

Article

Production and Quality of *Canavalia rosea* (Sw.) DC. Seedlings Under the Influence of Substrate and Chemical Fertilization

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Abstract

The success in the recovery of degraded areas is dependent on the acquisition of quality seedlings coupled. However, nursery activity is complex and involves significant operational and input costs. The present work had as its objective to evaluate the effects of the substrate and the chemical fertilization on the production and quality of *Canavalia rosea* (Sw.) DC. seedlings and their respective production costs. Ten treatments were tested, consisting of two substrates with sand: clay:coconut fiber (2:1:1 and 1:2:1) and five fertilizations (without fertilizer, with simple superphosphate, simple superphosphate + micronutrients, with NPK 04-14-08, and NPK 04-14-08 + micronutrients). The emergence speed index, emergence percentage, seedling height, stem diameter, leaf number, leaf area, shoot, root, and total dry mass, and Dickson quality index were evaluated. The 1:2:1 substrate and the fertilization levels with simple superphosphate, with simple superphosphate + micronutrients, with NPK 04-14-08, and with NPK 04-14-08 + micronutrients were higher than the control, with values 17% higher for seedling height, 5.4% for the number of leaves, and 18.9% for leaf area. Aiming at the low cost and the quality of the seedlings, it is recommended to use the substrate in the proportion 1:2:1, and fertilization with simple superphosphate.

Keywords: Atlantic forest; beach bean; initial growth; mineral nutrition; restinga



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1. Introduction

The degradation of coastal ecosystems, especially restinga areas, has highlighted the urgent need for the development of ecological restoration projects. Among the native species with great potential for these projects, *Canavalia rosea* (Sw.) DC., commonly known as beach bean, stands out. It is a species of the Fabaceae family, distributed throughout all tropical and subtropical coastal areas of the world [1]. This species is a creeping, herbaceous, perennial legume with a stoloniferous habit that plays a fundamental ecological role in dune fixation, soil protection against wind erosion, and enrichment of degraded areas due

to its biological nitrogen fixation capacity [2]. Furthermore, *C. rosea* can be used as food, for pharmaceuticals, and bioactive compounds, and, being a perennial herbaceous species with a stoloniferous habit, it controls soil erosion in dry and sandy coastal areas [3].

Despite its ecological relevance and potential use in coastal landscaping, the successful establishment of *C. rosea* in the field depends directly on the initial survival of the plants, which demands the production of high-quality seedlings. The nursery phase is one of the most critical stages of the production process, and the morphological and physiological quality of these seedlings is strongly influenced by the nutritional and physical conditions provided during their initial development [4]. Among the factors that most influence the quality and final cost of the seedling, the substrate and fertilization management play central roles.

The substrate acts as mechanical support and a reservoir of water and oxygen for the root system. For coastal dune species, adapted to sandy soils with low water retention, finding a substrate that balances porosity and water retention capacity is a challenge that directly impacts root architecture and plant vigor. Thus, the substrate used for seedling production must contain raw materials with good biological and physicochemical characteristics in order to promote an increase in dry matter in the aerial part and root and accelerate seedling growth [5].

Organic materials are increasingly being used as alternatives to substrates in seedling production. Coconut fiber is emerging on the market as an alternative to the impact generated by the accumulation of discarded coconuts, given the high consumption of coconut water, which brings environmental and logistical difficulties [6]. In addition to the environmental, economic, and social importance of using coconut husk as fiber, it presents excellent physicochemical properties for seedling production, such as high porosity, good aeration capacity, and high cation exchange capacity due to its inertness, all considering the abundance of the raw material [7].

In addition, chemical fertilization emerges as an essential tool to accelerate growth in nurseries. The strategic supply of macronutrients and micronutrients can optimize the photosynthetic rate and biomass accumulation. Adequate nutrition allows the root system to explore larger volumes of substrate, contributing to increased water and nutrient absorption, ensuring plant growth [8], and making them more vigorous to withstand adversities in the field [9]. Furthermore, according to the aforementioned authors, in forest nurseries, fertilizers composed of water-soluble nitrogen, phosphorus, and potassium are used; however, native forest species may have specific nutritional requirements, making it necessary to study which nutrients are suitable for producing quality seedlings for each species.

Thus, the quality standard required for *C. rosea* seedlings takes into account morphological, growth, and development characteristics. To withstand the critical conditions of water deficit, intense ultraviolet radiation, and mechanical abrasion from sandy wind, these seedlings must exhibit a good germination rate, thick stem diameter, plant height, number of leaves, biomass accumulation, and high Dickson Quality Index, consolidated morpho-physiological indicators that translate into high survival rates and adaptive capacity of seedlings in the field [10].

Considering the natural habitat of *C. rosea* (sandy soils of low fertility), it is assumed that the species responds positively to the addition of nutrients via chemical fertilization and the use of enriched substrates. Thus, we hypothesize that the use of substrates with higher levels of chemical fertilization promotes positive effects that increase the quality and growth of *C. rosea* seedlings in an economically viable way. Therefore, the objective was to evaluate the cost and effects of the substrate, with different proportions of sand:clay:coconut

fiber, and chemical fertilization on the production and quality of *C. rosea* seedlings in tubes, through morphological variables.

