Journal of
Environment
(JE)

Thermally Dried Sewage Sludge: A Solution for Circular Economy and Sustainable Agriculture

CARI Journals

Journal of Environment
ISSN 2789-3863 (Online)
Vol. 5, Issue No. 5, pp 1 – 17, 2025
www.carijournals.org

Thermally Dried Sewage Sludge: A Solution for Circular Economy and Sustainable Agriculture

[1]*Gabriele Kuhn Dupont, [2]Marco Aurélio da Silva Carvalho Filho, [3]Carlos Itsuo Yamamoto, [4]Gustavo Rafael Collere Possetti

[1]Professor, Undergraduate Chemistry Course, International University Center UNINTER
Postgraduate Program in Chemical Engineering, Federal University of Paraná (UFPR)
https://orcid.org/0000-0003-4683-912X
[2]Lecturer, Postgraduate Program in Food Technology, State University of Ponta Grossa (UEPG)
International University Center UNINTER
[3]Researcher, Postgraduate Program in Chemical Engineering
Federal University of Paraná (UFPR)
[4]Sanitation Specialist, Paraná Sanitation Company (SANEPAR)

Accepted: 29th Nov, 2025, Received in Revised Form: 10th Dec, 2025, Published: 24th Dec, 2025

Abstract

Purpose: To evaluate the physicochemical composition, nutrient profile, and regulatory compliance of thermally dried sewage sludge (DSS) produced at a full-scale wastewater treatment plant in southern Brazil, assessing its potential for agricultural reuse within circular economy frameworks.

Methodology: A 12-month monitoring campaign was conducted from November 2022 to October 2023. Monthly DSS samples were collected post-thermal drying (300 °C, 50 min) and analyzed for moisture, volatile matter, ash, pH, total organic carbon (TOC), macronutrients (P, K, Ca, Mg), nitrogen fractions (TKN, TAN), and heavy metals regulated by Brazilian standards.

Findings: Moisture content varied widely (1.35–30.61%), influenced by seasonal precipitation. Volatile matter and ash averaged 44.91% and 38.85%, respectively, while TOC averaged 20.45%. Phosphorus (2.03–2.49%) and calcium (1.07–1.35%) were present at agronomically relevant levels, whereas potassium remained low (0.08–0.15%). All heavy metals complied with national thresholds, except for one isolated zinc exceedance (8,800 $mg \cdot kg^{-1}$). Overall, DSS demonstrated suitability for agricultural application under regulated conditions.

Unique Contribution to Theory, Practice and Policy: This study provides the first comprehensive dataset on thermally dried sewage sludge in Brazil, supporting its safe reuse as a nutrient source and reinforcing circular economy strategies in the sanitation sector. The findings offer a scientific basis for policy development and biosolids valorization, contributing to sustainable waste management and resource recovery.

Keywords: *Thermally Dried Sewage Sludge, Circular Economy, Nutrient Recycling, Biosolids, Sustainable Agriculture*

1. Introduction

Thermally dried sewage sludge (DSS) has emerged as a sustainable alternative for managing wastewater treatment byproducts, offering opportunities for nutrient recovery and circular economy implementation. In Brazil, annual sludge generation is estimated at 0.372 million tons (Menezes, 2022), and despite lower volumes compared to industrialized nations, the country faces persistent challenges in treatment and valorization. Landfilling remains the predominant disposal route, conflicting with principles of resource recovery and sustainable management.

According to the National Basic Sanitation Information System (SINISA), 62.3% of sewage is collected in Brazil, of which 78.6% undergoes treatment (SINISA, 2024). However, sludge management is still limited: 42% of municipalities treat part of the generated sludge, while 41% do not treat any fraction. Sanitary landfills receive 48% of treated sludge and 37% of untreated sludge (Comineti et al., 2025). This scenario highlights the need for alternatives that promote nutrient recycling and reduce environmental impacts.

