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Circular Economy Through the Effect of Biosolids on Arrowroot *(Maranta arundinacea)* Rhizome Production: Physicochemical Analysis of Soil and Initial Crop Development

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Abstract

Sewage Sludge (SS) can improve the agricultural condition of tropical soils, which are generally acidic and deficient in nutrients and organic matter, thereby promoting better crop development as a positive outcome. The objective of this study was to apply different doses of SS to a tropical soil cultivated with arrowroot and to analyze the physicochemical changes in the soil using Tukey's test and Principal Component Analysis (PCA), as well as to evaluate the initial crop development over a three-month cultivation period. For comparison, arrowroot was also grown in natural soil conditions and with chemical fertilizer.

Treatments with SS doses (50%, 100%, 200% and 400%) significantly improved soil physicochemical fertility parameters, including pH, P, K, Ca, Mg, S and Organic Matter (OM), compared to the control and chemical fertilizer treatments. The treatments with SS doses of 4.6, 9.2 and 18.4 t ha^{-1} did not show significant differences in initial plant height, number and weight of arrowroot rhizomes. However, they performed better than the control, chemical fertilizer and 36.4 t ha^{-1} treatments, with statistically significant differences observed.

Therefore, the study recommends that SS application should not exceed 18.4 t ha^{-1} in tropical soils for the cultivation of arrowroot *(Maranta arundinacea)*. PCA showed that S, P, Ca and Electrical Conductivity (EC) undergo substantial changes in their concentrations when SS is applied to the soil. From an agricultural perspective, the study demonstrates that cleaner production in tropical soils is feasible within the framework of a circular economy in Wastewater Treatment Plants (WWTPs), which can reduce the disposal of SS in landfills by considering it as an agricultural product, thereby promoting sustainable development.

Keywords: Fertilizer; Agriculture; Control; Fertilization; Rhizomes

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Introduction

The agricultural recycling of Sewage Sludge (SS) promotes a circular economy within Wastewater Treatment Plants (WWTPs), aligning with sustainable development. In this context, SS ceases to be considered waste and instead becomes a valuable product generated by WWTPs, contributing to cleaner agricultural production and sustainability [1,2].

SS can improve the agricultural condition of tropical soils, which are typically acidic and sandy and consequently deficient in nutrients and organic matter

[3,4]. As a result, improved crop development is a positive outcome [5]. This enhancement in crop growth is likely due to increased nutrient concentrations, improved organic matter content and better soil pH conditions [5,6]. Sousa and Figueiredo observed that soil pH reached near-neutral levels along with a significant increase in Phosphorus (P) content [6]. For example, Boswell reported approximately a 30% increase in fescue yield with SS application (5.6 t ha^{-1}) compared to control treatments, while forage yield increased by approximately 150% compared to NPK fertilizers (2.5 kg ha^{-1}) [7]. To ensure the efficient use of SS, studies must be conducted to verify its effectiveness compared to conventional chemical fertilizers [8].

The use of chemical fertilizers contributes to soil acidification, increasing the demand for agricultural gypsum and lime, thereby intensifying the exploitation of natural resources and generating greenhouse gases [3,8]. Additionally, it is estimated that natural phosphorus reserves may be depleted within the next century [9,10].

Furthermore, approximately 80% of phosphorus available in natural rock reserves has low bioavailability and contains high levels of radioactive elements such as uranium [11]. There is a consensus among researchers that SS has strong potential to meet phosphorus requirements and should be utilized as a means of recovering this essential nutrient.

An important factor in SS application to agricultural crops is the appropriate dosage for each crop [12]. Studies indicate that changes in soil parameters are directly dependent on the applied dose [13]. This study was based on CONAMA Resolution 375/06, which establishes that SS application rates should be calculated according to the nitrogen requirements of the crop and the nitrogen availability in SS [14].

Another important aspect is the increasing search for alternative natural starch sources, driven by population growth and the potential scarcity of conventional starch sources such as maize, potato and wheat [15].