2. Materials and Methods

The experiment was conducted in a greenhouse with 30% shade cloth at the Federal University of Espírito Santo—São Mateus Campus, located at approximately 38 m altitude. The region has an Aw (humid tropical) climate, according to the Köppen classification [11]. The meteorological data for the study area during the experiment were obtained from the automatic surface observation meteorological station of the National Institute of Meteorology located in the municipality (Figure 1).

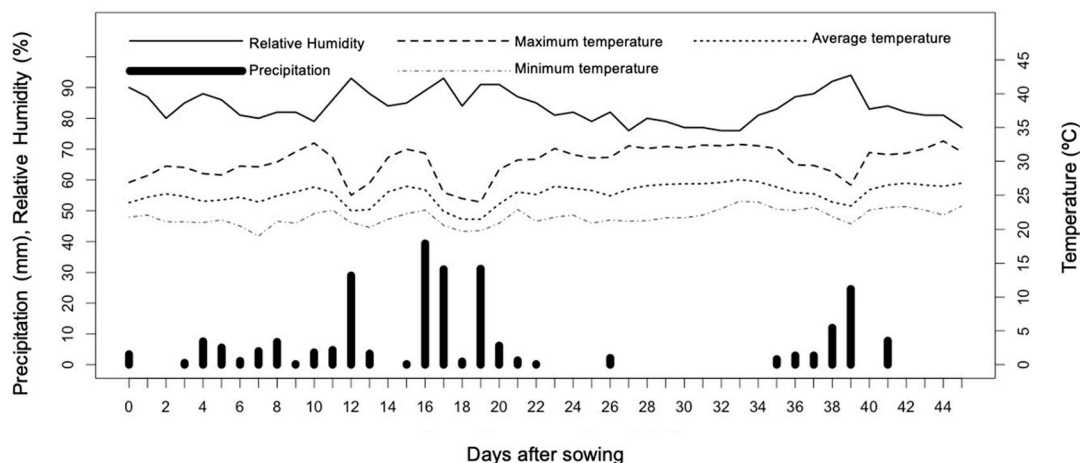


Figure 1. Precipitation, relative humidity, maximum, minimum, and average temperature during the period during which the experiment was conducted, in the municipality of São Mateus, ES.

The experimental design was in randomized blocks, in a 2×5 factorial scheme, corresponding to two substrates and five fertilizations, corresponding to ten treatments, whose representation is in Table 1. Each treatment was composed of seven plants per plot and three blocks, totaling 210 plants in the experimental field (Figure 2). The fertilization of the substrates was adapted from the manual for the production of seedlings of native forest species [12].

Table 1. Treatments and their respective substrate and fertilization formulations for the production of *Canavalia rosea* seedlings.

Treatments	Composition
S ₁ A ₀	Mixture of sand + clay + coconut fiber (2:1:1)
S ₁ A ₁	Mixture of sand + clay + coconut fiber (2:1:1) + 1.5 kg m ⁻³ Simple superphosphate
S ₁ A ₂	Mixture of sand + clay + coconut fiber (2:1:1) + 1.5 kg m ⁻³ Simple superphosphate + 150 g m ⁻³ FTE BR12 (micronutrients)
S ₁ A ₃	Mixture of sand + clay + coconut fiber (2:1:1) + 1.93 kg m ⁻³ NPK 04-14-08
S ₁ A ₄	Mixture of sand + clay + coconut fiber (2:1:1) + 1.93 kg m ⁻³ NPK 04-14-08 + 150 g m ⁻³ FTE BR12 (micronutrients)
S ₂ A ₀	Mixture of sand + clay + coconut fiber (1:2:1)
S ₂ A ₁	Mixture of sand + clay + coconut fiber (1:2:1) + 1.5 kg m ⁻³ Simple superphosphate
S ₂ A ₂	Mixture of sand + clay + coconut fiber (1:2:1) + 1.5 kg m ⁻³ Simple superphosphate + 150 g m ⁻³ FTE BR12 (micronutrients)
S ₂ A ₃	Mixture of sand + clay + coconut fiber (1:2:1) + 1.93 kg m ⁻³ NPK 04-14-08
S ₂ A ₄	Mixture of sand + clay + coconut fiber (1:2:1) + 1.93 kg m ⁻³ NPK 04-14-08 + 150 g m ⁻³ FTE BR12 (micronutrients)

The preparation of the coconut fiber used in the substrates was carried out with a coconut crusher, model Trc40 from the Trapp® brand, with a power of 5 hp, and dried on plastic canvas until complete dehydration. The sand and clay were collected from extraction deposits, areas that will later be revegetated with these seedlings. The substrates were prepared in volumetric proportions, according to the treatments described previously, with

the application of 250 g m^{-3} of dolomitic limestone for all treatments and homogenized for subsequent filling of the tubes. The nutritional composition of the substrates with a mixture of sand + clay + coconut fiber (2:1:1) (S_1) and a mixture of sand + clay + coconut fiber (1:2:1) (S_2) can be seen in Table 2.



Figure 2. Beginning of emergence of *Canavalia rosea*, with plots arranged in a randomized block design.

Table 2. Chemical characteristics of the substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio (S_1) and substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio (S_2).

