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Sustainable Management of Wastewater Sludge Through Composting with Effective Microorganisms: Enhancing the Growth of *Tecoma stans*

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Abstract: The mismanagement of sewage sludge generated by wastewater treatment plants poses significant environmental and health risks, necessitating the exploration of sustainable alternatives for its reuse in forestry production. This study aims to assess the impact of sewage sludge stabilization and composting, utilizing effective microorganisms (EM), on the growth performance of *Tecoma stans*. A completely randomized experimental design was implemented in two phases. In the first phase, four treatments were tested with 12 kg of mixture in each: Treatment 1 (T1) (100% sludge with EM), Treatment 2 (T2) (75% sludge and 25% organic waste with EM), Treatment 3 (T3) (50% sludge and 50% organic waste with EM), and Treatment 4 (T4) (25% sludge and 75% organic waste with EM). The second phase involved testing five composite substrates, mixing agricultural soil with compost derived from each treatment and a control substrate, for the cultivation of *Tecoma stans* seedlings. Each substrate was tested with 20 experimental units, containing 15 seedlings per unit, totaling 300 seedlings. T3 demonstrated superior results in the first phase, containing 34.78% organic matter, 1.39% nitrogen, a carbon/nitrogen (C/N) ratio of 14.7, and a pH of 7.4, adhering to Chilean, Food and Agriculture Organization (FAO), and Mexican standards. In the second phase, T3 exhibited enhanced seedling growth, with an optimal nitrogen concentration and a Dickson quality index (DQI) of 0.768. The findings suggest that composting sewage sludge with organic residues in equal proportions and inoculating with EM produces mature, high-quality compost that meets international standards for forestry applications. This approach offers a sustainable solution for wastewater sludge management, promoting environmental restoration and supporting local forestry development.

Keywords: Effective microorganisms; Stabilization; Dickson quality index; Forestry; Soil substrates; Sewage sludge management; Composting; *Tecoma stans*; Environmental impact

1. Introduction

In recent decades, the continuous global urban growth has led to increased production of activated sludge from wastewater treatment plants (Cockburn et al., 2023). This represents a challenge, as inadequate management of this activated sludge brings negative consequences to the local environment, such as soil and water contamination and eutrophication, especially health risks due to pathogens, parasites, and harmful chemicals (Li et al., 2024a).

To counteract and mitigate the negative impacts of this problem, it is essential to implement sustainable alternatives for managing this waste and avoiding its uncontrolled disposal (Rosas-Vargas & Ramón-Valencia, 2020). One promising option is composting, which allows sludge to be turned into a valuable resource for agriculture and gardening; however, key parameters must be controlled to ensure the quality and safety of the compost (Kelley et al., 2022). Previous studies have shown that the incorporation of EM into composting significantly improves compost quality, as evidenced by research on soil improvement and the restoration of degraded ecosystems (Greff et al., 2022; Wang et al., 2024).

The incorporation of EM, such as bacteria and yeasts, optimizes the composting process and the final product while improving the physical, chemical, and biological properties of the compost. In addition, it mitigates sanitary risks after the elimination of harmful microorganisms by displacing pathogens and phytopathogens (Bonetta et al., 2022).

The addition of compost to the soil has a significant impact on its physical, chemical, and organic characteristics (Sharaf et al., 2021), promoting ideal nutrient cycling that enhances the ability of vegetation to grow and establish. Therefore, using compost in agricultural soils is considered a reliable strategy for improving the physical characteristics of most crops, particularly those with a poor structure and low levels of organic matter (Kranz et al., 2020).

It is essential to conduct comprehensive research to determine the potential effect of sewage sludge composting on agricultural and forestry production (Wang et al., 2018). Many studies have indicated a trend toward recognizing sewage sludge composting as an integral practice for improving industrial (Zambrano Riquelme et al., 2023), agricultural (da Silva et al., 2021; Li et al., 2024b), and forestry (Siqueira et al., 2017) production, environmental restoration, and local economic development (Bacilio-Jiménez et al., 2022). However, the ongoing need for detailed research has also been emphasized to optimize composting techniques, assess long-term effects on ecosystems, and promote effective implementation at practical and policy levels (Nguyen et al., 2022).

This study allows to fully leverage the benefits of sewage sludge treatment and its application in the cultivation of locally important forest plants. By integrating these approaches, the advantages of both sludge treatment and forest production can be maximized, leading to more sustainable waste management and boosting the production of native plants. In this way, the study contributes to the sustainable management of residual sludge while enhancing the forest production of native species such as *Tecoma stans*, thereby strengthening not only environmental conservation but also local economic development. This, in turn, has a positive impact on both the environment and the local economy.

This study aims to implement a process of stabilization and composting of sewage sludge by incorporating EM, thereby thoroughly evaluating the quality of the resulting compost pursuant to three international standards, i.e., Chilean Standard NCh2880, Mexican Standard NMx-AA-180-SCF and the criteria proposed by FAO (Dirección General de Normas, 2018; Román et al., 2013; SAG, 2011). In addition, this study aims to determine the influence of the compost obtained on the DQI on seedlings of the native species Tecoma stans through a rigorous quantitative analysis (Bacilio-Jiménez et al., 2022).