Arrowroot *(Maranta arundinacea)* is a perennial herb found in tropical forests that has gained interest from the starch industry in Brazil [16]. This interest is due to its unique starch properties, including excellent digestibility, gel-forming capacity and distinctive physicochemical characteristics such as high amylose content (~30%) [17].

The objective of this study was to evaluate, using Tukey's test and Principal Component Analysis (PCA), whether there are significant differences among six treatments in the cultivation of arrowroot *(Maranta arundinacea)* in terms of soil physicochemical properties (fertility parameters) and initial crop development. Treatment I consisted of natural soil (control), Treatment II involved chemical fertilization (NPK) and Treatments III, IV, V and VI consisted of different SS application rates of 4.6, 9.2, 18.4 and 36.4 t ha^{-1}, respectively [18].

Materials and Methods

Experimental management

The experiment was conducted in a greenhouse located at the Instituto Salesiano São Vicente, School Farm of the Universidade Católica Dom Bosco (UCDB), which serves as a research base for UCDB, in the municipality of Campo Grande, Mato Grosso do Sul, Brazil (latitude 20°26′37″ S, longitude 54°38′52″ W, average altitude 532 m).

The experimental period extended from May to June 2019. The average greenhouse temperatures during this period were 21.6, 21.8 and 22.9°C, respectively.

A randomized block design was adopted, consisting of six treatments with five replications (6 × 5).

The treatments were as follows:

- **Treatment I:** Natural soil condition (control);
- **Treatment II:** Chemical fertilization [18].

The SS doses were calculated according to CONAMA resolution 375/06, which establishes that the application rate should be determined based on the nitrogen requirement of the crop and the nitrogen availability in the SS [14].

- **Treatment III:** 50% of the calculated SS application rate (68 g pot^{-1});
- **Treatment IV:** 100% of the calculated SS application rate (optimal dose, 136 g pot^{-1});
- **Treatment V:** 200% of the calculated SS application rate (272 g pot^{-1});
- **Treatment VI:** 400% of the calculated SS application rate (544 g pot^{-1}).

The application rate was calculated using the following equation:

$$\text{Application Rate } (\text{t ha}^{-1}) = \frac{\text{Recommended N } (\text{kg ha}^{-1})}{\text{Available N } (\text{kg t}^{-1})}$$

Where:

- AR=Application rate (t ha^{-1})
- Np=Recommended nitrogen for the crop (kg ha^{-1})
- Nd=Nitrogen available in SS (kg t^{-1})

$$\text{Application Rate} = \frac{157}{17.33} = 9.06 \text{ t ha}^{-1}$$

After applying the respective doses, irrigation was carried out daily with 2 L of water per pot, from Monday to Friday, until the end of the experiment.

Selection of arrowroot rhizomes

The rhizomes were collected from a previous experiment conducted at the UCDB School Farm campus. They were visually selected, removing those showing signs of necrosis [19].

Healthy rhizomes were then classified, with fresh masses ranging from 57.89 g to 108.20 g, lengths from 20.24 cm to 25.52 cm and diameters between 20 mm and 42 mm. All rhizomes were distributed among different blocks to maintain uniformity within treatments.

Physicochemical characteristics of soil and biosolids

The SS used in this study were obtained from the Los Angeles Wastewater Treatment Plant, which is responsible for treating approximately 90% of the domestic sewage generated in the municipality.

The SS samples were collected directly from the disposal site. Characterization analyses of the SS were performed according to CONAMA Resolution 375/06 **(Table 1)** [14].

Table 1: Physicochemical characteristics of the biosolids.

Parameter	Result	Units
pH	7.6	-
Nitrogen (Kjeldahl)	41,310	mg kg^{-1}
Ammoniacal nitrogen	7,047	mg kg^{-1}
Nitrite	< 2.00	mg kg^{-1}
Nitrate	< 2.00	mg kg^{-1}
Total phosphorus	12,980	mg kg^{-1}
Total potassium	1,247.90	mg kg^{-1}
Total calcium	17.34	mg kg^{-1}
Total magnesium	4	mg kg^{-1}
Total sulfur	12.4	mg kg^{-1}
Moisture	98	%

Characterization of the initial soil and post-experiment evaluation

The soil, characterized as sandy and of low fertility, was collected from a depth of 0 cm-20 cm at the campus of the Instituto Salesiano São Vicente, in an area without agricultural cultivation and containing only native vegetation from the Cerrado biome.