Nutrient	Unit	Substrate	
		S_1	S_2
P	(mg/dm ³)	5	5
K		210	130
S		16	16
Ca	(cmolc/dm ³)	0.2	0.7
Mg		0.1	0.1
pH		5.0	5.7
Organic matter	dag/dm ³	0.4	0.5
Fe	(mg/dm ³)	46.0	26.0
Zn		0.1	0.1
Cu		0.1	0.1
Mn		1.0	1.0
B		0.38	0.14
Na		19.0	31.0
Sum of Bases	(cmolc/dm ³)	0.92	1.27
Effective CTC		1.22	1.27
Base saturation	(%)	33.85	45.81

The tubes used in seedling production had a conical shape, with a capacity of 290 cm³, perforated at the lower end, with eight grooves and dimensions of 19.0 cm in height and 5.4 cm in internal diameter at the upper opening. The irrigation frequency was four times a day for 15 min using sprinklers, totaling an average rainfall of 8 mm day^{−1}.

The *C. rosea* seeds were collected and provided by the José Bahia Socio-Cultural and Environmental Center, undergoing a three-month storage period in paper bags with a temperature of approximately 5 °C and a humidity of approximately 50%. During preparation, they were placed in a glass beaker, immersed for 15 min in a solution containing 1% of the fungicide Captan® (Adama, Brazil, Londrina) [13] and subsequently washed with distilled water. There was partial elimination of the tegument in the region opposite the hilum of all seeds, as suggested by Costa et al. [14], and soon after, one seed was sown per tube. The seedlings remained in the greenhouse for 45 days after sowing.

During emergence, the emergence speed index (ESI) was determined through daily seedling counts, as proposed by Maguire [15]. The emergence of cotyledons was adopted as an emergence criterion. At the end of the experiment, 45 days after sowing, a period in which the seeds had already expressed their maximum germination capacity [16], the percentage of emergence (%E), height (H), stem diameter (SD), number of leaves (NL), leaf area (LA), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), and Dickson quality index (DQI) [17].

$$ESI = \frac{E1}{N1} + \frac{E2}{N2} + \dots + \frac{En}{Nn} \quad (1)$$

where: ESI = emergence speed index; E1, E2, ... En = number of seedlings counted in the first count, second count, and last count; N1, N2, ... Nn = number of days from sowing to the first, second, and last count.

$$DQI = \frac{TDM}{\frac{SH}{SD} + \frac{SDM}{RDM}} \quad (2)$$

where: DQI = Dickson quality index; TDM = total dry mass, in g; SDM = shoot dry mass, in g; RDM = root dry mass, in g; SH = seedling height, in cm; SD = stem diameter, in mm.

The height of the seedlings was measured with a ruler graduated in millimeters, from the collar region to the apical bud. The collar diameter was obtained using a digital caliper in millimeters. To determine the dry mass of the plants, the seedlings were separated into aerial parts and roots. The roots were washed in running water, and subsequently, both parts were placed in separate, identified paper bags and dried in an oven at 65 °C until they reached a constant weight. They were then weighed on a Gehaka® BK300 semi-analytical balance (Gehaka®, Brazil, São Paulo), with a precision of 0.01 g.

To determine the leaf area, all trifoliate leaves of *C. rosea* were scanned using an HP® Deskjet F4280 scanner (HP®, Brazil, São Paulo), and the images were saved in TIF format at 75 dpi. Each leaf was composed of 3 leaflets. The length (L) along the main vein and the maximum width (W) of the leaf blade, in cm, of the last leaflet of each compound leaf were measured (Figure 3), and subsequent reading of the leaf area of each plant was carried out with the ImageJ® software version 1.51v [18], which was calibrated as described by Santos et al. [19]. Subsequently, the equation $ELA = 2.2951(LW)^{0.9474}$ was used with the length and width to determine the leaf area according to Pinheiro et al. [20].

For the statistical analyses, the mean of the seven plants in each of the three blocks was used. The data were subjected to analysis of variance using the F test ($p < 0.05$), and when significant, the interactions were broken down and the means compared using the Tukey test ($p < 0.05$), using the 'ExpDes.pt' data package version 1.2 [21] in the R software version 3.5.1 [22].

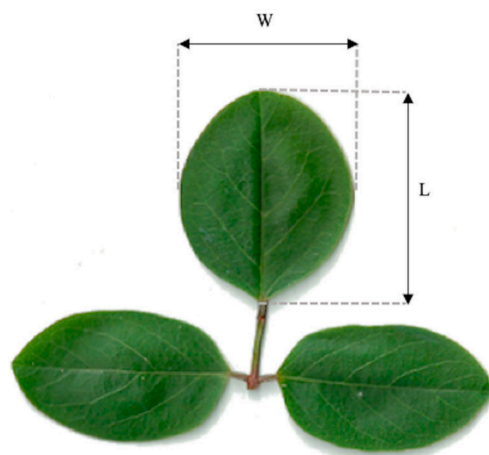


Figure 3. Representation of the measurement of length (L) along the main vein and maximum width (W) of the leaf blade of the last leaflet of leaves of *Canavalia rosea* seedlings.

To determine the production cost per cubic meter of the treatments (substrate + fertilization), the cost of each product and its proportion in the formulation were calculated. Market prices for sand, clay, and fertilizers in the São Mateus—ES region during 2018 were used. For the cost of coconut fiber, only the freight cost for transporting the coconuts and the labor time for shredding them were taken into account.

