Composted Sewage Sludge as a Substrate for Commercial Seedlings of *Peltophorum dubium* (Spreng) Taub.

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Abstract: Sewage sludge in natura is rich in nutrients, water, and organic matter and is essential for plant development. However, sewage sludge is diluted with water when composted, which could hamper plant growth. Therefore, supplementation with chemical fertilization may be necessary. This study evaluated the performance of composted sewage sludge (CSS) in producing *Peltophorum dubium* (Spreng.) Taub. seedlings with and without chemical fertilization via fertigation. The experiment was completely randomized in a 3 × 4 factorial scheme, with four fertigation (Ca(NO$_3$)$_2$(H$_2$O)$_3$: 0.87; (NH$_4$)$_2$(H$_2$PO$_4$): 0.21; KCl: 0.47; (NH$_4$)$_2$SO$_4$: 0.11; CH$_4$N$_2$O: 0.54; MgSO$_4$: 0.52; Fe (13%): 0.03; B(OH)$_3$: 6.00; CuSO$_4$: 0.60; ZnSO$_4$: 1.40; MnSO$_4$: 6.00; Na$_2$MoO$_4$: 0.16 g L$^{-1}$) doses: zero, standard, duplicate, and quadruplicate. In addition, three substrates were used: commercial substrate as the control, sewage sludge composted with sugarcane bagasse (LBC), and sewage sludge composted with *Eucalyptus* bark (LCE). The development of the seedlings was measured through the following variables: height, stem diameter, shoot/root ratio, leaf dry mass, root dry mass, total dry mass, green color index, the Dickson Quality Index, and the accumulation of nutrients in plant tissue. The seedlings produced with LCE that were subjected to the standard dose (1×) and the quadruplicate dose (4×) had the statistically highest mean values for most variables. Nevertheless, supplementation with chemical fertilization was necessary. Composted sewage sludge with eucalyptus bark, at the standard dosage, can be used for the commercial production of *P. dubium* seedlings, thus preventing the dangerous disposal of waste and strongly decreasing associated environmental hazards.

Keywords: biosolids; waste recycling; circular economy; forest ecosystems

1. Introduction

Sewage sludge represents the final residue in treating anthropogenic waste, which has no economic value in standard waste stations in some countries. Hence, sewage sludge waste requires a proper discard system to prevent environmental damage. However, the complexity and the high costs of processing sewage sludge have caused anthropogenic waste to be discarded in local landfills [1], causing significant environmental damage due to pathogens and high rates of heavy metals in the sewage sludge [2].

The production quantity of sewage sludge is proportional to population development, raising the environmental impact concern. However, these impacts encourage the prospection of sustainable actions to reuse the organic residue [3].

The high concentrations of nutrients, water, and organic matter in sewage sludge are desirable for producing substrate and fertilizers. Indeed, sewage sludge residue is mainly
applied as organic fertilizer and/or substrate for seedlings in forestry and agricultural areas [4].

The CONAMA (Conselho Nacional do Meio Ambiente, National Environmental Council) Resolution No 498/2020 [5] regulates the usage of sewage sludge in nature in Brazil due to its high concentration of heavy metals and pathogens [6,7]. For this reason, the residue must be processed at high temperatures and compounded with other structuring materials for use in agricultural and forestry areas [8]. Indeed, composting SS significantly decreases the pathogenic load, and the organic matter content is stabilized, thus reducing heavy metal availability for plants and the entire food chain.

Unfortunately, the nutrient content of sewage sludge is decreased during processing [9], and it needs to be supplemented with chemical fertilizers. The fertigation method consists of the application of a fertilizer via water irrigation [10], which is widely used in the agricultural and forestry sectors to complement the chemical fertilizers in the substrates, which results in the rapid absorption of fertilizers by the roots [11].

However, the development and nutritional requirements of the seedlings of native species via fertigation demand a broad study effort [12]. In addition, the growing concern of native deforestation requires a program of native forestry restoration and the remedying of degraded areas [13]. Culturing forestry species with sewage sludge results in an adequate growth performance of the seedlings since the compound has a high organic matter content, similar to that in forest soils that undergo litter decomposition [14].