At the end of the experiment, for the evaluation of soil fertility parameters, 100 g of soil was collected from each pot corresponding to its respective treatment. These samples were mixed and sent for analysis, which was carried out in accordance with the methodology established by Embrapa [20].

Soil fertility parameters were determined based on pH, macronutrients (P, K, Ca, Mg and S) Organic Matter (OM) and Electrical Conductivity (EC) [21]. These authors established reference values to classify soil fertility parameters in Cerrado soils as very low, low, medium, adequate and high. The results obtained for each treatment were classified according to these reference values.

For the macronutrients potassium, calcium and magnesium, unit conversions were applied (from cmolc dm^{-3} to mg dm^{-3}) to facilitate interpretation of the results. These transformations were applied both to the reference values from Sousa and Lobato and to the laboratory analyses conducted at the end of the experiment [20,21].

Application rate of sewage sludge and chemical fertilizer for treatment determination

The application rate of Sewage Sludge (SS) was calculated according to CONAMA Resolution 375 (CONAMA, 2006), based on the availability of Nitrogen (N) in the SS relative to the nitrogen demand of the arrowroot crop [18].

$$\text{Application Rate (t ha}^{-1}\text{)} = \frac{\text{Recommended N (kg ha}^{-1}\text{)}}{\text{Available N (kg t}^{-1}\text{)}}$$

Where:

TA: Application rate (t ha^{-1});

Np: Recommended nitrogen for the crop (kg ha^{-1});

Nd: Nitrogen available in SS (kg t^{-1}).

$$\text{Application rate} = \frac{157}{17.33} = 9.06\ \text{t ha}^{-1}$$

Cesar et al. reported that the maximum productivity of arrowroot rhizomes (47 t ha^{-1}) was obtained with a nitrogen fertilization rate of 157 kg ha^{-1} (0.157 t ha^{-1}) [18]. For calculation purposes, this value was approximated to 0.2 t ha^{-1} and converted to grams per cubic decimeter, resulting in 0.1 g dm^{-3}.

Since the pots contained 30 dm^3, this value was multiplied by 30, resulting in 3 g pot^{-1} (30 dm^3) as the nitrogen fertilization rate for chemical fertilizer.

Treatments

The treatments were defined as follows:

- **Treatment I:** No fertilization (control);
- **Treatment II:** Chemical nitrogen fertilization according to Cesar et al. [18];

- **Treatment III:** Nitrogen fertilization from 50% of the SS application rate (68 g pot^{-1} of SS);
- **Treatment IV:** Nitrogen fertilization from 100% of the SS application rate (base rate, 136 g pot^{-1} of SS);
- **Treatment V:** Nitrogen fertilization from 200% of the SS application rate (272 g pot^{-1} of SS);
- **Treatment VI:** Nitrogen fertilization from 400% of the SS application rate (544 g pot^{-1} of SS).

Evaluation of the initial development of arrowroot crop

The evaluation of the initial development of the crop was carried out after 90 days of cultivation. The parameters assessed included average plant height, number of rhizomes per treatment and rhizome weight.

Statistical analysis

Statistical analyses were applied to the results of the initial development of the arrowroot crop. Analysis of Variance (ANOVA) was performed and the means were compared using Tukey's test at a 5% significance level, using SISVAR 4.0 software.

One of the multivariate data analysis techniques used was Principal Component Analysis (PCA), which allows the evaluation of interrelationships among a large number of variables while quantifying their significance. Based on linear combinations of variables, PCA aims to reduce and eliminate redundant data to achieve better representation. The resulting reduced set of variables is referred to as principal components [22,23].