3. Results

It is noted that only the shoot dry mass variable showed an interaction between the substrate and fertilizer factors (Table A1). For seedling height, number of leaves, leaf area, and total dry mass, the factors were studied in isolation when significant, and the other variables did not show statistical differences. It is also observed that the percentage of emergence of *C. rosea* seeds in the tested substrates is considered high, with an average above 90% (Table 3), although the seeds underwent a storage period. The average emergence speed index observed in the tested substrates was 5.67 seeds day^{−1} (Table 3), with seedling emergence beginning six days after sowing (Figure 4).

Table 3. Percentage of emergence and emergence speed index of *C. rosea* seeds under different substrates and chemical fertilization.

Fertilizing	Emergence (%)				Emergence Speed Index (Seeds Day ^{−1})			
	S ₁	S ₂	Average	Sd	S ₁	S ₂	Average	Sd
A ₀	95.24	90.48	92.86 a	3.36	5.59	4.91	5.25 a	0.48
A ₁	95.24	100.00	97.61 a	3.36	5.98	5.79	5.89 a	0.13
A ₂	100.00	90.48	95.24 a	6.73	5.96	5.57	5.77 a	0.27
A ₃	100.00	90.48	95.24 a	6.73	5.92	5.45	5.68 a	0.33
A ₄	100.00	90.48	95.24 a	6.73	5.96	5.52	5.74 a	0.31
Sd	2.61	4.26	-	-	0.16	0.32	-	-
Average	98.09 A	92.37 A	95.23	-	5.88 A	5.45 A	5.67	-

S₁ = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S₂ = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A₀ = no fertilization; A₁ = fertilized with 1.5 kg m^{−3} of single superphosphate; A₂ = fertilized with 1.5 kg m^{−3} of single superphosphate + 150 g m^{−3} FTE BR12; A₃ = fertilized with 1.93 kg m^{−3} of NPK 04-14-08; A₄ = fertilized with 1.93 kg m^{−3} of NPK 04-14-08 + 150 g m^{−3} FTE BR12. Means followed by the same lowercase letter vertically and uppercase letter horizontally do not differ by Tukey's test at 5% probability. Sd = standard deviation.

Among the substrate levels studied, the sand:clay:coconut fiber mixture in a 1:2:1 ratio (S₂) provided seedlings with a statistically higher average height than substrate S₁,

reaching 14.87 cm (Table 4). When analyzing the fertilizer factor, we observed that the fertilized levels (A_1 , A_2 , A_3 , and A_4) showed statistically higher averages than level A_0 . The substrates with single superphosphate (A_1), single superphosphate + micronutrients (A_2), NPK 4-14-8 (A_3), and NPK 4-14-8 + micronutrients (A_4) were statistically equal to each other (Table 4).

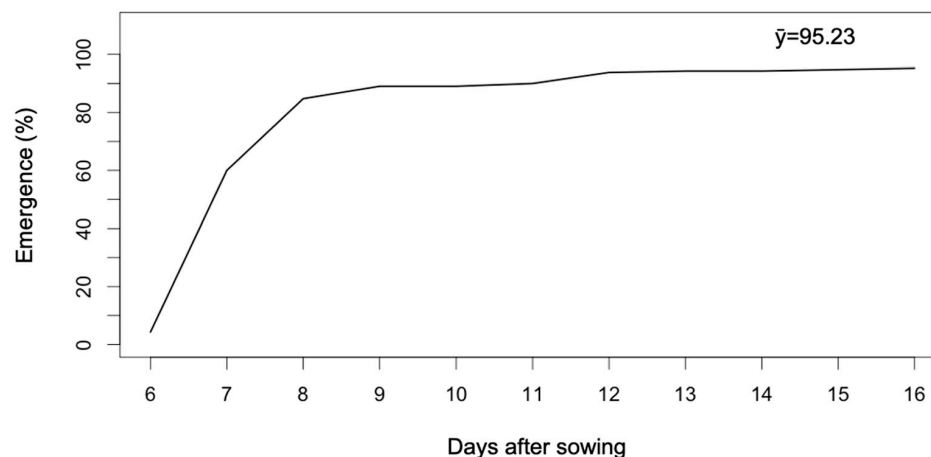


Figure 4. Percentage of emergence of *C. rosea* seedlings grown under different substrates and chemical fertilization.

Table 4. Seedling height and stem diameter of *C. rosea* seedlings grown under different substrates and chemical fertilization, 45 days after sowing.

Fertilizing	Seedling Height (cm)				Stem Diameter (mm)			
	S_1	S_2	Average	Sd	S_1	S_2	Average	Sd
A_0	9.25	8.94	9.09 b	0.22	3.39	3.55	3.47 a	0.11
A_1	14.79	16.37	15.58 a	1.12	3.53	3.55	3.54 a	0.01
A_2	12.15	16.05	14.10 a	2.76	3.43	3.61	3.52 a	0.13
A_3	14.02	15.79	14.90 a	1.25	3.55	3.56	3.55 a	0.007
A_4	13.29	17.20	15.24 a	2.76	3.47	3.48	3.47 a	0.007
Sd	2.16	3.36	-	-	0.07	0.05	-	-
Average	12.70 B	14.87 A	13.78	-	3.47 A	3.55 A	3.51	-

S_1 = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S_2 = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A_0 = no fertilization; A_1 = fertilized with 1.5 kg m^{-3} of single superphosphate; A_2 = fertilized with 1.5 kg m^{-3} of single superphosphate + 150 g m^{-3} FTE BR12; A_3 = fertilized with 1.93 kg m^{-3} of NPK 04-14-08; A_4 = fertilized with 1.93 kg m^{-3} of NPK 04-14-08 + 150 g m^{-3} FTE BR12. Means followed by the same lowercase letter vertically and uppercase letter horizontally do not differ by Tukey's test at 5% probability. Sd = standard deviation.