*Peltophorum dubium* (Spreng.) Taub. (*P. dubium* hereafter) has economic and commercial value [15] and is employed in forest restoration programs due to its rapid growth and robustness [16]. In addition, this species develops in various substrate types. However, the root and aerial growth of *P. dubium* is higher when produced with a substrate that contains organic matter [17]. Additionally, its growth at the seedling stage using composted sewage sludge compounded with other organic materials as commercial substrate has never been studied, presenting a total novelty.

The objectives of the present work were to (i) evaluate the production of *P. dubium* seedlings with sewage sludge substrate compounded with sugarcane bagasse and *eucalyptus* bark with different fertilizer levels and (ii) compare these seedlings with those produced with a peat-based commercial substrate, carbonized rice bark, and vermiculite, which are widely used in forestry nurseries. We hypothesize that the use of composted sewage sludge as a commercial substrate improves and enhances the production of *P. dubium* seedlings.

### 2. Materials and Methods

The experiment was conducted in the “Pesquisa em Produção de Mudas Florestais” nursery of the Ciência Florestal Department of the Ciências Agronômicas Faculty, São Paulo State University (Lat. – 22.855, Long – 48.433), Botucatu municipality (Brazil). The experiment lasted nine months. According to the international classification method of Koppen, the region’s climate is temperate and warm [18,19]. The Sanitation Company of the State of São Paulo (Sabesp) provided the sewage sludge in natura.

The compost types were sewage sludge with sugarcane bagasse (SSB) and sewage sludge with *eucalyptus* bark (SEB), both in a 1:1 proportion (v:v). The composting lasted 45 days, and the compost was later transferred to the forest nursery. Commercial substrate (CS), which comprised peat (*Sphagnum* sp.), vermiculite, and carbonized rice bark, was used as the control.

The substrates were physically and chemically characterized (Table 1) to determine the total porosity, macro- and microporosity, water retention, pH, and electric conductivity (EC) [20,21]. The chemical analysis of the substrate followed the “analytical protocol in the chemical characterization of plant substrates” [20].
Table 1. Substrate physical–chemical analysis before the experiment started. Physical analysis: macro- (Macro) and microporosity (Micro), total porosity (TP), water retention capacity (WRC), pH, electric conductivity (EC). Chemical analysis: macro- and micronutrients.

<table>
<thead>
<tr>
<th>Substrates</th>
<th>CS</th>
<th>SSB</th>
<th>SEB</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP (%)</td>
<td>79.3</td>
<td>79.2</td>
<td>75.9</td>
</tr>
<tr>
<td>Macro (%)</td>
<td>36.2</td>
<td>41.5</td>
<td>24.6</td>
</tr>
<tr>
<td>Micro (%)</td>
<td>43.1</td>
<td>37.7</td>
<td>51.2</td>
</tr>
<tr>
<td>WRC (mL)</td>
<td>22.4</td>
<td>19.6</td>
<td>26.6</td>
</tr>
<tr>
<td>pH</td>
<td>6.7</td>
<td>6.4</td>
<td>6.5</td>
</tr>
<tr>
<td>EC (mS⁻¹)</td>
<td>0.164</td>
<td>0.147</td>
<td>0.169</td>
</tr>
<tr>
<td>N (g kg⁻¹)</td>
<td>9.0</td>
<td>16.0</td>
<td>44.0</td>
</tr>
<tr>
<td>P (g kg⁻¹)</td>
<td>1.8</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>K (g kg⁻¹)</td>
<td>13.8</td>
<td>6.7</td>
<td>7.9</td>
</tr>
<tr>
<td>Ca (g kg⁻¹)</td>
<td>2.7</td>
<td>8.4</td>
<td>17.8</td>
</tr>
<tr>
<td>Mg (g kg⁻¹)</td>
<td>1.5</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>S (g kg⁻¹)</td>
<td>6.5</td>
<td>13.8</td>
<td>29.3</td>
</tr>
<tr>
<td>B (mg kg⁻¹)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>Cu (mg kg⁻¹)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe (mg kg⁻¹)</td>
<td>0.15</td>
<td>0.29</td>
<td>0.94</td>
</tr>
<tr>
<td>Mn (mg kg⁻¹)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Zn (mg kg⁻¹)</td>
<td>0.01</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Na (mg kg⁻¹)</td>
<td>9.24</td>
<td>9.22</td>
<td>10.09</td>
</tr>
</tbody>
</table>

CS: commercial substrate (CS) constituted of peat (sphagnum), vermiculite, and toasted rice bark; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with eucalyptus bark.