2. Materials and Methods

2.1 Experimental Design

The experiment was conducted in the composting area of the municipal garden center in the Viques District, located in the Huancayo Province, Junín Department, Peru. Viques is located at coordinates of 12° 09′ 44″ S and 75° 13′ 45″ W in the southeast of the Mantaro Valley at an altitude of 3314 m.a.s.l. This geographical location in the central Andean region of Peru provides optimal environmental conditions for the experimental composting research. The cold and dry climate is favorable for the controlled process and adequate growth of the native species evaluated, in addition to being able to be replicated in cities with similar characteristics, Ecuador and Bolivia, among others (Ccopi-Trucios et al., 2023).

A completely randomized experimental design divided into two stages was implemented. In the first stage, four stabilization and composting treatments of sewage sludge were used, each consisting of 12 kg of mixture. T1 included 100% sewage sludge with EM (12 kg of sludge); T2 consisted of 75% sewage sludge and 25% organic waste with EM (9 kg of sludge and 3 kg of organic waste); T3 comprised 50% sewage sludge and 50% organic waste with EM (6 kg of sludge and 6 kg of organic waste); and T4 was made up of 25% sewage sludge and 75% organic waste with EM (3 kg of sludge and 9 kg of organic waste). For the second stage, five treatments were used to evaluate the effect of different substrates on the quality index of *Tecoma stans* seedlings.

2.2 Composting Process

During the composting process and its subsequent efficiency evaluation, various specialized tools and materials were used. In the field, a plastic sheet of 1 m × 8 m (width × length) was used to form the base of the compost beds, which was secured with ½ inch nails. Additionally, 16 specific containers were used for composting, where the experimental process was conducted. To ensure precise parameter measurements, instruments such as a caliper and a cutter were employed.

Regarding the materials, a 0.01 g precision scale was used for weighing samples, manila envelopes, EM and microorganism nourishment in the form of cane molasses to stimulate the decomposition process (Álvarez-Sánchez et al., 2021). Distilled water was used to avoid chlorine to maintain optimal conditions for microorganisms without inhibiting them. Sewage sludge was extracted from a treatment plant with local oxidation lagoons. Crushed fruit and vegetable waste from nearby markets were essential components for the composting and were incorporated into the compost bins.

Once obtaining the sewage sludge from the oxidation ponds of the water treatment plant in the Viques District, it was mixed and previously conditioned to facilitate its handling. Crushed organic waste collected from local markets was used as complementary material for composting.

To activate the EM, a specific FAO process was followed (Román et al., 2013) by using cane molasses and distilled water in a closed container. This activation process was performed one week prior to the collection of the crushed organic waste and sewage sludge. Regarding the sludge, it was properly conditioned, including the removal of part of the moisture and the reduction of its compaction to facilitate its handling. Then, the treatments were prepared, interspersing layers of sewage sludge and organic waste in the compost beds along with the addition of EM.

During the composting process, EM was applied three times at 30-day intervals to stabilize key parameters such as organic matter, nitrogen, and pH of the sewage sludge. Periodic analyses were conducted to measure the concentration of organic matter, nitrogen levels, and pH of the compost at different stages of the process. These analyses included gravimetric analysis for organic matter, and pH measurements using a pH meter. This process involved carefully planned work that included microorganism activation, sludge conditioning and periodic applications for three months to attain successful stabilization.

Compost analyses were conducted at 30, 60, and 90 days after the composting process began, allowing for the monitoring of key quality parameters such as the C/N ratio, pH, organic matter content, and total nitrogen, following international standards such as the Chilean Standard NCh2880, the Mexican Standard NMX-AA-180-SCF, and the criteria proposed by the FAO (Román et al., 2013). PH, organic matter content, and nitrogen levels were measured at these intervals. Samples were analyzed in the soil laboratory of the Santa Ana Experimental Station of the National Institute of Agricultural Innovation (INIA). The C/N ratio was determined through elemental analysis of carbon and nitrogen; pH was measured using a pH meter; organic matter content was analyzed through high-temperature combustion (gravimetric method); and total nitrogen was determined using a spectrophotometric technique.

2.3 Seedling Evaluation

For the second stage of the study, *Tecoma stans* seeds were collected to assess the effectiveness of compost as a fertilizer for germinated seedlings. Five treatments were established: four based on compost from each stabilization treatment and one control with conventional substrate consisting of 60% arable soil and 40% peat. The control treatment was selected to evaluate the differences with the conventional substrate without the addition of compost, allowing for comparison of the specific effects of the different compost treatments on seedling growth.

