1 / 50 FV	2.21c	26.27b	11.90a	0.88c	0.36b	0.09c
90 C2 / 10 SS	2.19c	25.41b	11.60b	0.84c	0.34b	0.08c
50 PB / 50 FV	2.18c	22.46c	10.32b	0.68d	0.29c	0.08d
90 C1 / 10 FV	2.16c	21.40c	9.91a	0.62d	0.27c	0.07d
90 C1 / 10 SS	2.12c	25.83b	12.19a	0.84c	0.34b	0.08c
90 SS / 10 PB	2.11c	26.68b	12.64b	0.90c	0.37b	0.09c
90 PB / 10 FV	2.10c	25.26b	12.04b	0.80c	0.39b	0.09c
90 C2 / 10 PM	2.04d	23.89c	11.72b	0.72d	0.30c	0.07d
90 C1 / 10 PB	2.02d	25.40b	12.58a	0.79c	0.32b	0.07d
90 PB / 10 PM	1.92d	20.82c	10.83b	0.53d	0.28c	0.06d
90 CF / 10 PB	1.84d	17.93c	9.72b	0.36d	0.18c	0.05d
50 CF / 50 PB	1.83d	19.64c	10.74b	0.99c	0.36b	0.10c
10 C2 / 90 PB	1.80d	22.83c	12.70a	0.60d	0.30c	0.06d
10 CRH / 90 PB	1.79d	18.29c	10.23a	0.36d	0.20c	0.05d
90 C2 / 10 FV	1.77d	21.34c	12.09a	0.51d	0.22c	0.05d
50 C1 / 50 PB	1.71d	21.75c	12.70a	0.52d	0.22c	0.05d
50 C2 / 50 PB	1.65d	20.08c	12.14a	0.42d	0.19c	0.04d

[1]Means followed by equal letters, in the columns, do not differ by Scott-Knott's test, at 5% probability. [2]C1, charcoal with granulometry between 1.0–3.0 mm; PM, peat moss; CS1, commercial substrate based on peat moss; CRH, carbonized rice husk; PB, semi-decomposed pine bark; SS, sewage sludge; FV, fine vermiculite; CF, coconut fiber; CS2, commercial substrate based on pine bark; and C2, charcoal with granulometry between 3.0–5.0 mm.

Before seedling plantation in the field, mechanical mowing was conducted in the total area of the experiment, followed by the control of leaf-cutting ants with a natural bait made with orange peel (Perri et al., 2017). The planting lines were marked with a subsoiler at a 50-cm depth, with a spacing of 3.0 m between the lines and 1.5 m in the line. A manual planter was used for sowing in July 2014, when 100 g of the N-P_2O_5-K_2O (4-14-8) fertilizer were applied per pit.

Post-planting cultural practices consisted of mechanical mowing every 6 months and the control of leaf-cutting ants whenever necessary. Seedling survival was evaluated at 1, 2, 3, 6, 12, 18, and 24 months after planting, while base diameter at 10 cm from the soil and total plant height were assessed at 6, 12, 18, and 24 months after planting in the field.

At the end of the plant measurement period, height increment and diameter increment were also determined. For this, the values measured at 24 months after planting were subtracted from those obtained at planting.

From the base diameter at 24 months, the transversal area and the basal area were estimated, considering 2,500 plants per hectare.

The experiment was set in a randomized complete block design, with 36 treatments and five blocks of three plants per plot. Data were checked for normality by Shapiro-Wilk's test, at 5% probability, and for homogeneity of variances by Bartlett's test, also at 5% probability, and, then, subjected to the analysis of variance. Averages were compared by Scott-Knott's test, at 5% probability. For survival and field growth evaluations, a split-plot design was used. Pearson's correlation analysis was applied to compare the effects of the morphological characteristics of seedlings, substrate characteristics, and plant survival and growth in the field.

Results and Discussion

Seedling survival differed significantly between treatments at 6, 12, 18, and 24 months after planting in the field (Table 4). The lowest survival at 24 months was 60% for seedlings produced in the 90C1/10PB, 50C2/50PB, 10C2/90PB, and 50C2/50FV substrates. At the same evaluation time, 100% survival was observed for seedlings grown in 10CRH/90FV, 90SS/10PB, 10C1/90PM, and 50C2/50PM. Therefore, the survival rate was higher for seedlings produced in substrates with a higher microporosity, probably due to the plant's better growth in diameter and the substrate's higher water holding capacity in the first days after planting. Shalizi et al. (2019) also reported the relationship between the initial growth of *E. benthamii* and substrates with a higher microporosity, when subjecting the seedlings produced in substrates with different physical characteristics to drought stress.