For the variables number of leaves and leaf area of the seedlings, the S_2 substrate level showed the best averages, with approximately 4 leaves and 180.06 cm^2 , respectively (Table 5). Regarding the fertilizers tested, levels A_1 , A_2 , A_3 , and A_4 showed statistically higher averages than level A_0 for both variables (Table 5); this result may be related to the nutritional supply to the seedlings.

Regarding the dry mass of the aerial part, where a significant interaction was observed between the substrate and fertilizer factors (Table 6), it is noted that substrate S_1 was inferior to substrate S_2 at levels A_2 and A_4 , showing that the addition of micronutrients did not have a significant effect on the dry mass of the aerial part of *C. rosea* seedlings in the substrate with the highest sand fraction. Studying the fertilizers within each substrate level in relation to the dry mass of the aerial part, it was found that in substrate S_1 , the fertilizer levels were statistically equal, and in substrate S_2 , the fertilizer level A_0 (1.33 g) showed

a lower average than the other levels (Table 6). The treatments that provided the highest average shoot dry mass were S₁A₀ (1.44 g), S₁A₁ (1.75 g), S₁A₃ (1.69 g), S₂A₁ (1.77 g), S₂A₂ (2.00 g), S₂A₃ (1.80 g), and S₂A₄ (2.01 g).

Table 5. Number of leaves and leaf area of *C. rosea* seedlings grown under different substrates and chemical fertilization, 45 days after sowing.

Fertilizing	Number of Leaves				Leaf Area (cm ²)			
	S ₁	S ₂	Average	Sd	S ₁	S ₂	Average	Sd
A ₀	3.67	3.44	3.56 b	0.16	122.67	123.23	122.95 b	0.39
A ₁	4.04	4.52	4.28 a	0.34	156.72	193.38	175.05 a	25.92
A ₂	4.20	4.35	4.27 a	0.11	154.40	185.01	169.70 a	21.64
A ₃	4.16	4.44	4.30 a	0.20	165.49	188.65	177.06 a	16.38
A ₄	4.24	4.63	4.44 a	0.27	158.06	210.05	184.06 a	36.76
Sd	0.23	0.48	-	-	16.62	33.18	-	-
Average	4.06 B	4.28 A	4.17	-	151.47 B	180.06 A	165.76	-

S₁ = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S₂ = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A₀ = no fertilization; A₁ = fertilized with 1.5 kg m⁻³ of single superphosphate; A₂ = fertilized with 1.5 kg m⁻³ of single superphosphate + 150 g m⁻³ FTE BR12; A₃ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08; A₄ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08 + 150 g m⁻³ FTE BR12. Means followed by the same lowercase letter vertically and uppercase letter horizontally do not differ by Tukey's test at 5% probability. Sd = standard deviation.

Table 6. Shoot dry mass and root dry mass of *C. rosea* seedlings grown under different substrates and chemical fertilization, 45 days after sowing.

Fertilizing	Shoot Dry Mass (g)				Root Dry Mass (g)			
	S ₁	S ₂	Average	Sd	S ₁	S ₂	Average	Sd
A ₀	1.44 Aa	1.33 Ab	1.38	0.08	0.71	0.69	0.70 a	0.01
A ₁	1.75 Aa	1.77 Aa	1.76	0.01	1.04	0.93	0.99 a	0.08
A ₂	1.55 Ba	2.00 Aa	1.77	0.32	1.02	0.87	0.94 a	0.11
A ₃	1.69 Aa	1.80 Aa	1.74	0.08	1.02	1.04	1.03 a	0.01
A ₄	1.56 Ba	2.01 Aa	1.78	0.32	0.86	0.94	0.90 a	0.06
Sd	0.12	0.27	-	-	0.14	0.13	-	-
Average	1.60	1.78	1.69	-	0.93 A	0.89 A	0.91	-

S₁ = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S₂ = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A₀ = no fertilization; A₁ = fertilized with 1.5 kg m⁻³ of single superphosphate; A₂ = fertilized with 1.5 kg m⁻³ of single superphosphate + 150 g m⁻³ FTE BR12; A₃ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08; A₄ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08 + 150 g m⁻³ FTE BR12. Means followed by the same lowercase letter vertically and uppercase letter horizontally do not differ by Tukey's test at 5% probability. Sd = standard deviation.

In the total dry mass variable, the factors were studied separately. It was found that both substrate levels, S₁ and S₂, were statistically similar. Regarding fertilizer, levels A₁ (2.75 g), A₂ (2.72 g), A₃ (2.77 g), and A₄ (2.69 g) provided better average total dry mass, differing statistically from A₀, with an average of 2.09 g (Table 7). Not showing significance for this index, the average DQI found in the tested treatments was 0.45 (Table 7).