In the first stage, substrates were prepared with a composition of 3 parts arable soil, 2 parts compost, and 1 part sand. The treatments were: (T1) 3 parts arable soil + 2 parts compost from T1 (first stage) + 1 part sand; (T2) 3 parts arable soil + 2 parts compost from T2 (first stage) + 1 part sand; (T3) 3 parts arable soil + 2 parts compost from T3 (first stage) + 1 part sand; (T4) 3 parts arable soil + 2 parts compost from T4 (first stage) + 1 part sand; and (T5) control treatment, consisting of common nursery substrate (3 parts arable soil, 2 parts compost, and 1 part sand). The soil analysis revealed a pH of 7.83, an organic matter content of 1.36%, a phosphorus concentration of 2.7 ppm, a potassium concentration of 96 ppm, and a nitrogen content of 0.09%.

Additionally, 20 experimental units were used for each treatment, each consisting of 15 *Tecoma stans* seedlings. Each treatment included 60 seedlings, resulting in a total of 300 seedlings. These were distributed in 7 × 10 cm bags, with 15 bags per experimental unit, totaling 60 bags per treatment.

The seeds of *Tecoma stans* were selected from local specimens in excellent phytosanitary condition, ensuring they met quality criteria in terms of germination and vigor. This process included evaluating characteristics such as seed appearance and size. Sowing was carried out on October 12, 2022, and after 21 days, the seedlings emerged. Fourteen days later, the 300 seedlings, which were 4-6 cm in height, were transplanted individually into the prepared bags. During the two months of experimentation, periodic measurements of seedling height and stem diameter were taken every three days using standardized measuring instruments. A millimeter ruler was used to measure the height, and a digital caliper was used to measure the stem diameter.

Finally, at the end of the experimental phase, which took 60 days after transplanting and 90 days from sowing, the plants were weighed and dried. Four seedlings were selected from each tub, totaling 16 seedlings per treatment. Drying was carried out using a home oven, and weighing was performed with a precision scale, allowing for the calculation of the DQI (Bhattarai et al., 2022) for the samples by considering the morphological and growth characteristics of the seedlings developed in substrates composed of compost from the different sewage sludge stabilization treatments. The following equation was used to calculate the DQI:

$$DQI = \frac{Dw(gr)}{\frac{Th(cm)}{Dn(mm)} + \frac{Dws(gr)}{Drw(gr)}} \tag{1}$$

To evaluate the quality of the compost resulting from each treatment, three international standards were referred to, i.e., the Chilean Standard NCh2880, the Mexican Standard NMx-AA-180-SCF and the one proposed by FAO (Román et al., 2013), which define compost quality criteria based on the parameters above, including organic matter, nitrogen, C/N ratio and pH (Dirección General de Normas, 2018; Román et al., 2013; SAG, 2011).

Once the field and laboratory phases were completed and all necessary data were collected, the data were organized, cleaned, and systematized for analysis. Descriptive statistical of reference analyses were conducted, followed by inferential analyses, including significance tests, mean comparisons using Analysis of Variance (ANOVA), and Tukey's post-hoc test through with the R software (R Core Team). These analyses assessed the effect of different stabilization and composting treatments of sewage sludge on the quality index of *Tecoma stans* seedlings.

3. Results and Discussion

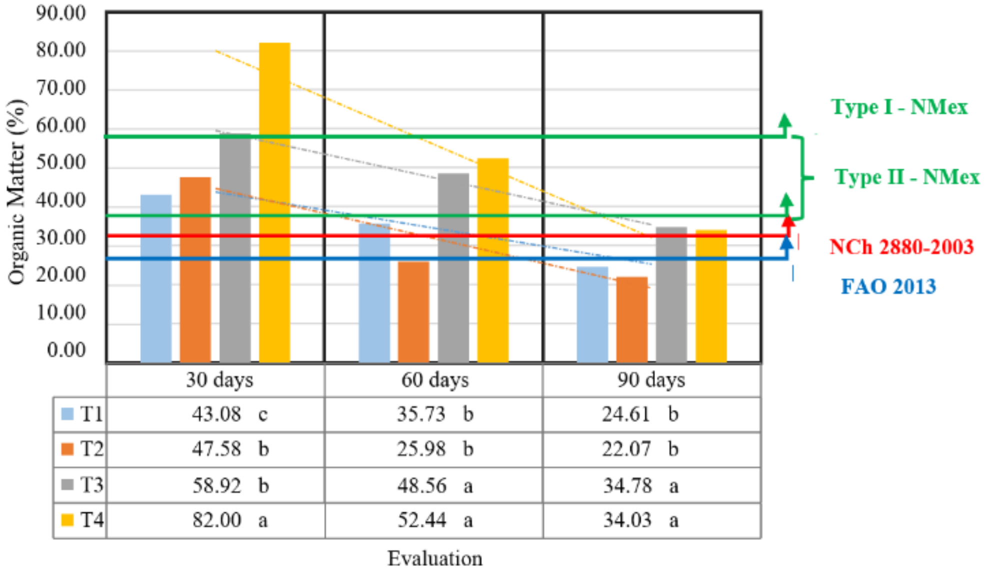
Table 1 shows the ANOVA performed. It can be deduced that there is a significant difference between the means of the sewage sludge stabilization and composting treatments with EM at a significance level of α=0.05.