Similar growth tendencies were found for height and diameter (Figures 1 and 2). At 18 and 24 months, both variables increased with seedling growth. Different growth tendencies were only observed for seedlings produced in substrates 90C1/10SS, 50C2/50FV, and 10CRH/90FV. Seedling morphological characteristics at the time of field planting directly affected their diameter at 24 months; however, substrate characteristics did not affect the initial growth of the seedlings. Seedling size is important for predicting the success of a plantation because it is directly related to the plant's capacity to overcome weed competition and develop new roots (Khanal et al., 2018; Riikonen & Luoranen, 2018). It should be noted that, compared with diameter, height seems to be much more dependent on environmental factors, such as weed competition and plant density (Resquin et al., 2018).

As a reflect of growth on diameter, transversal and basal area followed the same trend at 24 months after field planting (Table 5). Knowing the performance of forest species seedlings in the field is an essential tool to determine the best cultural practices to be adopted in nurseries for a better morphophysiological performance after planting. According to Grossnickle & El-Kassaby (2016), most morphological attributes are nondestructive, easy to measure, and reliable to establish qualitative standards for seedlings. In fact, in the present study, morphological characteristics, such as stem diameter, height, and shoot and root dry biomass, had a positive effect on the increase in individual and total basal area.

The results of Pearson's correlation confirm the importance of seedling diameter at the end of the nursery production phase (Table 6). The significant correlation between the survival of seedlings at 6 months and their diameter at the end of the nursery period evidences the importance of this characteristic for the establishment of the plant in the field. However, after field planting, height and diameter were only

Table 4. Survival of *Eucalyptus benthamii* seedlings produced in 36 substrates at 1, 2, 3, 6, 12, 18, and 24 months after planting in the field, in the municipality of Pinhais, in the state of Paraná, Brazil[(1)].

Substrate[(2)]	Survival (%)						
	1 month	2 months	3 months	6 months	12 months	18 months	24 months
10 CRH / 90 FV	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA
90 SS / 10 PB	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA
10 C1 / 90 PM	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA
50 C2 / 50 PM	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA	100.00aA
10 CRH / 90 PM	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	93.33aA	93.33aA
90 C2 / 10 SS	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	93.33aA	93.33aA
50 PB / 50 PM	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	93.33aA	93.33aA
CS2	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	93.33aA	93.33aA
90 PB / 10 FV	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	86.67aA	86.67aA
CS1	100.00aA	100.00aA	100.00aA	93.33aA	93.33aA	86.67aA	86.67aA
10 CRH / 90 SS	100.00aA	100.00aA	100.00aA	93.33aA	86.67aA	86.67aA	86.67aA
50 CRH / 50 PM	100.00aA	100.00aA	100.00aA	86.67aA	86.67aA	86.67aA	86.67aA
50 C1 / 50 PM	100.00aA	93.33aA	93.33aA	86.67aA	86.67aA	86.67aA	86.67aA
50 C1 / 50 PB	100.00aA	100.00aA	100.00aA	86.67aA	86.67aA	86.67aA	80.00aA
10 CRH / 90 PB	100.00aA	100.00aA	100.00aA	80.00bB	80.00bB	80.00bA	80.00bA
50 CF / 50 FV	100.00aA	100.00aA	100.00aA	80.00bB	80.00bB	80.00bA	80.00bA
90 CRH / 10 CF	100.00aA	86.67aA	86.67aA	80.00aB	80.00aB	80.00aA	80.00aA
10 CF / 90 FV	100.00aA	100.00aA	100.00aA	86.67bA	80.00bB	73.33bB	73.33bB
90 C1 / 10 SS	100.00aA	100.00aA	100.00aA	86.67bA	73.33bB	73.33bB	73.33bB
50 CRH / 50 FV	100.00aA	100.00aA	100.00aA	80.00bB	73.33bB	73.33bB	73.33bB
50 SS / 50 PB	100.00aA	100.00aA	100.00aA	80.00bB	73.33bB	73.33bB	73.33bB
90 PB / 10 PM	100.00aA	100.00aA	100.00aA	73.33bB	73.33bB	73.33bB	73.33bB
50 C1 / 50 FV	100.00aA	100.00aA	93.33aA	80.00bB	80.00bB	73.33bB	73.33bB
50 C1 / 50 SS	100.00aA	93.33aA	93.33aA	80.00aB	80.00aB	80.00aA	73.33aB
50 CRH / 50 PB	100.00aA	93.33aA	93.33aA	73.33bB	73.33bB	73.33bB	73.33bB
90 CF / 10 PB	100.00aA	86.67aA	86.67aA	80.00aB	73.33aB	73.33aB	73.33aB
50 PB / 50 FV	100.00aA	80.00aA	80.00aA	73.33aB	73.33aB	73.33aB	73.33aB
90 C2 / 10 FV	100.00aA	100.00aA	100.00aA	80.00bB	73.33bB	66.67bB	66.67bB
90 C1 / 10 FV	100.00aA	93.33aA	93.33aA	80.00bB	66.67bB	66.67bB	66.67bB
50 CRH / 50SS	100.00aA	93.33aA	93.33aA	73.33bB	73.33bB	66.67bB	66.67bB
50 CF / 50 PB	100.00aA	86.67aA	86.67aA	66.67bB	66.67bB	66.67bB	66.67bB
50 C2 / 50 FV	100.00aA	100.00aA	100.00aA	80.00bB	73.33bB	73.33bB	60.00bB
10 C2 / 90 PB	100.00aA	100.00aA	100.00aA	73.33bB	66.67bB	60.00bB	60.00bB
90 C1 / 10 PB	100.00aA	86.67aA	86.67aA	66.67bB	60.00bB	60.00bB	60.00bB
50 C2 / 50 PB	100.00aA	86.67aA	73.33bA	60.00bB	60.00bB	60.00bB	60.00bB
90 C2 / 10 PM	100.00aA	93.33aA	86.67aA	58.33bB	58.33bB	58.33bB	58.33bB