Analyzing the production cost of the substrates, it appears that the lowest production cost was for the sand:clay:coir fiber substrate in a 1:2:1 ratio (S₂), costing R\$ 63.47 m⁻³, around 9% cheaper than the sand:clay:coir fiber mixture in a 2:1:1 ratio (S₁) (Table 8). Among the fertilizer levels tested, the one that presented the highest cost was the substrate fertilized with NPK 4-14-8 + FTE BR12 (A₄), R\$ 3.68 m⁻³, approximately 124% more expensive than the substrate fertilized with simple superphosphate, A₁ (R\$ 1.64 m⁻³).

Table 7. Total dry mass and Dickson quality index of *C. rosea* seedlings grown under different substrates and chemical fertilization, 45 days after sowing.

Fertilizing	Total Dry Mass (g)				Dickson Quality Index			
	S ₁	S ₂	Average	Sd	S ₁	S ₂	Average	Sd
A ₀	2.15	2.02	2.09 b	0.09	0.45	0.46	0.46 a	0.007
A ₁	2.80	2.70	2.75 a	0.07	0.46	0.41	0.44 a	0.03
A ₂	2.57	2.87	2.72 a	0.21	0.50	0.43	0.47 a	0.05
A ₃	2.71	2.83	2.77 a	0.08	0.48	0.46	0.47 a	0.01
A ₄	2.43	2.95	2.69 a	0.38	0.43	0.42	0.42 a	0.007
Sd	0.25	0.38	-	-	0.03	0.02	-	-
Average	2.53 A	2.67 A	2.60	-	0.47 A	0.44 A	0.45	-

S₁ = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S₂ = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A₀ = no fertilization; A₁ = fertilized with 1.5 kg m⁻³ of single superphosphate; A₂ = fertilized with 1.5 kg m⁻³ of single superphosphate + 150 g m⁻³ FTE BR12; A₃ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08; A₄ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08 + 150 g m⁻³ FTE BR12. Means followed by the same lowercase letter vertically and uppercase letter horizontally do not differ by Tukey's test at 5% probability. Sd = standard deviation.

Table 8. Cost per cubic meter of the ten treatments used, based on 2018 purchase prices in the São Mateus-ES region.

Treatments	Cost of Substrate/m ³ (R\$) *	Cost of Fertilizer/m ³ of Substrate (R\$) *	Total Cost/m ³ (R\$) *
S ₁ A ₀	69.72	0.00	69.72
S ₁ A ₁	69.72	1.64	71.35
S ₁ A ₂	69.72	1.88	71.60
S ₁ A ₃	69.72	3.44	73.15
S ₁ A ₄	69.72	3.68	73.40
S ₂ A ₀	63.47	0.00	63.47
S ₂ A ₁	63.47	1.64	65.10
S ₂ A ₂	63.47	1.88	65.35
S ₂ A ₃	63.47	3.44	66.90
S ₂ A ₄	63.47	3.68	67.15

* US\$ 1.00 = R\$ 3.85; S₁ = substrate with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio; S₂ = substrate with a mixture of sand + clay + coconut fiber in a 1:2:1 ratio; A₀ = no fertilization; A₁ = fertilized with 1.5 kg m⁻³ of single superphosphate; A₂ = fertilized with 1.5 kg m⁻³ of single superphosphate + 150 g m⁻³ FTE BR12; A₃ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08; A₄ = fertilized with 1.93 kg m⁻³ of NPK 04-14-08 + 150 g m⁻³ FTE BR12.

4. Discussion

The substrates with a mixture of sand + clay + coconut fiber in a 2:1:1 ratio (S₁) and in a 1:2:1 ratio (S₂) provided a high percentage of emergence of *C. rosea* seeds, with an average of over 90%, even though the seeds had undergone a storage period. These findings are similar to those found by Gonçalves et al. [23] in *C. rosea* seeds freshly collected from ripe fruits to germinate under ambient conditions, in topsoil and sand, observing 100% germination in both substrates. However, Costa et al. [14] obtained germination of less than 20% in a BOD-type germinator at a temperature of 25 °C when no type of scarification was performed on the *C. rosea* seed, and germination of approximately 90% when the same scarification used in this work was performed, highlighting the importance of this practice for the germination process of seeds of this species.

It should be noted that the lack of significant differences in germination percentage between substrates S₁ and S₂ may be related to nutrient availability, specifically due to the equal amount of phosphorus present in both substrates, since this nutrient is fundamental for initial development and energy metabolism [24]. Furthermore, substrates S₁ and S₂ presented pH values of 5.0 and 5.7, respectively, values considered ideal for the absorption of micronutrients such as iron and manganese, favoring the germination process [25,26].

Furthermore, corroborating the findings of this study, Gonçalves et al. [23] achieved emergence above 80% eight days after sowing. Sixteen days after sowing, the emergence evaluation was completed, with 95.23% of the seedlings having emerged. This finding is also important for the nurseryman, as the high speed of germination followed by seedling emergence are characteristics of interest in seedling production. The faster the seedling emerges, the less vulnerable it will be to environmental adversities [27], allowing for the production of vigorous seedlings in a short period of time. In addition, the sowing and transplanting time of the seedlings to the field is reduced, saving space, irrigation, fertilization, and nursery labor.