Table 1. ANOVA for organic matter content after 30, 60, and 90 days after sludge stabilization and composting

Days	Variation Sources	Sum Squared	Degrees of Freedom	Mean Squares	F Calculated	F Tabulated (0.05)
30	Treatment	3632.4	3	1210.8	13.39	3.49
	Error	1084.9	12	90.41	-	-
	Total	4717.8	15	-	-	-
60	Treatment	1765	3	588.33	10.94	3.49
	Error	645.20	12	53.76	-	-
	Total	2410.0	15	-	-	-
90	Treatment	503.97	3	167.99	12.82	3.49
	Error	157.18	12	13.09	-	-
	Total	661.16	15	-	-	-

Figure 1 compares the organic matter content per treatment with three international standards. According to the Chilean Standard NCh2880-2003, T3 at 90 days allowed the obtained compost to be considered class A, with 34.78%, exceeding the 25% required without usage restrictions. When comparing with the Mexican Standard NMx-AA-180-SCFI-2018, T3 and T4 obtained 34.7 and 34%, respectively, within the 30% to 50% range established for type II compost, which can only be used in forest production and soil conditioners. Finally, the T3 compost met the FAO standard by obtaining 34.7%, exceeding the 20% required, which is widely usable in seedlings, nurseries and pots. A significant difference in organic matter content was observed between treatments, evidencing a decreasing trend during composting. These positive results are attributed to the proper activation and periodic application of EM, the C/N ratio, the decomposition of organic matter, and the sanitization of the compost (Domínguez-Gutiérrez et al., 2022). However, further studies are required to determine optimal EM doses and their combination with compost.

The comparison of means in the amount of organic matter after 30 days showed that there was a significant effect and difference between the means of the treatments. The mean of T4 was the highest compared with that of T2 and T3 which did not show a significant difference. Finally, the mean of T1 was the lowest. At the same time, at 60 and 90 days, there was a considerable effect and difference between the mean of the treatments, with T3 and T4 being the highest without showing a significant difference between them, in comparison with T1 and T2 that did not show a significant difference either. Therefore, T3 had a better concentration of organic matter in all cases.



	30 days	60 days	90 days
T1	43.08 c	35.73 b	24.61 b
T2	47.58 b	25.98 b	22.07 b
T3	58.92 b	48.56 a	34.78 a
T4	82.00 a	52.44 a	34.03 a

Figure 1. Comparison of organic matter content per treatment with respect to international standards
Note: Different letters within each experimental site represent significant differences by the Tukey test ($p \leq 0.05$).

These positive results were caused by the correct activation and periodic application of EM that balanced the C/N ratio, the decomposition of organic matter and the sanitization of the compost as discussed by Greff et al. (2022). Furthermore, the decreasing trend of organic matter content during the composting shows the progressive mineralization of the organic substrate (Domínguez-Gutiérrez et al., 2022).

However, more studies are required to determine optimal doses of EM and its combination with compost to maximize quality for agroecological and forestry purposes. However, there is superficial work on this quality improvement, as shown by Panisson et al. (2021). Likewise, the effects of compost on other physicochemical and biological parameters of the soil, as well as on plant health and yield of various crops, must be evaluated not only for forest species but also with staple crops such as fruits and vegetables, which are more sensitive to changes and effects of compost. However, there are excellent achievements and results regarding the growth of these crops (Machado et al., 2021).

The ANOVA in Table 2 confirms the existence of statistically significant differences between treatments concerning total nitrogen content after 30, 60 and 90 days of composting. This indicates that incorporating different proportions of EM and organic waste in the treatments had a differential effect on nitrogen dynamics during the stabilization and composting processes.

Table 2. ANOVA for total nitrogen after 30, 60, and 90 days after sludge stabilization and composting

Days	Variation Sources	Sum Squared	Degrees of Freedom	Mean Squares	F Calculated	F Tabulated (0.05)
30	Treatment	20.71	3	6.90	-	-
	Error	2.197	12	0.18	37.69	3.49
	Total	22.91	15	-		
60	Treatment	6.58	3	2.19	-	-
	Error	0.35	12	0.03	75.34	3.49
	Total	6.93	15	-		
90	Treatment	4.86	3	1.62	-	-
	Error	0.31	12	0.03	63.47	3.49
	Total	5.17	15	-		

Figure 2 shows the results of total nitrogen in the compost after 30, 60, and 90 days of composting. Initially, a wide range of values was observed between treatments, from 3.42% in T4 to 0.32% in T1. During the process, there was a trend towards stabilization of nitrogen content, with less dramatic differences between treatments at the end of the experiment (2.02% in T4 and 0.59% in T1 at 90 days). These results show the effect of mineralization of organic matter and the volatilization of nitrogenous forms during the composting (Sommer, 2001), reaching relatively uniform values among the different treatments when obtaining a mature compost. The Tukey test showed significant differences among the means of total nitrogen of the treatments. T4 showed the highest average nitrogen content, statistically differing from the rest. T2 and T3 showed similar means to each other, while T1 obtained significantly lower nitrogen concentration. These results of the comparison of means confirm the differential effect of the proportions of organic inputs and EM used in each treatment on the dynamics and retention of nitrogen during sewage sludge composting.