[(1)]Means followed by equal letters, lowercase in the rows and uppercase in the columns, do not differ from each other by Scott-Knott's test, at 5% probability. [(2)]CRH, carbonized rice husk; FV, fine vermiculite SS, sewage sludge; PB, semi-decomposed pine bark; C1, charcoal with granulometry between 1.0–3.0 mm; PM, peat moss; C2, charcoal with granulometry between 3.0–5.0 mm; CS2, commercial substrate based on pine bark; CS1, commercial substrate based on peat moss; and CF, coconut fiber.

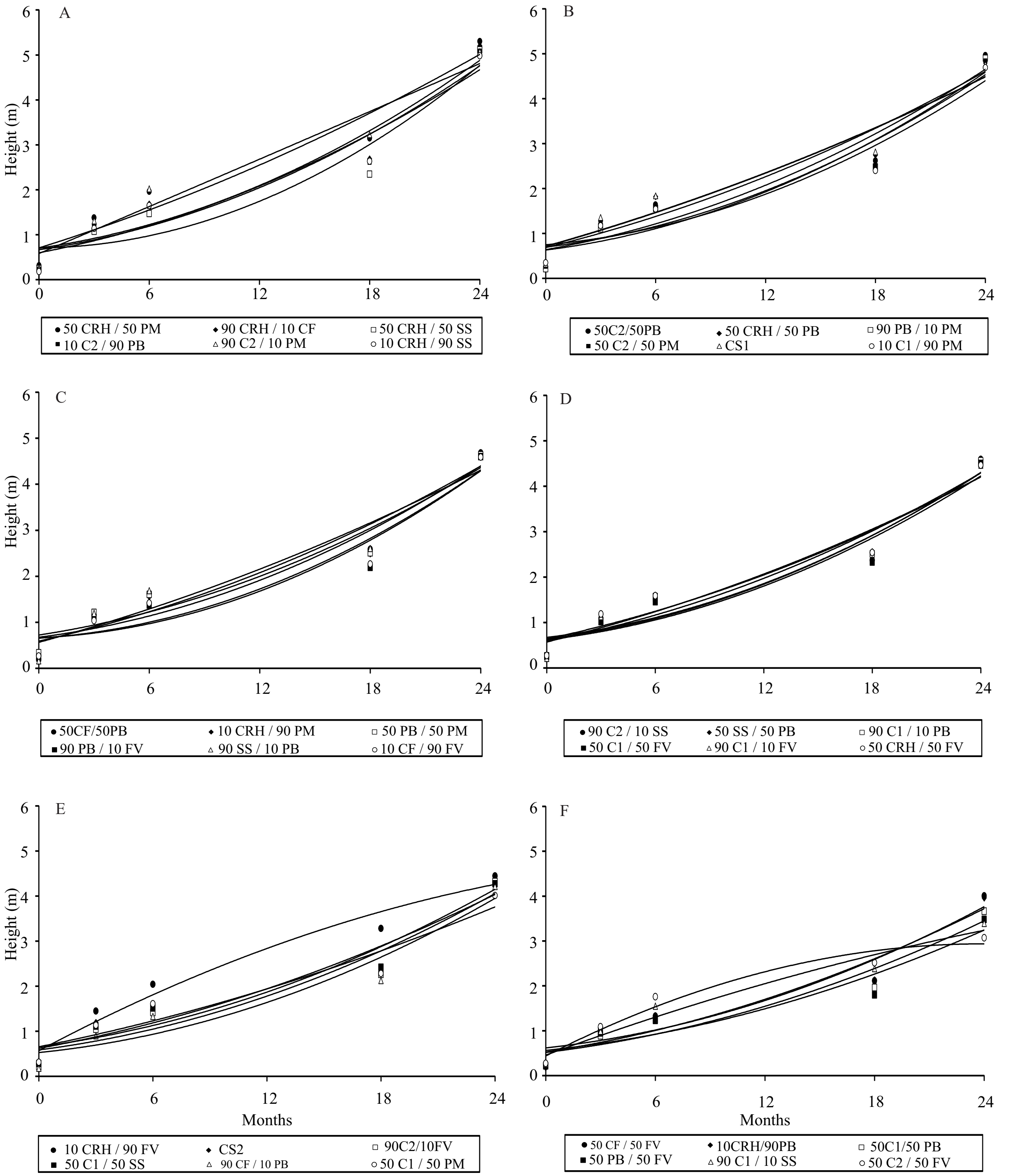

Figure 1. Growth trend for the height of *Eucalyptus benthamii* seedlings produced in 36 substrates and average height at 24 months after planting in the field. CRH, carbonized rice husk; PM, peat moss; CF, coconut fiber; SS, sewage sludge; C2, charcoal with granulometry between 3.0–5.0 mm; PB, semi-decomposed pine bark; CS1, commercial substrate based on peat moss; C1, charcoal with granulometry between 1.0–3.0 mm; FV, fine vermiculite; and CS2, commercial substrate based on pine bark.