Each substrate was subjected to four fertigation doses as follows: zero doses (without fertilization); standard dose (1 ×), which is mainly used by commercial forest nurseries [22]; duplicated dose (2 ×), with doubled quantity of the standard dose; and quadruplicated dose (4 ×), with quadruple of the standard dose.

The fertigation was manually applied two times per week, between 16 h and 16:30 h, through the Venturi system, characterized by a closed system and low pressure. The fertigation formulation (Table 2) was the same used by Brazilian commercial nurseries and, for this reason, is at this moment named “standard”.

Table 2. Fertilizing composition of the standard formulation used in the fertigation forest nurseries.

<table>
<thead>
<tr>
<th>Fertilizers</th>
<th>Conc. (g L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium nitrate</td>
<td>0.87</td>
</tr>
<tr>
<td>MAP (Monoammonium phosphate)</td>
<td>0.21</td>
</tr>
<tr>
<td>Potassium chloride</td>
<td>0.47</td>
</tr>
<tr>
<td>Ammonia sulfate</td>
<td>0.11</td>
</tr>
<tr>
<td>Urea</td>
<td>0.54</td>
</tr>
<tr>
<td>Magnesium sulfate</td>
<td>0.52</td>
</tr>
<tr>
<td>Iron 13%</td>
<td>0.03</td>
</tr>
<tr>
<td>Boric acid</td>
<td>6.00</td>
</tr>
<tr>
<td>Cooper sulfate</td>
<td>0.60</td>
</tr>
<tr>
<td>Zinc sulfate</td>
<td>1.40</td>
</tr>
<tr>
<td>Manganese sulfate</td>
<td>6.00</td>
</tr>
<tr>
<td>Sodium molybdate</td>
<td>0.16</td>
</tr>
<tr>
<td>pH</td>
<td>6.22</td>
</tr>
<tr>
<td>EC (mS⁻¹)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The Venturi system dilution factor was used to calculate quantities of the utilized fertilizers.

The experiment was conducted by a factorial arrangement 3 × 4 entirely randomized outline (i.e., three substrate types × four fertigation doses), totaling 12 treatments. Each treatment had three repetitions with 20 seedlings, counting 60 seedlings per treatment. The arboreal native species *P. dubium* was selected for the present study, which has orthodox
seeds with tegmental dormancy. The seed dormancy was broken through thermal shock with 92 °C hot water, and seeds were later transferred to cold water for 24 h [23,24]. After this process, the seeds were planted in tubes with the substrate.

The sewage sludge was sieved through 5.5 mm granulometry to remove larger detritus. Posteriorly, the biosolid was moisturized with water, homogenized through the concrete mixer, and later used to fill the plastic tubes. Each tube received two seeds of P. dubium, posteriorly disposed in trays and stored in a bed with 50% shade for germination. The tubes remained in the bed for approximately 60 days to germinate the seedlings. Posteriorly, the seedlings were separated into beds with transparent plastic to receive each treatment. The irrigation consisted of a 12 mm water blade with a twice-daily frequency [25].

The aerial height and the stem diameter were measured monthly with a centimeter-graded ruler and a digital pachymeter (0.01 mm), respectively. At the end of the experiment, the seedlings’ aerial part (stalk and leaf) and root were separated from drying in a stove at 65 °C for 72 h to obtain the aerial dry mass (MSA), root dry mass, and total dry mass. Posteriorly, the dried material was weighed on an analytical scale (0.001 g precision) for chemical analysis.