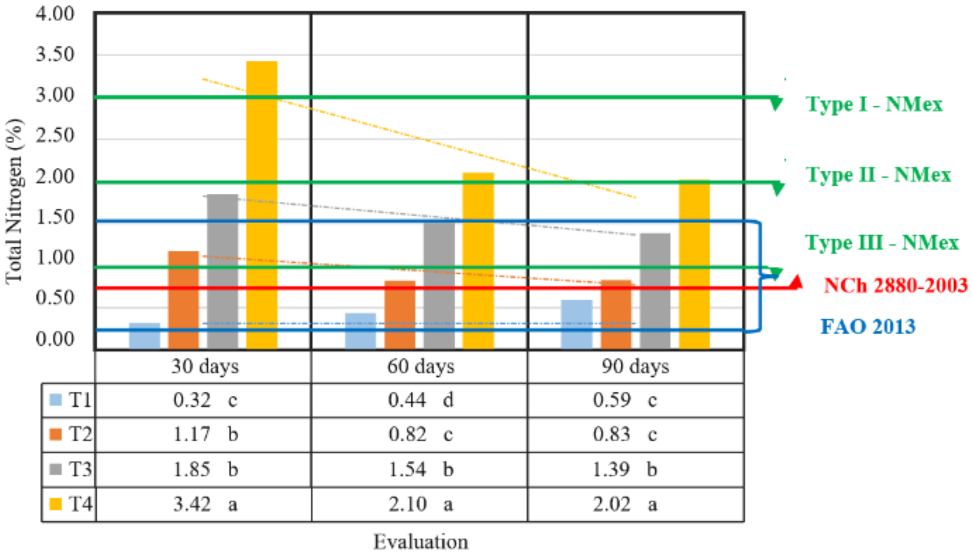


Figure 2. Comparison of total nitrogen content per treatment with respect to international standards
Note: Different letters within each experimental site represent significant differences by the Tukey test ($p \leq 0.05$).

The resulting compost met the quality standards of the FAO, Mexican, and Chilean norms concerning total nitrogen (Figure 2), confirming the contribution of this nutrient by EM (Morra et al., 2021). However, a decreasing trend of nitrogen was observed in T2, T3, and T4, which is attributable to losses due to volatilization and leaching of this nutrient (Sommer, 2001). In contrast, T1 slightly increased its nitrogen, possibly due to an inadequate initial C/N ratio that prolonged its mineralization (Machado et al., 2021). Improving nitrogen availability during composting requires adjusting the EM doses and enhancing the initial C/N ratio; however, the compost obtained demonstrated its usefulness as a nitrogen fertilizer for agricultural and forestry species (Sayara et al., 2020).

The ANOVA (Table 3) indicated the existence of statistically significant differences between treatment means regarding the C/N ratio after 30, 60, and 90 days of composting ($p \leq 0.05$). This confirms that the different proportions of organic inputs and EM used in each treatment had a differential effect on the C/N balance during the stabilization and composting of the sewage sludge. Monitoring over three periods made it possible to evaluate the evolution of the differences in the C/N ratio as the composting process progressed.

Table 3. ANOVA of the C/N ratio after 30, 60, and 90 days after sludge stabilization and composting

Days	Variation Sources	Sum Squared	Degrees of Freedom	Mean Squares	F Calculated	F Tabulated (0.05)
30	Treatment	11902.57	3	3967.52	35.66	3.49
	Error	1334.77	12	111.23		
	Total	13237.35	15	-		
60	Treatment	2837.44	3	945.81	86.57	3.49
	Error	131.10	12	10.92		
	Total	2968.54	15	-		
90	Treatment	446.85	3	148.95	24.44	3.49
	Error	73.11	12	6.09		
	Total	519.963	15	-		

Figure 3 shows the results after 30, 60, and 90 days of the sewage sludge stabilization and composting treatments with EM with respect to the C/N ratio. After 30 days, the initial C/N ratio in T1 was excessively high (81.44), indicating a nitrogen deficiency and a slow decomposition of organic matter. Likewise, T2 and T3 presented an appropriate initial C/N ratio between 20-40, which favored efficient composting. T4 treatment had a very low C/N ratio (14), with an excess of nitrogen that could cause volatilization losses. In all cases, there was a decrease in the C/N ratio during composting over the days, evidencing the mineralization of organic matter (Manu et al., 2021). T2 and T3 reached final C/N values (15.2 and 14.7) within the optimal range for a mature compost, while T1 ended with a still high C/N ratio (24.4), indicating immature compost. Finally, T4 ended with a compost with excess nitrogen (C/N = 9.8).