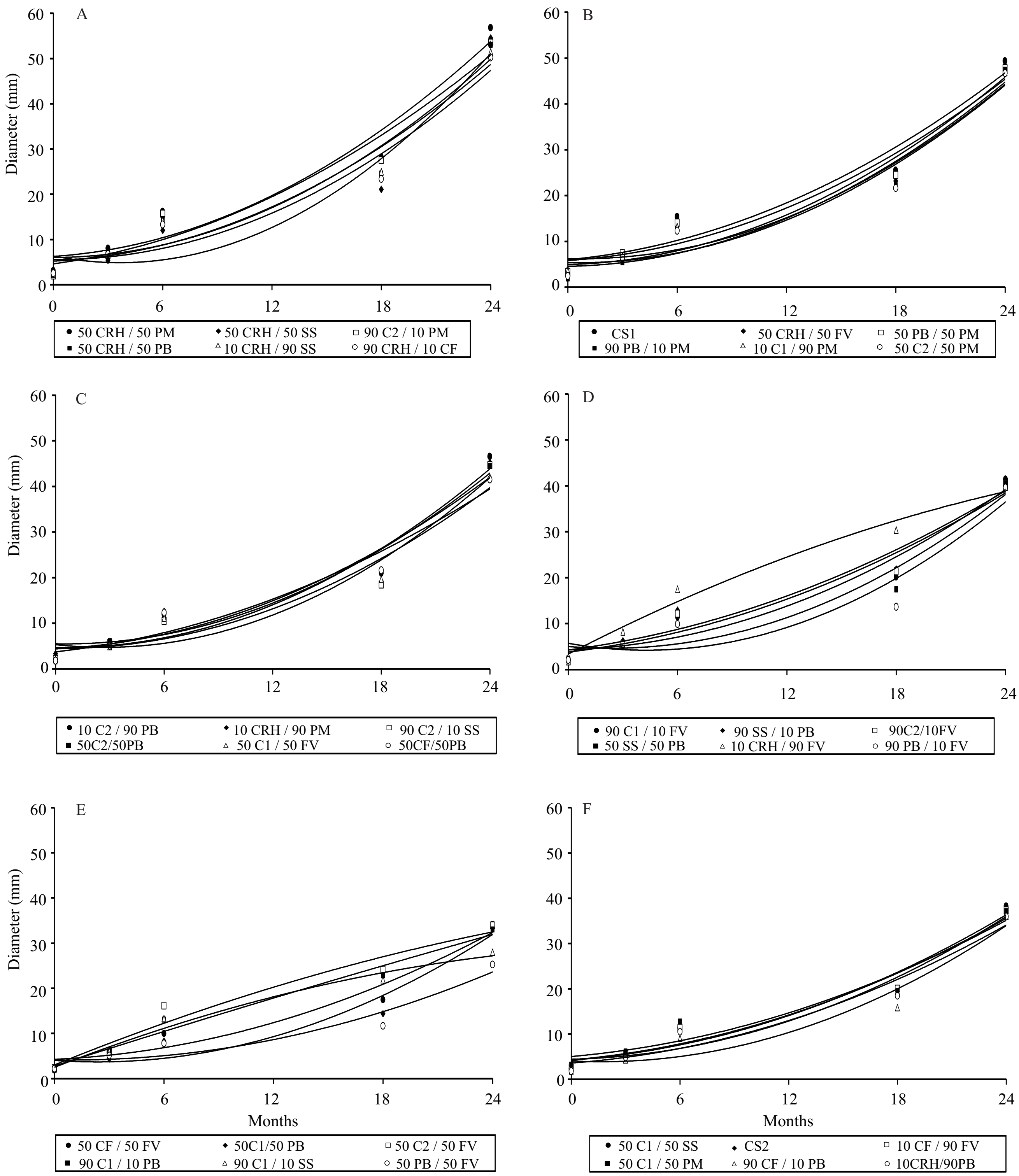

Figure 2. Growth trend for the diameter of *Eucalyptus benthamii* seedlings produced in 36 substrates and average height at 24 months after planting in the field. CRH, carbonized rice husk; PM, peat moss; SS, sewage sludge; C2, charcoal with granulometry between 3.0–5.0 mm; PB, semi-decomposed pine bark; CF, coconut fiber; CS1, commercial substrate based on peat moss; FV, fine vermiculite; C1, charcoal with granulometry between 1.0–3.0 mm; and CS2, commercial substrate based on pine bark.

Table 5. Increment in diameter (DI), increment in height (HI), transversal area (TA), and basal area (BA) at 24 months after planting in the field of *Eucalyptus benthamii* seedlings produced in 36 substrates, in the municipality of Pinhais, in the state of Paraná, Brazil(1).