Data Analysis

The total dry mass was calculated by adding the aerial dry mass and root dry mass values. Accumulation of each plant nutrient was acquired from the nutrient values content and plant biomass. The Dickson Quality Index (DQI) [26] was calculated to evaluate the seedling quality by the following Equation (1):

\[
DQI = \frac{\text{Total dry mass}}{\text{Aerial height} + \text{Aerial dry mass} + \text{Root dry mass}} 
\]

The variance analysis (ANOVA) of seedling growth variables was verified using the homogeneity variables and the Shapiro–Wilk normality test, and later the ANOVA and the Scott–Knot (p < 0.05) tests. The levels of one factor within the other were calculated for all variables with interactions between them. The fertigation doses were analyzed by polynomial regressions (quantitative factor) with the rising of measured variables. The statistical analysis was performed using Infostat software v. 2020 [27] and R software 2023.06.1 [28,29].

3. Results

The P. dubium seedlings’ height (Figure 1) was significantly (p < 0.05) correlated with substrate factors and fertigation doses. Thereby, the seedlings’ height growth was higher with zero fertigation dose and sewage sludge composted with eucalyptus bark (SEB). With the standard (1×) and quadruplicated (4×) doses produced with commercial substrate (CS) and SEB, the seedling heights were similar. The growth of seedlings planted with the SEB and duplicated (2×) dose was notable. Nonetheless, the seedling’s height in all the substrates was higher with the 4× and 1× treatments, respectively.

The height vs. fertigation dose relationship is better described by a polynomial regressions function. In particular, the seedling height reached by plants growing on the SC (Figure 2a) substrate shows an increasing trend with the increase in fertigation doses. On the SC substrate, the maximum plant height was reached at a 3.3× dose, with seedlings of 24 cm. For SSB (Figure 2b) the same dose (3.3×) showed the maximum plant height (20.5 cm). On the SEB substrate (Figure 2c) the maximum height of 23.5 cm was observed with the 4× dose.
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Figure 1. Interactions of fertigation doses with substrates in *P. dubium* seedling heights after 150 days of sowing. Mean values in the boxplot (red asterisk) followed by the same lowercase letter (fertigation doses) or uppercase letter (substrate) did not differ according to the Scott–Knot test (*p* < 0.05). Treatments: commercial substrate (CS); SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with *eucalyptus* bark. Zero: no fertigation; 1: standard dose; 2: duplicated dose; 4: quadruplicated dose.

Figure 2. Polynomial height regression of the *P. dubium* seedlings with different doses of fertigation and produced with the commercial substrate (a) (SC), sewage sludge with sugarcane bagasse (b) (SSB), and sewage sludge with *eucalyptus* bark (c) (SEB).

The variations in the stem diameter variable (Figure 3) were influenced by both the fertigation doses and the used substrate. At increasing fertigation doses, we usually observed a statistically significant (*p* < 0.05) increase passing from 0 to 1, 2, and 4× doses. Looking at the observed differences among investigated substrates, at the 0 dose, the SEB substrate showed a significantly higher stem diameter, as well as at all the other investigated doses (1, 2, 4×), but was similar to CS at 1 and 4× doses. SSB usually showed the worst performances with the relevant exclusion of the 0 dose.

By investigating stem diameter performance (Figure 4a–c) through regression analyses, we observed its increase with the increasing fertigation doses. In particular, the stem diameter of the *P. dubium* seedlings grown in the SC substrate (Figure 4a) reached its maximum value of 6.12 mm at the 3.1× dose. The same dose was responsible for the maximum value (6 mm) reached by *P. dubium* seedlings in the SEB substrate (Figure 4c). The maximum value (5.2 mm) in the SSB substrate was observed for a dose ranging from 2 to 2.5×.
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Figure 3. Interaction between treatments with increasing fertigation doses and the influence on the stem diameter (mm) variable in the production of P. dubium seedlings with 150 days seeding. Boxplot mean values (red asterisk) followed by the same lowercase (fertigation doses) or capital letter (substrates) did not differ according to the Scott–Knott test (p < 0.05). Treatments: CS: commercial substrate; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with eucalyptus bark. Zero: no fertigation; 1: standard dose; 2: duplicated dose; 4: quadruplicated dose.

Figure 4. Polynomial regressions of the stem diameter of P. dubium seedlings in different fertigation doses produced with the commercial substrate (SC), sewage sludge with sugarcane bagasse (SSB), and sewage sludge with eucalyptus bark (SEB).