The C/N ratio of the compost obtained showed significant differences among treatments. T2 and T3 achieved an adequate final C/N ratio of 15.2 and 14.7, respectively, meeting the mature compost standards of the three regulations. This is attributed to an initial balanced C/N ratio of 20-40, which optimized the decomposition of organic matter and the activity of the inoculated EM (Kalamdhad & Kazmi, 2009).

The mean comparison test showed significant differences in the C/N ratio among treatments after 30, 60 and 90 days. T1 offered consistently higher means (denoted by the letter *a*), thus differentiating it from the rest. T2, T3 and T4 showed similar means to each other at the different evaluated times, with no statistically significant differences. These results confirm that the proportion of sewage sludge and organic waste used in T1 resulted in an imbalance of the C/N balance. In contrast, the other therapies stabilized an adequate C/N ratio during the composting.

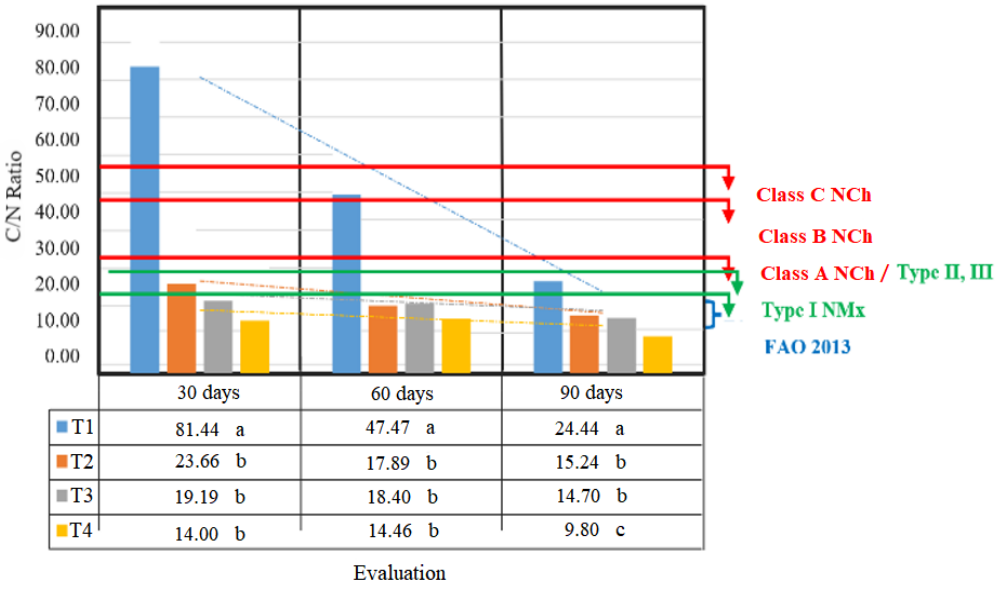


Figure 3. Comparison of C/N ratio per treatment with respect to international standards
Note: Different letters within each experimental site represent significant differences by the Tukey test ($p \leq 0.05$).

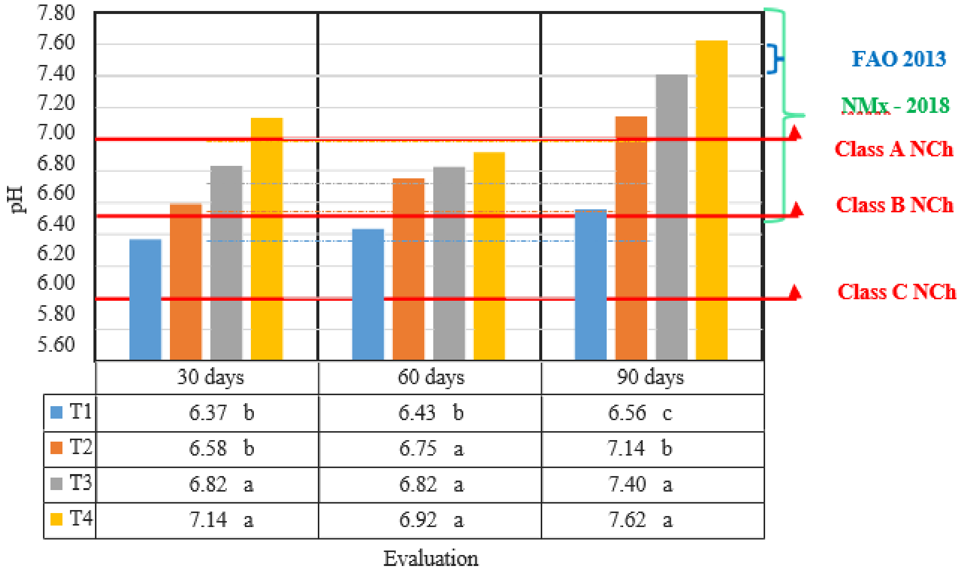
T1 maintained a high C/N value of 24.4 at the end of composting, indicating immaturity due to an increased initial C/N ratio of 81.4 that limited nitrogen availability. On the other hand, in T4, the very low initial C/N of 14 produced a compost with excess nitrogen (final C/N of 9.8), probably due to losses of nitrogen in ammoniacal form, similar to those obtained by other authors (Chen et al., 2021). In addition, it is understood that it is necessary to determine adequate proportions of organic waste and sludge to achieve a balanced initial C/N ratio of 20 to 30, which guarantees obtaining a superior quality compost according to international standards.