Substrate(2)	DI (mm)	HIb (m)	Transversal area (m^2)	Basal area (m^2 ha^{-1})
50 CRH / 50 PM	53.7a	4.9a	0.0026a	555.9a
50 CRH / 50 SS	51.7a	4.5b	0.0024a	401.9c
90 C2 / 10 PM	51.5a	4.8a	0.0023a	322.7d
50 CRH / 50 PB	50.2a	4.8a	0.0023a	299.6d
10 CRH / 90 SS	50.1a	4.6b	0.0021a	453.5b
90 CRH / 10 CF	47.7b	4.9a	0.0020a	381.1c
CS1	45.8b	4.3b	0.0020a	319.7d
50 CRH / 50 FV	46.1b	4.2b	0.0019a	318.1d
50 PB / 50 PM	44.5b	4.3b	0.0018a	344.6d
90 PB / 10 PM	45.5b	4.5b	0.0018a	303.2d
10 C1 / 90 PM	43.3b	4.0c	0.0018a	448.0b
50 C2 / 50 PM	44.2b	4.6b	0.0018a	509.6a
10 C2 / 90 PB	44.8b	4.8a	0.0018a	176.0f
10 CRH / 90 PM	41.9b	4.3b	0.0017a	375.8c
90 C2 / 10 SS	42.5b	4.3b	0.0016a	356.6c
50 C2 / 50 PB	42.9b	4.8a	0.0016a	223.2f
90 SS / 10 PB	39.8c	4.2b	0.0015b	363.8c
50 C1 / 50 FV	39.8c	3.9c	0.0014b	245.8e
90 C1 / 10 FV	39.3c	4.3b	0.0014b	248.6e
50 CF / 50 PB	39.7c	4.5b	0.0014b	209.6f
90 C2 / 10 FV	38.7c	4.1b	0.0013b	241.9e
50 SS / 50 PB	38.1c	4.3b	0.0013b	253.8e
10 CRH / 90 FV	37.0c	4.2b	0.0013b	320.9d
90 PB / 10 FV	37.5c	4.0c	0.0013b	280.7e
10 CF / 90 FV	39.8c	4.3b	0.0012b	272.1e
50 C1 / 50 SS	35.9c	4.0c	0.0012b	237.4e
CS2	35.3c	4.2b	0.0012b	213.5f
50 C1 / 50 PM	32.1d	3.7c	0.0011b	235.8e
90 CF / 10 PB	34.2c	4.0c	0.0011b	198.7f
10 CRH / 90 PB	34.1c	3.8c	0.0011b	198.5f
50 CF / 50 FV	31.9d	3.9c	0.0009b	187.0f
50 C2 / 50 FV	31.6d	3.0d	0.0009b	134.8g
50 C1 / 50 PB	31.5d	3.4d	0.0009b	188.1f
90 C1 / 10 PB	31.0d	4.3b	0.0009b	120.5g
90 C1 / 10 SS	25.9e	3.1d	0.0006b	120.4g
50 PB / 50 FV	23.3e	3.3d	0.0005b	71.2g

(1)Means followed by equal letters, in the columns, do not differ by Scott-Knott's test, at 5% probability. (2)CRH, carbonized rice husk; PM, peat moss; SS, sewage sludge; C2, charcoal with granulometry between 3.0–5.0 mm; PB, semi-decomposed pine bark; CF, coconut fiber; CS1, commercial substrate based on peat moss; FV, fine vermiculite; C1, charcoal with granulometry between 1.0–3.0 mm; and CS2, commercial substrate based on pine bark.

correlated with seedling biometric characteristics in the first measurements, since this relationship weakens as the plants establish themselves and begin their effective growth (Khanal et al., 2018; Shalizi et al., 2019).

Substrates with a greater water holding capacity promote a better growth of *E. benthamii* seedlings during the nursery phase (Kratz et al., 2017). In the field, the morphological characteristics of the seedlings produced in these substrates reflect in a better survival

Table 6. Pearson's correlations between the morphological characteristics[(1)] of *Eucalyptus benthamii* seedlings grown in 36 substrates in the nursery and substrate characteristics[(2)] on seedling survival at 1, 2, 3, 6, 12, 18 and 24 months after planting in the field, as well as height, diameter, diameter increment (DI), height increment (HI), individual basal area (BA_i), and total basal area (BA_T) at 24 months after planting in the field, in the municipality of Pinhais, in the state of Paraná, Brazil.