The height vs. diameter (H/D) ratio varied according to the fertigation doses (Figure 5) and the used substrate. In all investigated cases, i.e., regardless of the used substrate, we clearly observed a significant trend (p < 0.05) as reported: 4× > 2× = 1× > 0. Looking at comparisons among substrates, they usually showed similar performances, with the relevant exception of (i) SEB at the 0 dose, showing a statistically higher (p < 0.05) H/D ratio, and (ii) the 1× dose, where SSB showed the worst performances.

The substrates and fertigation dose factors of the aerial dry mass, root dry mass, and total dry mass variables did not present interactions (Figure 6A,B). However, there was an isolated factor influence. The biomass of the seedlings produced with the SEB substrate (Figure 6A) always showed statistically higher values (p < 0.05) compared to CS and SSB. Both the aerial dry mass (ADM) and total dry mass (TDM) showed the significantly highest (p < 0.05) mean values when the 4× fertigation dose was applied (Figure 6B). The root dry mass presented a statistically similar mean value with all fertigation doses except for the zero dose, showing the lowest mean values.
Figure 5. Height and stem diameter ratio of *P. dubium* seedlings and interactions of each treatment with increasing fertigation doses with the substrates 150 days after seeding. Boxplot mean values (red asterisk) followed by the same lowercase (fertigation doses) or capital letter (substrates) did not differ according to the Scott–Knott test (*p* < 0.05). Treatments: CS: commercial substrate; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with *eucalyptus* bark. Zero: no fertigation; 1: standard dose; 2: duplicated dose; 4: quadruplicated dose.

Figure 6. Interactions between substrates (A) and fertigation doses (B) and the influence on biomass, i.e., aerial dry mass (ADM), root dry mass (RDM), and total dry mass (TDM) (g), of the *P. dubium* seedlings after 150 days of seeding. Boxplot mean values followed by the same lowercase (fertigation doses) did not differ according to the Scott–Knott test (*p* < 0.05). Treatments: CS: commercial substrate; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with *eucalyptus* bark. Zero: no fertigation; 1: standard dose; 2: duplicated dose; 4: quadruplicated dose.

The polynomial regressions showed that the total dry mass of seedlings produced with SEB and CS increased with the fertigation doses. In particular, at the 3.0× dose, the maximum values were observed for both substrates, by reaching 6.83 g and 6.6 g, respectively (Figure 7a–c). The regression of the SEB substrate showed that the standard (0×) and 4× doses were more favorable in promoting an increase in seedling height, nearing the maximum point of the regression series.
The total dry mass (Table 3) of the seedlings produced in the SEB substrate usually showed higher Ca and S macronutrient contents; SEB together with CS also featured significantly (p < 0.05) higher N, P, K, and Mg content when compared to SSB. The 4× fertigation dose always corresponded with the significantly highest (N, K, and S) macro- and micronutrient dry mass accumulation. Also, for B, Cu, Mn, and Na, the SEB substrate showed the highest or comparable (with CS and SSB for Fe, with SSB for Zn) micronutrient contents. Looking at the fertigation doses, the observed results are quite dependent on the applied dose. Indeed, the highest dose (4.0×) corresponds to the highest B values, while the same dose showed comparable Mn and Zn contents to the 1.0, 2.0×, and 0–2.0× doses, respectively. Copper and Fe reached their highest at the 2.0× applied doses, while Na did so at the 1.0× dose.

**Table 3.** Macro- and micronutrient accumulation in total dry mass of the *Peltophorum dubium* seedlings 150 days after seeding.