In Table 4, as the calculated F values are greater than the tabulated F values, it can be deduced that there is a significant difference between the means of the stabilization and composting treatments at a significance level of α=0.05 after 30, 60, and 90 days.

Table 4. ANOVA of pH after 30, 60, and 90 days after sludge stabilization and composting

Days	Variation Sources	Sum Squared	Degrees of Freedom	Mean Squares	F Calculated	F Tabulated (0.05)
30	Treatment	1.301	3	0.43	14.50	3.49
	Error	0.358	12	0.02		
	Total	1.660	15	-		
60	Treatment	0.524	3	0.17	14.11	3.49
	Error	0.148	12	0.01		
	Total	0.673	15	-		
90	Treatment	2.534	3	0.84	61.79	3.49
	Error	0.164	12	0.01		
	Total	2.698	15	-		

Figure 4 shows the average pH results of the compost after 30, 60, and 90 days of treatment. Initially, variability among treatments was observed, with pH values ranging from 7.135 in T4 to 6.368 in T1 after 30 days.



	30 days	60 days	90 days
T1	6.37 b	6.43 b	6.56 c
T2	6.58 b	6.75 a	7.14 b
T3	6.82 a	6.82 a	7.40 a
T4	7.14 a	6.92 a	7.62 a

Figure 4. Comparison of pH per treatment with respect to international standards
Note: Different letters within each experimental site represent significant differences by the Tukey test ($p \leq 0.05$).

As composting progressed, the treatments tended to stabilize in more similar pH ranges, evidencing the buffering effect of EM. At 90 days, the averages ranged from 7.623 in T4 to 6.558 in T1, indicating adequate pH regulation towards neutrality in all treatments at the end of the experiment. These results demonstrate the positive impact of incorporating EM on pH control during sewage sludge composting.

The comparison of pH means after 30, 60 and 90 days shows that there was a significant effect and difference between the means of the stabilization and composting treatments. The means of T2, T3 and T4 were the highest and showed no significant difference between them. However, the means of T1 was the lowest and also showed no significant difference between them.

The pH analysis showed significant differences between treatments at the end of composting, where T2, T3 and T4 reached pH values between 7.1 and 7.6, meeting the optimal pH ranges (6.5-8) concerning the three quality standards. This is attributed to the ability of EM to regulate acidity during the decomposition of organic matter, as confirmed by various researchers (Domínguez-Gutiérrez et al., 2022; Li et al., 2023).

In contrast, T1 had a final pH of 6.6, slightly below the range of mature compost. This could be caused by a high initial C/N ratio that prolonged the production of organic acids and acidified the surrounding environment. Likewise, the lower microbial activity in this treatment may have limited the neutralization of acidity. The excessive acidity in T1 classifies this compost as Class B according to Chilean standards, which is restrictive for certain agricultural uses and pH-sensitive species.

The determination of compost quality is traditionally based on the analysis of physical, chemical and microbiological parameters, especially in Peru, where there are still no technical standards for evaluating sewage sludge compost, even though it is considered a hazardous waste. However, this study showed that the compost from T3 and T4 meets the standards and quality indexes by applying the international standards of Chile, Mexico, and FAO. This is due to the positive effect of EM in controlling key parameters such as organic matter, nitrogen, C/N ratio and pH during composting. The compliance with international criteria indicates the great potential for using this compost as a sustainable organic fertilizer or amendment (Bernal et al., 2017).

It is necessary to develop a national standard for composting sludge from industrial water treatment that considers its various potential uses. In addition, further studies should be conducted to determine optimal EM doses for the composting process to maximize the quality and safety of the final product. Nevertheless, these results set a precedent for promoting the beneficial use of sewage sludge through controlled composting.

Figure 5 shows the calculated DQI data for *Tecoma stans* seedlings, according to the model of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP). A DQI greater than 0.7 indicates high-quality seedlings (Leeabai et al., 2022; Raimi et al., 2024), which confirms the effectiveness of the compost from T3 in enhancing seedling vigor. Regarding plant quality, it is observed that all individuals above the third quartile correspond to high-quality plants; those between the first and third quartiles correspond to medium-quality plants; and those below the first quartile correspond to low-quality plants. Thus, the following estimation of the effect of the produced and evaluated compost was obtained: T3 provided *Tecoma stans* plants with high quality (>0.7058); T2, T4, and T5 provided plants with medium quality (0.3074-0.7058); and T1 provided *Tecoma stans* plants with low quality (<0.3074).