It was observed that the substrate composed of sand, clay, and coconut fiber in a 1:2:1 ratio (S_2) promoted increases in seedling height, number of leaves, and leaf area. This suggests that the substrate with higher clay content (S_2) likely possesses a larger specific surface area [28] and facilitated better utilization of applied fertilizers due to its higher cation exchange capacity, organic matter content, and base saturation. Furthermore, fertilizing the substrate with single superphosphate (A_1), single superphosphate plus micronutrients (A_2), NPK 4-14-8 (A_3), and NPK 4-14-8 plus micronutrients (A_4) resulted in significant gains compared to the unfertilized substrate (A_0). Thus, the importance of fertilization for plant development is evident.

Observing the reduced growth of *C. rosea* in the substrate without added nutrients (A_0), we can infer that phosphorus (P) was likely the limiting nutrient for seedling growth, given that substrates containing N, K, and micronutrients showed development similar to that of substrates containing only P. However, this inference is merely a suggestion; it should be viewed with caution and analyzed in future studies regarding substrates for *C. rosea* seedling production.

It should be noted that the height of the seedlings is a characteristic that allows the initial growth potential to be measured in the field, being considered one of the oldest parameters for the classification and selection of seedlings, and when used in isolation, it is efficient for estimating the quality standard of seedlings in nurseries, as it is a non-destructive and easily measured variable [29–31].

The treatments tested did not differ significantly in terms of collar diameter, with an average diameter of 3.51 mm. This indicates that seedlings from any substrate tested in this work may have high potential for survival and growth in the field. For Gonçalves et al. [32], the diameter of the appropriate stem for seedlings of forest species must be between 5 and 10 mm, a range higher than that found in this study. However, it is known that the development of forest species is very variable, which may be an intrinsic morphological characteristic of this species, indicating that these proposed values are not applicable to *C. rosea*, as found by Delarmelina et al. [33], for *Sesbania virgata*.

It is possible to note that the addition of micronutrients did not provide gains in the dry mass of the aerial part of *C. rosea* seedlings in the S_1 substrate with a higher sand fraction. Micronutrients, although required in smaller quantities by plants, are essential for their development. Among the micronutrients present in FTE BR12 is boron, playing a role in cell elongation, nucleic acid synthesis, hormonal responses, membrane function and cell cycle regulation; zinc, being necessary for the activity of many enzymes and being required for the biosynthesis of chlorophyll; manganese, activating several enzymes in plant cells, including decarboxylases and dehydrogenases, involved in the citric acid cycle, activated by manganese ions; and copper, associated with enzymes involved in redox reactions, such as plastocyanine, which is involved in the transfer of electrons during the light-dependent reactions of photosynthesis [24].

Sandy soils are chemically poor, as they have a low cation exchange capacity and reduced specific surface area, resulting in a lower tendency to retain water and an increased

loss of nutrients through leaching [34,35]. This may explain what happened with the unsatisfactory development of the substrate with a higher sand fraction (S_1), in the variables plant height, number of leaves, leaf area, and dry mass of the aerial part. Thus, plants with adequate nutrition have greater reserves of dry matter in the aerial part [36].

In general, the treatments tested had no effect on root dry mass, with an overall average of 0.91 g. Better conditions for the establishment of seedlings, acquisition of nutrients and water, can be obtained with greater development of the root system. Thus, in situations of temporary scarcity of resources, the species is able to tolerate the adversities present in the field for longer [37].

The addition of fertilizer (A_1 , A_2 , A_3 , and A_4), regardless of the substrate (S_1 or S_2), provided better averages of total dry mass. According to Cruz et al. [38], the total dry mass must be taken into account to produce quality seedlings, and the higher the value, the better. It can be inferred that levels A_1 , A_2 , A_3 , and A_4 provided seedlings with greater potential for survival capacity in the field, thus highlighting the importance of nutrition for the dry mass of plants.

It is evident that, at all tested levels, the seedlings exhibited a Dickson Quality Index (DQI) greater than 0.2, a value recommended by Hunt [39] as an indicator of high-quality seedlings for forest species. The DQI is widely used as a reliable indicator of seedling quality because it accounts for morphological characteristics [9], providing insights into seedling robustness and biomass distribution balance [40], which are associated with higher survival rates after transplanting [41]. However, it should be noted that the 0.2 value serves merely as a reference for *C. rosea*, given that it is an herbaceous legume species; this specific value has not been validated for it under field conditions. It is worth highlighting that the quality standard presented in all substrates is related to the rusticity characteristics of *C. rosea*, which, even in natural conditions with sandy soils, poor in nutrients and high incidence of solar radiation, present root nodules with the capacity for biological nitrogen fixation [23,42–44].

Although all substrate and fertilizer levels produced seedlings with statistically similar quality indices, substrate level S_2 and fertilizer levels A_1 , A_2 , A_3 , and A_4 stood out, as these presented height, number of leaves, leaf area and total dry mass statistically higher than the other levels, and when there was an interaction for dry mass of the aerial part, the treatments S_2A_1 , S_2A_2 , S_2A_3 and S_2A_4 also presented higher averages. To determine the point for transplanting seedlings, nurseries have efficiently used the height of the plant as a criterion to estimate its quality [31]. However, seedlings with a higher size, number of leaves, leaf area, and satisfactory dry mass may imply greater potential for survival and initial growth in the field.