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Total Dry Mass: Macronutrient Accumulation (g Plant⁻¹)</th>
<th>Total Dry Mass: Micronutrient Accumulation (mg Plant⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>N: 163.3 a, P: 16.3 a, K: 107.1 a, Mg: 47.8 b, S: 23.0 a</td>
<td>B: 4.5 d, Cu: 15.9 b, Fe: 105.0 b, Mn: 60.4 a, Zn: 21.0 b</td>
</tr>
<tr>
<td>SSB</td>
<td>N: 123.0 b, P: 11.3 b, K: 78.6 b, Mg: 41.0 b, S: 14.8 b</td>
<td>B: 151.1 c, Cu: 175.8 b, Fe: 112.0 b, Mn: 57.7 a, Zn: 24.6 a</td>
</tr>
<tr>
<td>SEB</td>
<td>N: 166.4 a, P: 16.5 a, K: 105.1 a, Mg: 67.3 a, S: 20.0 a</td>
<td>B: 242.9 a, Cu: 186.8 a, Fe: 138.8 a, Mn: 62.0 a, Zn: 24.8 a</td>
</tr>
<tr>
<td>Fertilization Doses</td>
<td>N, P, K, Mg, S</td>
<td>B, Cu, Fe, Mn, Zn, Na</td>
</tr>
<tr>
<td>Zero</td>
<td>N: 34.0 d, P: 4.5 c, K: 32.2 c, Mg: 28.0 b, S: 6.1 c</td>
<td>B: 32.2 c, Cu: 105.0 b, Fe: 60.4 a, Mn: 21.0 b, Zn: 20.3 b</td>
</tr>
<tr>
<td>1×</td>
<td>N: 151.1 c, P: 15.9 b, K: 105.0 b, Mg: 60.4 a, S: 21.0 b</td>
<td>B: 175.8 b, Cu: 112.0 b, Fe: 57.7 a, Mn: 24.6 a, Zn: 21.3 b</td>
</tr>
<tr>
<td>2×</td>
<td>N: 242.9 a, P: 19.7 a, K: 138.8 a, Mg: 62.0 a, S: 24.8 a</td>
<td>B: 362.0 a, Cu: 7261.8 a, Fe: 672.7 a, Mn: 606.2 a, Zn: 5865.3 a</td>
</tr>
</tbody>
</table>
| CV         | 11.9% 21.1% 11.0% 17.2% 19.4% 26.3% | Mean values followed by the same lowercase, and line per stem do not differ according to the Scott–Knott test (p < 0.05). CS: commercial substrate; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with *eucalyptus* bark. Zero: no fertigation; 1×: standard dose; 2×: duplicated dose; 4×: quadruplicated dose. Coefficient of variation (CV).
4. Discussion

The substrate’s physical analysis showed that the SEB biosolid presented the highest microporosity and water retention. The eucalyptus bark, as it fragmented and decomposed during the composting process, generated fine particles that increased the density of the substrate. This density directly influences water retention, absorption of macronutrients and micronutrients, available water, electrical conductivity, and important physical–chemical features, thus influencing the initial seedlings’ growth [30].

Although CSS, the SSB substrate, presented the highest percentage of macroporosity and the lowest water retention capacity, the low nutritional value and fibers were not altered during the composting process, resulting in a porous substrate with a low water retention capacity, unfavorable for producing P. dubium seedlings.

Except for P, K, and Cu, the amounts of nutrients analyzed in the chemical analysis of the substrates were consistently higher in the SEB substrate. It is expected that sewage-sludge-based biosolids have high macro- and micronutrient concentrations [31]. In contrast, commercial substrates (CSs) tend to be inert [25]. The high P and K amounts observed in CSs are due to the well-known presence of superphosphate added during its development process, mixed with carbonized rice husks, i.e., a potassium-rich material [32].

The eucalyptus bark shows adequate Ca, K, Mg, Na, Mn, and Fe concentrations. Generally, Ca is the element with the highest availability (82–95%), followed by Mg and K (i.e., Ca > K > N > Mg > P), respectively [33]. The high concentrations of Ca in the eucalyptus bark are related to its lower mobility in the phloem and a structural component of the cell membrane [34]. Organic substrates usually contain more nutrients than commercial substrates [35], providing better use of nutrients and mineral fertilization by plants since [36,37] (i) they chemically are in organic form, thus (ii) being gradually released, a feature that (iii) effectively supplies the plant’s nutritional needs during the whole biological cycle. Additionally, due to their high availability, organic substrates are a low-cost commercial alternative [38].