The relationships among data can be interpreted through perceptual maps. The cumulative percentage of total variance should range between 70% and 90% to provide a reasonable representation of the original variance. The quantification of variable significance enables the explanation of groupings, where new variables, called orthogonal variables, are derived from a reduced set of uncorrelated data, known as Principal Components (PCs) [24].

Results and Discussion

Soil physicochemical fertility parameters

Table 2 shows that treatments with SS doses significantly improved soil physicochemical fertility parameters (pH, P, K, Ca, Mg, S and organic matter) compared to the control and chemical fertilizer treatments. Soil pH in SS treatments approached neutrality, which significantly increased the concentrations of chemical fertility parameters such as P, K, Ca, Mg and S compared to other treatments.

Table 2: Response of chemical parameters of tropical soil under control, chemical fertilizer and Sewage Sludge (SS) treatments according to Tukey's test at 0.05%.

Treatments	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	S (mg kg^{-1})
Control	6.75 ± 2.05b	0.05 ± 0.02c	0.17 ± 0.41b	0.07 ± 0.26b	2.31 ± 1.17b
Chemical fertilizer	24.13 ± 14.19b	0.42 ± 8.19c	0.73 ± 1.12b	0.34 ± 0.66b	1.63 ± 1.32b
50% SS	37.89 ± 25.32b	74.55 ± 11.73cba	17.92 ± 11.14b	5.44 ± 5.01ba	56.43 ± 3.92b
100% SS (dose)	58.78 ± 20.57b	149.86 ± 46.46a	20.14 ± 13.17b	10.95 ± 14.40ba	59.72 ± 12.24ba
200% SS	127.11 ± 17.1ba	114.93 ± 15.22ba	29.29 ± 4.97b	40.65 ± 21.94a	93.74 ± 12.97ba
400% SS	234.59 ± 94.86a	28.87 ± 52.18cb	166.96 ± 32.29a	13.84 ± 2.29ba	229.29 ± 193.06a

Several studies have also reported near-neutral soil pH conditions following SS application [6,25]. These studies conclude that when soil pH approaches neutrality, positive agricultural impacts occur, such as increased nutrient availability and reduced bioavailability of contaminants and pollutants [12]. This pH effect can be explained by the characteristics of SS, as its pH was close to neutral and when interacting with the soil, promoted similar conditions.

Higher SS doses resulted in higher concentrations of P, Ca, Mg and S, except for K, where the 100% and 200% doses were higher than the 400% SS dose. Thus, the study concluded that increasing SS doses generally leads to increased nutrient concentrations in the soil. This finding is consistent with studies indicating that changes in soil parameters depend directly on SS application rates and that higher doses result in greater nutrient availability [12,13].

Another positive outcome of SS treatments was the absence of soil salinization risk, which typically occurs at Electrical Conductivity (EC) values above 4000 µS cm^{-1} [26]. In contrast, chemical fertilizer application showed the highest EC increase (1475.1 ± 94.85), although no significant differences were observed among treatments. Electrical conductivity is a physical soil parameter closely correlated with pH and various chemical properties and is often referred to as a salinity index in soil science [12,27]. Soil salinization is a major limiting factor for agricultural productivity and can negatively impact soil quality [28].

Journal of Applied Sciences and Archaeology

Finally organic matter is a key soil chemical parameter. In tropical soils, improving organic matter is challenging due to high sand content and intense weathering processes [4]. However, SS application significantly increased organic matter content at all doses (50%, 100%, 200% and 400%), generally in a gradual manner. Interestingly, the 200% dose showed higher values than the 400% dose. This increase is attributed to the high organic matter content and moisture of SS, as indicated in **Tables 2** and **3**.

Table 3: Response of physicochemical parameters of tropical soil under control, chemical fertilizer and Sewage Sludge (SS) treatments according to Tukey's test at 0.05%.