Agricultural application of treated sludge is recognized as an efficient strategy to transform waste into a valuable input, supporting soil fertility and reducing dependence on synthetic fertilizers (Gusiatin et al., 2024). In Brazil, only 18% of municipalities adopt this practice, and studies on thermally dried sludge remain scarce. Thermal drying is considered a promising treatment method, as it reduces moisture, improves handling, and enhances sanitization, making sludge safer for agricultural application. Conventional treatment leaves sludge with high water content—up to 98% by mass—hindering direct use. By lowering residual moisture and stabilizing the material, thermal drying facilitates compliance with environmental and sanitary standards(Rietow et al., 2022).

In this context, the present study evaluates thermally dried sewage sludge produced at a large-scale wastewater treatment facility in southern Brazil over a 12-month period. The analysis includes physicochemical properties, nutrient content and trace metals, following national regulatory requirements. The findings provide essential data to support the safe agricultural reuse of DSS, contributing to circular economy principles and sustainable sludge management in developing regions.

2. Material and methods

2.1. Materials

The thermally dried sewage sludge (DSS) evaluated in this study was obtained from a municipal wastewater treatment plant located in Curitiba, Paraná, Brazil. The facility operates at an average flow of 1,680 L s^{-1} and employs upflow anaerobic sludge blanket (UASB) reactors for primary treatment. Subsequent processes include dissolved air flotation and centrifugation for sludge dewatering, followed by thermal drying in a rotary drum dryer. This configuration reflects a typical full-scale treatment system commonly adopted in Brazilian metropolitan areas, ensuring the applicability of the findings.

Thermal drying was carried out at an average temperature of 300 °C for approximately 50 minutes. One DSS sample was collected monthly at the outlet of the rotary dryer over a 12-month period, from November 2022 to October 2023. This sampling strategy was designed to capture seasonal variations in sludge composition and to verify compliance with quality and safety requirements for agricultural application under different environmental conditions.

Sampling procedures followed the guidelines established by (ABNT, 2004b) for solid waste collection from stockpiles. Samples were taken from two distinct sections of the pile—top and middle—immediately after discharge from the dryer and transferred into clean containers.

Prior to analysis, samples were homogenized and ground. A quartering technique was applied to obtain representative composite samples: the material was divided into four equal portions, two opposite quarters were retained and combined, while the remaining two were discarded. This procedure was repeated until the target sample mass was achieved.

2.2 Physicochemical Characterization of Thermally Dried Sewage Sludge

The physical characterization of DSS comprised the determination of moisture, volatile matter (VM), and ash (A) content. These parameters were quantified according to the procedures described by Naqvi et al. (2018) and Raveendravarrier et al. (2020).

The pH was measured using the potentiometric method 9045D, as recommended by the United States Environmental Protection Agency (US EPA, 2004). Total Organic Carbon (TOC) was determined by the dry oxidation method (ISO 10694, 1995). Total Kjeldahl nitrogen (TKN) and ammoniacal nitrogen (AN) were analyzed using the titrimetric method SMEWW 4500-NH_3 C, with a Kjeldahl distillation apparatus (APHA, 2017).

Elemental analysis was performed to quantify carbon (C), nitrogen (N), hydrogen (H), sulfur (S), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), as well as metals regulated by Brazilian standards for land application of sewage sludge (As, Ba, Cd, Pb, Cu, Cr, Hg, Mo, Ni, Se, and Zn). The assessment focused on macronutrient content and environmental risk indicators, in accordance with national and international regulatory frameworks.

C, N, H, and S contents were determined using a Flash 2000 elemental analyzer (Thermo Scientific), following ISO 10694:1995. Approximately 6 mg of sample and 3 mg of vanadium pentoxide were placed in a tin crucible. Analyses were performed in triplicate using cystine as the calibration standard. Combustion occurred under an oxygen atmosphere at 55 °C, with a scan time of 780 seconds.