The pH and electrical conductivity are pivotal features of every substrate used in seedling nurseries [39]. The pH of the investigated substrates ranged from 6.1 to 6.8 before fertigation. As expected (Table 2), the pH slightly increased once fertilization was applied, ranging from 6.3 to 7.1. According to Cacini et al. [40], the pH of organic substrates should range from 5.0 to 6.5, a variation favoring both plant growth and nutrient absorption capacity in the substrate. Our results partially disagree with those observed by the previous author. As a matter of fact, the investigated substrates had a pH slightly above that “recommended” by the author before and after fertigation. Despite this, except for zero doses and the SSB substrate, all treatments produced seedlings with satisfactory development. This demonstrates that organic substrates made with the reuse of by-products are less restrictive regarding pH ranges for plant seedling growth, thus being more adaptable for commercial uses.

The electrical conductivity records the concentration of ionized salts in the solution. Saline stress can affect water absorption and nutrients, altering plant metabolism [41]. Yet, high electrical conductivity values are generally observed in sewage-sludge-based substrates due to the high content of nutrients and organic matter [42]. However, in all investigated substrates, an adequate electrical conductivity for the growth of the plant’s seedlings (<1.0 mS cm\(^{-1}\)) [43] was observed.

Overall, the SEB substrate shows comparable vegetation growths with CS. More specifically, the height of the seedlings showed higher mean values when produced with SEB. Yet, the SEB and CS substrates showed similar mean values for the seedlings produced with the standard and highest doses (4\(\times\)). Additionally, all the observed height values are within the range determined by Silva et al. [43], where seedlings of native species showed a height ranging from 20 to 35 cm. As the fertigation dose increased, the height of the P. dubium seedlings also increased, which confirmed its nutritional requirement [44].

Regarding the stem diameters, the seedlings produced in SEB presented the highest growth. With the standard and 4\(\times\) doses, the CS and the SEB showed similar mean values,
while they performed better than SSB. According to Gonçalves et al. (2000) [43], seedlings of native species should present a stem diameter between 5 and 10 mm. Therefore, except for the zero dose, all substrates produced seedlings with adequate stem diameters, although the SEB substrate provided the seedlings with the highest mean values.

The seedlings produced with the SEB substrate presented the highest H/D ratio mean values. The observed H/D ratio values of all treatments gave a mean below 10, regardless of the substrate, including seedlings produced with zero doses, which is considered adequate according to Cargnelutti Filho et al. (2018) [45]. The H/D ratio represents the seedling development capacity. Therefore, lower values characterize superior seedling quality and survival capacity in the field.

The SEB compost presented the highest nutrient concentration from the beginning of the experiment, as reflected by both the chemical analysis and seedlings’ growth in terms of height and diameter. Consequently, this substrate produced a greater biomass of aerial and root parts, presenting superior development compared to the seedlings planted in all the other investigated substrates. The total dry mass is an essential morphological variable to estimate seedlings’ survival and initial growth in the field since a well-developed seedling is more resistant to edaphic adversities [46]. Furthermore, Alonso et al. (2017) [46] also observed that seedlings of three native species (i.e., *P. dubium* (Springer.) Taub. (Dry flour), *Lafoensia pacari* A. St.-Hil. (Foxglove) and *Ceiba speciosa* (A. St.-Hil.) Ravenna (Paineira)) showed a higher amount of aerial and root biomass when produced in sewage sludge composted with clayey soil and sand compared to the control substrate.

The processed sewage sludge, commonly named biosolid, contains high macronutrient, especially N, P, Ca, and Mg, and organic matter contents [25]. However, seedlings produced at zero doses did not reach height and diameter growth within the parameters defined by Gonçalves et al. [43], requiring supplementation with chemical fertilization via fertigation. Although raw sewage sludge contains high amounts of nutrients, the dilution effect may occur during composting [42]. According to Rocha et al. (2013) [47], the accumulation of nutrients in composted sewage sludge is insufficient for initial seedling growth, requiring fertilizers. The height and stem diameter of *P. dubium* seedlings improved as the fertigation doses gradually increased. With 150 days of seeding, the highest accumulation of nutrients was observed in their aerial part. These results corroborate the data obtained by Gonçalves et al. (1992) [48], where the seedlings of *P. dubium* at 128 days had higher concentrations of nutrients in the aerial part. Also, at 150 days, the accumulation of macro- and micronutrients in the aerial part of the seedlings was within the suitable standards, according to Malavolta et al. (1997) [49].