Treatments	pH	OM (g kg^{-1})	EC (µS cm^{-1})
Control	3.84 ± 0.22b	0.22 ± 0.12b	1278.7 ± 210.21a
Chemical fertilizer	4.21 ± 0.63b	0.60 ± 0.09b	1475.1 ± 94.85a
50% SS	6.02 ± 0.63a	0.46 ± 0.72ba	1406.5 ± 422.08a
100% SS (dose)	6.08 ± 0.08a	2.12 ± 0.96ba	853.55 ± 84.50a
200% SS	6.34 ± 0.44a	3.35 ± 1.81a	910.67 ± 234.5a
400% SS	7.12 ± 0.14a	3.07 ± 0.48ba	1333.6 ± 9.58a

Principal component analysis

In order to understand the relationships and impacts among the variables, as well as their statistical weights (loadings) and scores for each Principal Component (PC) in the soil analysis of the sampled points, **Table 4** presents the obtained results.

Table 4: Standardized weights and scores of soil chemical properties across sampling points.

Ponto	pH	P	OM	K	Ca	Mg	S	CE
PC1	-1,30	-0,58	-1,73	0,82	-0,62	-0,24	-0,03	0,51
PC 2	0,70	-0,69	-0,74	0,05	-0,21	0,30	0,33	-0,36
PC 3	0,98	-0,60	-0,56	0,19	0,80	-1,41	-0,08	-1,47
PC4	1,62	-0,25	0,93	-0,48	0,64	-0,45	0,09	0,98
PC5	-1,18	-0,02	0,40	0,04	-0,08	1,62	-1,39	-0,70
PC6	-0,29	0,25	0,92	-0,74	0,60	-1,76	0,68	0,65
PC7	0,37	3,12	-0,68	0,09	-0,42	-0,08	0,21	-0,66
PC8	-0,57	-0,70	-1,38	0,47	-0,98	0,92	0,81	-0,09

Scores are classified as either negative or positive, while component loadings can be categorized, according to Liu et al. into three classes: Strong (>0.75), moderate (0.75-0.50) and weak (0.50-0.30).

Based on the selection criterion established by Jolliffe, the cumulative percentage of total variance should range between 70% and 90% to provide a reasonable representation of the original variance [24]. According to this criterion, the selected principal components achieved a cumulative variance of 77.89%.

Florentino et al. in a similar study on sludge application in tropical soils using the same multivariate technique, reported a total variability of approximately 70% [3]. Similarly, Qishlaqi et al. in their study applying statistical methods for soil evaluation, obtained a cumulative variance of 71% using the same approach [29].

Parameters located near the center have lower scores and contributions, whereas those farther from the center exhibit higher contributions and scores. By analyzing only, the principal components with the greatest contribution (PC1 and PC2), as shown in **Figure 1**, it is observed that all elements were grouped in the present analysis except for S, P, Ca and EC. It is also evident in **Figure 1** that S and P had significant weight in the analysis, indicating that their concentrations changed with greater contribution and score.

Thus, this study demonstrates that Sewage Sludge (SS) can significantly increase the levels of these elements. However, attention must be given to the risk of soil salinization, which occurs at values above 4000 µS cm^{-1}.

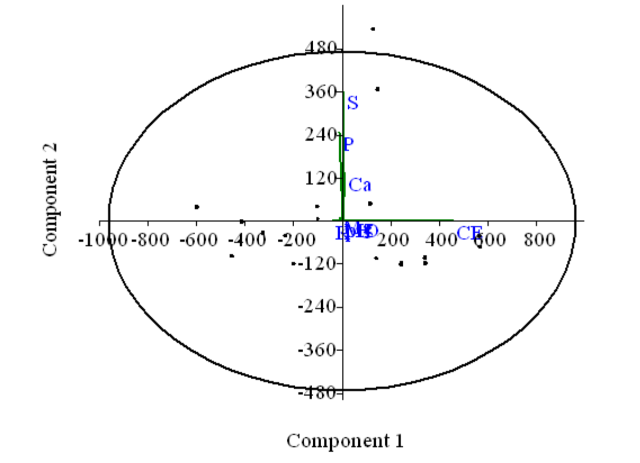

Figure 1: Principal component analysis.