For metal quantification, preliminary acid digestion was carried out using a modified EPA 3050B method. Briefly, 0.5 g of sample was transferred to a round-bottom flask, followed by the addition of 3 mL of hydrochloric acid, 1 mL of nitric acid, and 10 mL of distilled water. The mixture was subjected to reflux digestion for 30 minutes. After cooling, the digested solution was diluted to 100 mL with distilled water and analyzed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) on a Shimadzu ICPE-9000 instrument.

All analyses were conducted in triplicate, and results are expressed as mean ± standard deviation. Calibration curves and quality control samples were included in each analytical batch to ensure data reliability.

3. Results and discussion

3.1. Physical and chemical properties of DSS

The physical and chemical properties of DSS samples collected between November 2022 and October 2023 are presented in Table 1. After thermal treatment at 300 °C, the material discharged from the rotary drum dryer exhibited agglomerated particles with a predominantly spherical morphology. This structure indicates efficient removal of free water, interstitial moisture, and part of the surface-bound water during drying. However, hydration water, as described by Syed-Hassan et al. (2017), remains strongly associated with sludge flocs and is not eliminated under these conditions. Additionally, the granular configuration may trap residual surface water within the particle interior, meaning that the measured moisture content reflects both bound water and internally retained fractions.

The lowest moisture value (1.35%) was recorded in April 2023, coinciding with a period of reduced precipitation, as reported by the Paraná Rural Development Institute (IDR-Paraná) and the Environmental Technology and Monitoring System (SIMEPAR) (IDR-Paraná, 2024). This suggests that lower rainfall decreases the initial water content of incoming sludge, favoring the formation of smaller, denser granules with limited water retention after thermal drying. Conversely, the highest moisture content (30.61%) occurred in October 2023, corresponding to the month with the greatest precipitation in Curitiba (average of 413 mm).

Moisture content in the DSS samples collected throughout the 12-month monitoring period showed

Journal of Environment
ISSN 2789-3863 (Online)
Vol. 5, Issue No. 5, pp 1 – 17, 2025
www.carijournals.org

marked variability. This variation is largely attributed to operational and environmental factors rather than controlled laboratory conditions. Previous studies, which typically employed oven drying at 105 °C, report considerably lower and more stable moisture levels. For instance, Nang et al. (2025) observed an average moisture content of 4.0% in sewage sludge dewatered by decanter centrifuge and dried using a low-temperature industrial dryer, whereas Cristina et al. (2019) reported 11.2% for a pulverulent digestate subjected to thermal treatment at 200 °C. These discrepancies underscore the influence of drying technology and process parameters on the residual moisture of biosolids intended for agricultural application.

Table 1: Physical Properties and pH of Thermally Dried Sewage Sludge (Nov 2022 – Oct 2023).