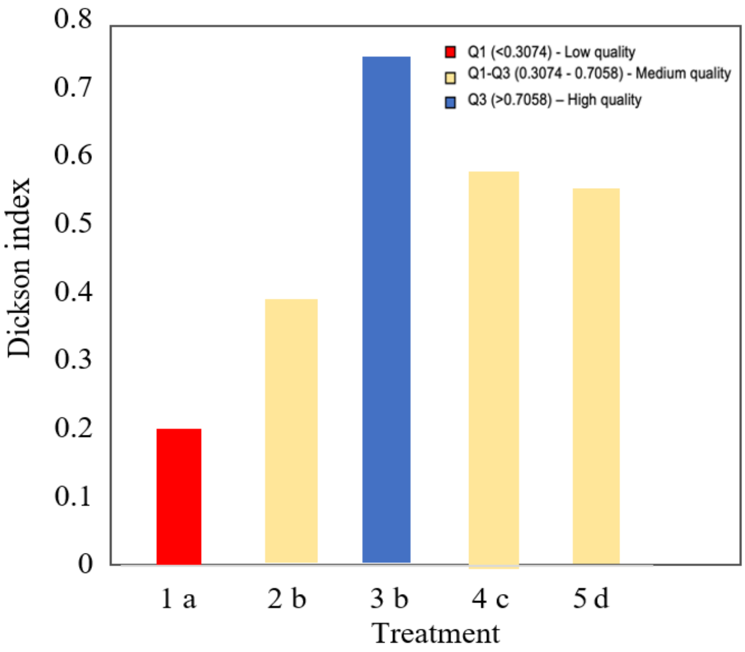


Figure 5. DQI per treatment on *Tecoma stans* seedlings, with T1 (100% residual sludge), T2 (75% residual sludge + 25% organic waste), T3 (50% residual sludge + 50% organic waste), T4 (25% residual sludge + 75% organic waste), and T5 (control treatment)

Note: Different letters within each experimental site represent significant differences by the Tukey test ($p \leq 0.05$).

The comparison of the DQI means showed a significant effect and difference between the treatments. T3 had the highest DQI, followed by T4 and T5 with no significant differences between them. T2 had an intermediate DQI, and T1 had the lowest DQI (Figure 5). This shows significant differences in the DQI among treatments for *Tecoma stans* seedlings. The compost from T3 met the requirements of the Chilean Standard NCh2880, exceeding the 25% organic matter requirement, and complied with the FAO standard regarding the optimal C/N ratio.

This produced higher-quality plants, differentiating it from the rest, while T1 and T2 generated low-quality seedlings. These results are consistent with previous studies that demonstrated improvements in the DQI of seedlings when applying optimized compost with EM in the case of *Pinus pseudostrobus* (Raimi et al., 2024). This confirms the positive effect of a mature and balanced compost in its parameters, such as that obtained in T3, on the growth and development of native species of environmental interest.

4. Conclusions

T3, comprising 50% sewage sludge, 50% organic waste, and EM, stood out with 34.78% organic matter, 1.39% nitrogen, a C/N ratio of 14.7, and a pH of 7.4, met the criteria for category A per Chilean Standard 2880, mature compost per FAO standards, and type II compost according to Mexican Standard 180. Therefore, composting sewage sludge mixed with organic waste and EM in equal proportions produces a mature and quality compost that can be used to improve the quality of *Tecoma stans* seedlings.

The DQI of 0.768 for seedlings from T3 (50% sewage sludge and 50% organic wastes) exhibited high quality and optimal nitrogen concentration. On the other hand, T4 with 25% sewage sludge and 75% organic waste showed the lowest value in the C/N ratio, which would make it impossible to classify the compost according to the minimum values established in the three evaluated standards by Chile, Mexico and FAO.

It is recommended to conduct further research to optimize the doses of EM and explore the potential applications of compost in other crops and forest species.

Author Contributions

Conceptualization, K.O.Q. and A.L.P.; methodology, K.O.Q. and D.C.T.; software, A.L.P.; validation, E.G.C. and F.C.B.; formal analysis, K.O.Q. and A.L.P.; investigation, K.O.Q., D.C.T., A.L.P. and E.G.C.; resources, F.C.B.; data curation, K.O.Q.; writing—original draft preparation, K.O.Q., A.L.P.; writing—review and editing, D.C.T. and A.L.P.; visualization, F.C.B.; supervision, E.G.C., F.C.B.; project administration, A.L.P. and A.L.P.; funding acquisition, E.G.C. and F.C.B. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

Dw	Dry weight
Th	Total height
Dws	Dry weight stem
Drw	Dry root weight
Dn	Diameter of neck