In a resting environment, as evidenced by Lourenço Junior and Cuzzuol [45], they found that *C. rosea* is more nutritionally demanding in absorbing N and K than P. This result was not observed in this study, as only fertilization with simple superphosphate fertilizer (source of P) in the substrate was sufficient for good seedling development in a greenhouse. According to Lambers et al. [46], when native species adapted to environments with low fertility are subjected to high nutritional levels, they accumulate nutrients instead of allocating them for growth, using them only in environments with limiting nutritional conditions. According to the authors, this is evidence of adaptive strategies developed by these plants to survive in environments with low fertility.

It is noteworthy that both substrates S_1 and S_2 contain coconut fiber in their composition, which has the characteristic of maintaining a favorable environment for seedling development, maintaining adequate moisture, preventing waterlogging and dehydration [47]. This is a sustainable alternative for the efficient production of seedlings [48,49].

The substrate containing a sand:clay:coconut fiber mixture in a 1:2:1 ratio improved morphological characteristics, specifically seedling height, number of leaves, and leaf area in *C. rosea* seedlings compared to S₁. This mixture could be adopted in the production process for this species, potentially reducing the time required to obtain seedlings ready for field transplanting. Regarding substrate fertilization, the use of single superphosphate is recommended, in addition to yielding development comparable to substrates enriched with single superphosphate plus micronutrients, NPK 04-14-08, or NPK 04-14-08 plus micronutrients, which produces seedlings with greater height, leaf count, leaf area, and biomass. However, future work is needed to identify whether other fertilizations favor the development of *C. rosea* post-planting in areas of low fertility, according to the theory of Lambers et al. [46], presented previously.

It should also be noted that although level A₀ (without added nutrients) is low cost, it is not recommended as it does not promote good seedling development. In addition to the cost of producing the substrate, it is important to take into account the quality of the seedlings [50].

5. Conclusions

The results demonstrate that substrate composition directly influences the growth and quality of *Canavalia rosea* seedlings. The substrate composed of sand, clay, and coconut fiber in a 1:2:1 ratio yielded the best vegetative performance while also offering lower production costs. Although the 1:2:1 substrate is inexpensive, its use without nutritional supplementation is not recommended, as the lack of fertilization significantly limits seedling growth. Among the fertilization levels tested, the application of 1.5 kg m⁻³ of single superphosphate proved to be the most suitable choice; it promoted significant increases in plant height, leaf number, leaf area, and biomass production while maintaining low production costs. Therefore, using a sand:clay:coconut fiber substrate in a 1:2:1 ratio combined with 1.5 kg m⁻³ of single superphosphate is recommended as a technically efficient and economically viable strategy for producing high-quality *Canavalia rosea* seedlings.

Despite the consistency of the results, the evaluation was conducted under controlled nursery conditions and covered only specific substrate combinations and fertilization levels; it did not consider other nutrient sources, alternative substrate materials, or seedling performance after transplanting to field conditions. Future research should evaluate the behavior of *Canavalia rosea* seedlings after field transplanting, assessing survival, initial growth, and establishment under various environmental conditions, particularly in restinga areas and coastal ecosystem restoration projects. Furthermore, investigating new substrate combinations using organic waste or low-cost alternative materials, as well as different fertilizer sources and dosages, is recommended to simultaneously optimize seedling quality, production process sustainability, and cost efficiency.

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Abbreviations

The following abbreviations are used in this manuscript:

ESI	Emergence speed index
%E	Percentage of emergence
H	Seedling height
SD	Stem diameter
NL	Number of leaves
LA	Leaf area
SDM	Shoot dry mass
RDM	Root dry mass
TDM	Total dry mass
DQI	Dickson quality index

Appendix A

Table A1. Summary of the analysis of variance of emergence percentage (%E), emergence speed index (ESI), seedling height (H), stem diameter (SD), number of leaves (NL), leaf area (LA), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM) and Dickson quality index (DQI) of *Canavalia rosea* seedlings grown under different substrates and chemical fertilization, 45 days after sowing.

Source of Variation	DF	Mean Square				
		%E	ESI	H	SD	NL
Block	2	6.80	0.35	4.76	0.153	0.098
Substrate	1	244.99 ^{ns}	1.40 ^{ns}	35.17 *	0.045 ^{ns}	0.354 *
Fertilizer	4	17.02 ^{ns}	0.36 ^{ns}	43.06 *	0.009 ^{ns}	0.727 *
Substrate × Fertilizer	4	57.85 ^{ns}	0.44 ^{ns}	4.78 ^{ns}	0.011 ^{ns}	0.118 ^{ns}
Residue	18	67.29	0.38	2.02	0.016	0.080
CV (%)		8.61	10.85	10.32	3.57	6.79

Source of variation	DF	Mean square				
		LA	SDM	RDM	TDM	DQI
Block	2	776.6	0.034	0.205	0.164	0.010
Substrate	1	6134.4 *	0.243 *	0.010 ^{ns}	0.154 ^{ns}	0.007 ^{ns}
Fertilizer	4	3595.8 *	0.174 *	0.098 ^{ns}	0.506 *	0.002 ^{ns}
Substrate × Fertilizer	4	537.0 ^{ns}	0.096 *	0.013 ^{ns}	0.111 ^{ns}	0.002 ^{ns}
Residue	18	269.1	0.016	0.057	0.099	0.008
CV (%)		9.90	7.42	26.23	12.10	19.50

^{ns} Not significant. * Significant at 5% probability, using the F test. CV = coefficient of variation, DF = degree of freedom.

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