Month/Year	pH	Moisture (%)	VM (%)	Ash (%)	P (%)	K (%)	Mg (%)	Ca (%)	TOC (%)	NTK (%)	NAT (%)
Nov/22	6.76 ± 0.20	8.07 ± 0.22	46.25 ± 1.01	45.68 ± 1.00	2.27 ± 0.1135	0.08 ± 0.004	0.26 ± 0.013	1.16 ± 0.058	21,18 ± 0,00	3.16 ± 0.00	<0.05
Dec/22	7.09 ± 0.03	16.41 ± 0.16	40.61 ± 0.23	39.14 ± 0.55	2.03 ± 0.1015	0.08 ± 0.004	0.26 ± 0.013	1.07 ± 0.0535	21,00 ± 0,18	3.06 ± 0.00	<0.05
Jan/23	7.03 ± 0.00	9.09 ± 0.14	42.95 ± 1.02	41.38 ± 0.89	2.37 ± 0.1185	0.09 ± 0.0045	0.32 ± 0.016	1.32 ± 0.066	20,08 ± 1,30	3.07 ± 0.00	<0.05
Feb/23	7.07 ± 0.04	8.99 ± 0.14	43.05 ± 1.03	41.94 ± 0.07	2.38 ± 0.119	0.09 ± 0.0045	0.3 ± 0.015	1.31 ± 0.0655	20,23 ± 1,16	3.19 ± 0.00	<0.05
Mar/23	7.08 ± 0.03	8.85 ± 0.10	48.13 ± 0.39	39.25 ± 0.29	2.4 ± 0.12	0.09 ± 0.0045	0.29 ± 0.0145	1.35 ± 0.0675	20,29 ± 1,04	3.29 ± 0.00	0.05 ± 0.00
Apr/23	7.08 ± 0.03	1.35 ± 0.03	52.47 ± 0.66	41.52 ± 0.67	2.34 ± 0.117	0.09 ± 0.0045	0.26 ± 0.013	1.3 ± 0.065	20,53 ± 1,09	3.73 ± 0.00	0.07 ± 0.01
May/23	5.60 ± 0.01	14.26 ± 0.13	44.65 ± 0.13	37.20 ± 0.11	2.17 ± 0.1085	0.09 ± 0.0045	0.25 ± 0.0125	1.1 ± 0.055	20,46 ± 1,02	3.33 ± 0.00	0.16 ± 0.01
Jun/23	5.61 ± 0.02	21.81 ± 0.27	42.06 ± 0.48	33.63 ± 0.57	2.45 ± 0.1225	0.08 ± 0.004	0.26 ± 0.013	1.24 ± 0.062	20,42 ± 0,96	3.19 ± 0.00	0.07 ± 0.01
Jul/23	5.78 ± 0.03	26.99 ± 1.57	40.11 ± 0.86	30.62 ± 0.74	2.49 ± 0.1245	0.1 ± 0.005	0.3 ± 0.015	1.34 ± 0.067	20,29 ± 0,98	3.22 ± 0.00	0.10 ± 0.01
Aug/23	6.02 ± 0.01	10.57 ± 0.77	49.60 ± 0.62	36.28 ± 1.11	2.12 ± 0.106	0.09 ± 0.0045	0.26 ± 0.013	1.27 ± 0.0635	20,09 ± 1,11	3.06 ± 0.00	0.06 ± 0.01
Sep/23	5.72 ± 0.01	18.81 ± 0.70	43.30 ± 0.58	34.94 ± 1.13	2.16 ± 0.108	0.09 ± 0.0045	0.24 ± 0.012	1.17 ± 0.0585	19,93 ± 1,17	3.26 ± 0.00	0.06 ± 0.01
Oct/23	6.18 ± 0.04	30.61 ± 0.98	35.39 ± 0.58	31.50 ± 0.43	2.35 ± 0.1175	0.15 ± 0.0075	0.32 ± 0.016	1.22 ± 0.061	19,94 ± 1,12	3.01 ± 0.00	<0.05

Values are expressed as mean ± standard deviation (SD). Parameters include pH, moisture content (M), volatile matter (VM), ash content; elemental composition of phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca); total organic carbon (TOC); total Kjeldahl nitrogen (NTK); and total ammoniacal nitrogen (NAT).

The samples analyzed in this study exhibited broader variations, influenced by factors such as local rainfall and the operational dynamics of the wastewater treatment plant (WWTP). During the evaluation period, the facility underwent expansion works, including the construction of activated sludge reactors, while the existing UASB reactors remained in operation. This transitional phase may have introduced operational variability, potentially influencing the moisture characteristics of the sludge subjected to thermal drying. These findings underscore the relevance of incorporating environmental and operational variables into the characterization of DSS, particularly when aiming at its agronomic valorization.

The physical composition of the DSS samples (Table 1) was predominantly characterized by volatile matter, which ranged from 40.11% to 52.47%, and ash content, which varied between 30.62% and 45.68% throughout the monitoring period. The volatile matter content of DSS in this study averaged 44.91%, which is slightly lower than values reported by Alvarez et al. (2015) and Onofre et al. (2015) who observed 54.20% and 51.44%, respectively. Similarly, the ash fraction in DSS (mean 38.85%) aligns closely with ranges documented in previous research, such as 37.20% (Alvarez et al., 2015), 38.57% (Onofre et al., 2015), and 35.60% (Cristina et al., 2019). These differences may reflect variations in sludge origin, pretreatment processes, and drying technologies, as earlier studies often employed controlled thermal conditions distinct from full-scale operational environments.