The accumulation of N observed in the total mass of seedlings produced with CS and SEB was more significant than in those made with SSB. According to Trigueiro and Guerrini [42], N is usually the most abundant nutrient in sewage sludge. It is the most critical compost required by plants, acting directly in the growth process [50].

Furthermore, the growth of seedlings was reduced with the lower fertigation doses by the omission of P. According to Souza et al. (2013) [51], *P. dubium* has growth limitations in terms of height and diameter in the absence of N, K, S, Ca, Mg, B, and Zn since the seedlings’ demand for N and P is more significant in the initial seeding stages, which act in the initial growth of height and diameter [32].

The Dickson Quality Index (*DQI*) [26] is the most reliable parameter for assessing seedling quality, which calculates the main morphological variables. The *DQI* (Table 4) demonstrated that the seedlings produced with SEB had the best rate compared to those made with CS and SSB. Although the seedlings subjected to the 4× dose stood out in most of the variables analyzed, the *DQI* proved that the standard and 2× doses formed the best-quality seedlings. Nonetheless, the standard dose is more advantageous regarding the economy of chemical fertilizers for seedling producers.
Table 4. Dickson Quality Index (DQI) of the seedlings of *P. dubium* per treatment, 150 days after seeding.

<table>
<thead>
<tr>
<th>Substrates</th>
<th>DQI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0.739</td>
</tr>
<tr>
<td>SSB</td>
<td>0.631</td>
</tr>
<tr>
<td>SEB</td>
<td>0.856</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fertigation Doses</th>
<th>DQI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>0.678</td>
</tr>
<tr>
<td>1x</td>
<td>0.808</td>
</tr>
<tr>
<td>2x</td>
<td>0.777</td>
</tr>
<tr>
<td>4x</td>
<td>0.705</td>
</tr>
</tbody>
</table>

CV (%) 29.5

Mean values followed by the same lowercase, and line per stem do not differ according to the Scott–Knott test (*p* < 0.05). CS: commercial substrate; SSB: sewage sludge composted with sugarcane bagasse; SEB: sewage sludge composted with *eucalyptus* bark. Zero: no fertigation; 1 ×: standard dose; 2 ×: duplicated dose; 4 ×: quadruplicated dose. Coefficient of variation (CV).

Seedling quality is directly associated with the field’s capacity for development and endurance [51]. Consequently, understanding the nutritional requirements of native forest species would optimize their management and the availability of nutrients [52].

The obtained outcomes show that the sewage sludge composted with *eucalyptus* bark (SEB) performed best in most investigated parameters. From an environmental perspective, the SEB substrate is the most efficient in *P. dubium* seedling production, being a promising alternative for the productive and commercial reuse of this residue instead of its landfill disposal. Moreover, SEB substrate would assist in the rising demand for seedlings of native plants to recover degraded areas [53]. As a matter of fact, seedling production represents an essential cost in soil restoration through reforestation programs [4]. One of the costs most affecting the overall commercial balance is represented by the use of commercial substrate [32]. Thus, by using by-products, this significant cost can be strongly reduced, making soil recovery and reforestation programs more feasible.

5. Conclusions

The seedlings produced with SEB presented better performances for most of the investigated parameters. Although seedlings planted in the substrate with the 4.0 × fertigation dose showed interesting performances too, the Dickson Quality Index confirmed that the seedlings produced with SEB substrate, supplemented with a 2.0 × dose, presented the highest quality. Thus, composted sewage sludge with *eucalyptus* bark at the standard dose represents the most suitable substrate for *P. dubium* seedling production. The experiment demonstrated that sewage sludge combined with natural by-products (*eucalyptus* bark, in this case) represents a highly recommendable substrate in commercial seedling production. More specifically, the seedlings produced with SEB demonstrated similar productivity performance to those produced with commercial fertilizers. This approach could represent an efficient alternative to improve nursery forestry, reducing traditional inputs (chemical fertilizers) and bringing positive socio-economic, environmental, and health effects.


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