	AD	TP	Micro	Macro	pH	EC
Diameter	-0.15^{ns}	0.24^{ns}	0.39*	-0.12^{ns}	-0.52**	0.04^{ns}
Height	0.09^{ns}	0.09^{ns}	0.33*	-0.22^{ns}	-0.32^{ns}	0.24^{ns}
H/D ratio	0.45**	-0.36*	-0.27^{ns}	-0.11^{ns}	0.54**	0.28^{ns}
SDB	-0.02^{ns}	0.20^{ns}	0.41*	-0.18^{ns}	-0.44**	0.16^{ns}
RDB	-0.03^{ns}	0.26^{ns}	0.44**	-0.14^{ns}	-0.49**	0.13^{ns}
DQI	-0.11^{ns}	0.27^{ns}	0.44**	-0.13^{ns}	-0.53**	0.06^{ns}
1 month	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}
2 months	0.18^{ns}	0.03^{ns}	0.26^{ns}	-0.23^{ns}	-0.09^{ns}	0.15^{ns}
3 months	0.14^{ns}	0.14^{ns}	0.28^{ns}	-0.14^{ns}	-0.12^{ns}	0.17^{ns}
6 months	0.08^{ns}	0.14^{ns}	0.47**	-0.29^{ns}	-0.26^{ns}	0.20^{ns}
12 months	0.07^{ns}	0.21^{ns}	0.47**	-0.24^{ns}	-0.39*	0.14^{ns}
18 months	0.07^{ns}	0.20^{ns}	0.47**	-0.25^{ns}	-0.41*	0.14^{ns}
24 months	0.05^{ns}	0.23^{ns}	0.47**	-0.21^{ns}	-0.45**	0.13^{ns}
Diameter	0.08^{ns}	0.13^{ns}	-0.06^{ns}	0.23^{ns}	-0.21^{ns}	0.12^{ns}
Height	0.10^{ns}	0.18^{ns}	-0.04^{ns}	0.25^{ns}	-0.21^{ns}	0.11^{ns}
DI	0.11^{ns}	0.16^{ns}	0.01^{ns}	0.18^{ns}	-0.17^{ns}	0.13^{ns}
HI	0.06^{ns}	0.18^{ns}	-0.03^{ns}	0.23^{ns}	-0.18^{ns}	0.04^{ns}
BA_i	0.11^{ns}	0.19^{ns}	0.02^{ns}	0.21^{ns}	-0.23^{ns}	0.13^{ns}
BA_T	0.13^{ns}	0.13^{ns}	0.23^{ns}	-0.06^{ns}	-0.31^{ns}	0.24^{ns}
	Diameter	Height	H/D ratio	SDB	RDB	DQI
1 month	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}
2 months	0.26^{ns}	0.35*	0.06^{ns}	0.26^{ns}	0.31^{ns}	0.25^{ns}
3 months	0.32^{ns}	0.38*	-0.04^{ns}	0.32^{ns}	0.37*	0.32^{ns}
6 months	0.54**	0.52**	-0.27^{ns}	0.49**	0.53**	0.52**
12 months	0.58**	0.53**	-0.32^{ns}	0.54**	0.58**	0.57**
18 months	0.56**	0.52**	-0.33^{ns}	0.52**	0.55**	0.55*
24 months	0.57**	0.50**	-0.38*	0.52**	0.56**	0.56**
Diameter	0.34*	0.36*	-0.12^{ns}	0.38*	0.37*	0.36*
Height	0.24^{ns}	0.22^{ns}	-0.15^{ns}	0.27^{ns}	0.27^{ns}	0.27^{ns}
DI	0.30^{ns}	0.31^{ns}	-0.12^{ns}	0.33^{ns}	0.33^{ns}	0.31^{ns}
HI	0.10^{ns}	0.05^{ns}	-0.11^{ns}	0.11^{ns}	0.11^{ns}	0.11^{ns}
BA_i	0.38*	0.37*	-0.17^{ns}	0.39*	0.39*	0.39*
BA_T	0.53**	0.55**	-0.24^{ns}	0.55**	0.55**	0.54**

[(1)]Morphological characteristics: diameter; height; H/D ratio, height/diameter ratio; SDB, shoot dry biomass; RDB, root dry biomass; and DQI, Dickson quality index. [(2)]Substrate characteristics: AD, apparent density; TP, total porosity; Micro, microporosity; Macro, macroporosity; pH; and EC, electrical conductivity.

and initial growth. Diameter, as well as biomass, are important morphological parameters to indicate seedling quality, and may be key to establish new parameters to determine the quality of *E. benthamii* seedlings.

Conclusions

1. Substrates affect the morphological characteristics of *Eucalyptus benthamii* seedlings in the nursery phase, and these characteristics are important for plant survival and initial growth after planting in the field.

2. Seedlings that show 100% survival after 24 months under field conditions were grown in substrates with a higher proportion of fine vermiculite, sewage sludge, and peat moss in the nursery phase, that is, in substrates with a higher microporosity.

3. The lowest survival of 60% is observed for seedlings produced in substrates with the predominance of charcoal with a granulometry between 1.0–3.0 or 3.0–5.0 mm and pine bark.

4. The initial growth of seedlings is not influenced by substrate characteristics, but diameter after 24 months is directly affected by seedling morphological characteristics at the time of field planting.

5. The significant correlation between the survival of seedlings at 6 months and their diameter at the end of nursery period evidences the importance of this characteristic for the establishment of the plant in the field, regardless of the used substrate.

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