The DSS samples analyzed in this study exhibited pH values ranging from neutral to slightly acidic, with measurements between 5.72 ± 0.01 (Set/23) and 7.085 ± 0.031 (Dec/22). This slightly acidic profile is consistent with values reported in the literature. For instance, Raveendravarrier et al. (2020) observed a pH of 5.23 in anaerobically treated sludge from fluidized bed biofilm reactors, dried at 105 °C for 6 hours. Similarly, Chan e Wang (2016) reported slightly acidic pH values, averaging 5.84, in sludge samples from various wastewater reclamation facilities. In contrast, Barros et al. (2006) recorded a pH of 7.56 in anaerobically treated sludge from UASB reactors, which corresponds to the more neutral pH values recorded in some of the DSS samples analyzed during this study

Furthermore, Shan et al. (2021) demonstrated that the application of sewage sludge with a pH of

6.04 enhanced soil fertility in saline-affected alluvial soils by lowering pH and increasing organic carbon, nitrogen, and phosphorus levels. A similar trend was reported by (Nahar and Shahadat Hossen, 2021), who observed that sludge application contributed to soil acidification, potentially improving nutrient availability depending on initial soil conditions.

The role of pH in regulating metal behaviour in soils is well established. Under acidic conditions, metal mobility increases, enhancing their vertical migration through soil profiles and uptake by plants. This is partially due to the reduced sorption capacity and increased desorption of metal ions from organic and mineral soil components at lower pH levels, potentially resulting in gradual metal release over time. Therefore, to ensure the environmentally safe application of sewage sludge as a soil amendment, continuous monitoring of metal concentrations is essential(Uddin et al., 2025).

The average TOC content observed in the DSS samples of this study (Table 1) was around 20.45%, which is notably lower than the values reported in previous studies involving dried sewage sludge. For instance, Cristina et al. (2019) reported a TOC of 37.30% for sludge dried at 200 °C, while Sava et al. (2024) found a TOC of 26.72% in anaerobically treated sludge. Such discrepancies are likely due to variations in sludge source and the applied drying temperatures. In this study, the application of a higher drying temperature (300 °C) likely promoted thermal degradation of labile organic matter, resulting in reduced TOC content.

The TOC values obtained in this study are comparable to those reported by Ignatowicz (2017), who found concentrations between 21.0% and 22.0% in composted municipal sludge. This similarity indicates that thermal drying may induce organic matter transformations analogous to those occurring during composting, particularly in terms of carbon stabilization and the reduction of volatile organic fractions. Naqvi et al. (2018) emphasized that exposure to high temperatures during sludge drying promotes volatilization and oxidation of labile carbon compounds, which explains the observed decrease in organic carbon content.

TKN and TAN values (Table 1) exhibited notable variation throughout the sampling period. TAN ranged from <0.05% to 0.16% (May 2023), while TKN varied between 2.62% (December 2023) and 4.63% (July 2023). For instance, Cristina et al. (2019) reported TKN and TAN values of 5.00% and 0.25%, respectively, for sewage sludge dried at 200 °C, while Giannopoulos et al. (2025) observed TKN of 4.65% and TAN of approximately 0.30% in air-dried sludge with 5% moisture content. These differences underscore the impact of drying intensity on nitrogen dynamics, particularly the volatilization of ammoniacal nitrogen and partial loss of organic nitrogen compounds.

Additionally, Onofre et al. (2015) reported a TAN concentration of 1.55%. These differences underscore the impact of drying intensity on nitrogen dynamics, particularly the volatilization of ammoniacal nitrogen and partial loss of organic nitrogen compounds. Petryk et al. (2024) reported TAN of 0.58%, a value more comparable to those found in the present study, possibly reflecting similarities in drying methodology or sludge origin.