Journal of Applied Sciences and Archaeology

Initial development of arrowroot crop

The treatments with Sewage Sludge (SS) doses (III, IV and V), corresponding to 4.6, 9.2 and 18.4 t ha^{-1}, did not show significant differences in the initial development of plant height, number and weight of arrowroot rhizomes. However, they performed better than treatments I, II and VI (control, chemical fertilizer and 36.4 t ha^{-1}), with statistically significant differences observed. Therefore, the study recommends that the SS application rate should not exceed 18.4 t ha^{-1} in tropical soils for the cultivation of arrowroot *(Maranta arundinacea)*. Treatment VI, which involved a 400% SS dose (four times the optimal dose calculated according to CONAMA Resolution 375/06), showed inferior performance compared to the other treatments, with significant differences observed.

The three parameters used to evaluate the initial development of the arrowroot crop were plant height, number of rhizomes and rhizome weight. The SS doses of 50%, 100% and 200% yielded the best results **(Table 4)**. The 400% dose resulted in excessive nutrient levels, which inhibited plant development, indicating that nutrient excess is detrimental. The average plant height observed **(Table 3)** was 21.72 cm ± 3.37 cm at 90 days after planting in the 50% SS treatment. This value is lower than those reported by Neves et al. and Gomes who observed maximum plant heights of 120 cm at 270 days and 166.35 cm at approximately 212 days after planting, respectively [30,31].

However, it should be noted that the evaluation period in those studies was longer than in the present study (90 days). According to Coelho arrowroot plants grow slowly during the first 90 days regardless of cultivation practices, followed by rapid growth in subsequent months, reaching maximum development around 240 days after planting [32]. The 100% SS dose showed the highest yield, producing 14 rhizomes and the greatest weight (96.74 g ± 7.75 g). Arrowroot grows best under conditions of high organic matter content, which explains the higher productivity observed with SS treatments, as they significantly increased soil organic matter **(Tables 2 and 5)** [30].

Table 5: Response of initial development parameters of arrowroot according to Tukey's test at 0.05%.

Doses	Plant height (cm)	Rhizome number (nº)	Rhizome weight (g)
Control	10.2 ± 4.1cb	1.6 ± 0.9cb	3.6 ± 2.1dc
Chemical fertilizer	11.2 ± 3.9cb	1.6 ± 0.6cb	5.7 ± 2.9dcb
50% SS	21.7 ± 3.4a	3.8 ± 0.5a	9 ± 0.38ba
100% SS	19.6 ± 3.8ba	3.6 ± 0.6a	10 ± 0.6a
200% SS	19.3 ± 8.8ba	2.8 ± 0.8ba	7 ± 3.5cba
400% SS	7.9 ± 4.1c	1.2 ± 0.5c	1.9 ± 0.5d

Conclusion

Based on the results of this study, we conclude that Sewage Sludge (SS) is an important resource that can contribute to cleaner agricultural production in tropical soils and integrate Wastewater Treatment Plants (WWTPs) into a circular economy, thereby promoting sustainable development.

Treatments with SS doses of 68, 136, 272 and 544 g pot^{-1} (III, IV, V and VI) significantly improved soil physicochemical fertility parameters (pH, P, K, Ca, Mg, S and OM) compared to the control and chemical fertilizer treatments.

Treatments III, IV and V, corresponding to 4.6, 9.2 and 18.4 t ha^{-1}, did not differ significantly in initial plant height, rhizome number or rhizome weight, but performed better than treatments I, II and VI (control, chemical fertilizer and 36.4 t ha^{-1}), with statistically significant differences observed.

Therefore, the study recommends that SS application should not exceed 18.4 t ha^{-1} in tropical soils for arrowroot *(Maranta arundinacea)* cultivation.

Finally, PCA revealed that S, P, Ca and Electrical Conductivity (EC) were most impacted by SS application. This is beneficial for increasing nutrient levels but also highlights the potential risk of soil salinization.

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