The calcium content in DSS samples ranged from 1.07% (Dec/23) to 1.35% (Mar/23), while magnesium varied between 0.24% (Sep/23) and 0.32% (Jan and Oct/23). These concentrations are within the expected range for sludge derived from urban and industrial sources, although they tend to be lower than values reported in earlier studies Cristina et al. (2019) observed 4.64% Ca and 1.16% Mg, and Raveendravarrier et al. (2020) reported 4.51% Ca and 1.20% Mg. Chan and Wang (2016) also presented higher values, with 2.70% Ca and 0.55% Mg. In contrast, the results from this study are more comparable to those of Rodrigues et al. (2024), who reported 1.41% Ca and 0.42% Mg, and Petryk et al. (2024), with 0.54% Mg.

The presence of Ca and Mg in DSS is relevant for its agronomic potential and chemical behavior. Calcium contributes to soil pH regulation, structural stability, and root development (Batista et al., 2018), whereas magnesium plays a critical role in photosynthesis and plant metabolic processes. As highlighted by Ignatowicz (2017), sewage sludge enriched with organic matter and containing adequate levels of Ca and Mg can act as a mineral-organic fertilizer with liming properties. Nevertheless, its application should be carefully adjusted to soil chemical characteristics and crop requirements to ensure balanced nutrient supply and avoid potential excesses or deficiencies.

Potassium exhibited the lowest concentrations among the analyzed nutrients, ranging from 0.08% to 0.15%. Even the maximum value (0.15%) was considerably lower than those reported in previous studies, such as 6.87% (Raveendravarrier et al., 2020), 4.72% (Petryk et al., 2024), and 1.34% (Onofre et al., 2015). Cristina et al. (2019), using thermal treatment at 200 °C, also observed a slightly higher level (0.18%) than that found here. This trend is consistent with Ignatowicz (2017), who identified potassium as the least abundant element in sewage sludge due to its high solubility and removal during wastewater treatment. Consequently, when DSS is applied as a soil amendment, complementary potassium fertilization is recommended to ensure adequate nutrient supply.

Phosphorus, in contrast, was present at significantly higher concentrations, ranging from 2.03% to 2.49%, which aligns with values reported in the literature (1.76–2.30%). Its agronomic relevance is underscored by the essential role of phosphorus in crop productivity and the growing concern over global phosphate rock depletion(Zhu et al., 2022). Recovery of phosphorus from sewage sludge represents a sustainable strategy for nutrient management, supporting circular economy principles and reducing dependence on non-renewable resources. Previous studies have demonstrated the benefits of sludge application for improving soil fertility and crop yields. For example, Nahar and Shahadat Hossen (2021) reported increases in soil organic carbon, nitrogen, phosphorus, and potassium following sludge incorporation, resulting in enhanced carrot growth. Similar improvements in maize, fava bean, and sweet potato performance have been documented by Mlaiki et al. (2025) and Ragonezi et al. (2022), reinforcing the potential of DSS as a nutrient-rich amendment for sustainable agriculture.

3.2 Regulatory Parameters for DSS Land Application

In Brazil, the classification and permissible use of treated sewage sludge are regulated by three main institutions: CONAMA, MAPA, and IAT. Each regulatory body establishes specific thresholds for chemical parameters to ensure environmental safety and protect public health.

CONAMA defines chemical limits for biosolids categorized as Class 1 or Class 2, based on contaminant concentrations. Class 1 biosolids contain lower levels of potentially toxic elements and are suitable for unrestricted agricultural use, including food crop cultivation. Class 2 biosolids, with higher contaminant levels, may be applied under restricted conditions (CONAMA, 2020). MAPA regulates the use of sewage sludge in agricultural products by setting maximum contaminant levels for materials registered as plant substrates, organic fertilizers, or soil conditioners. These regulatory thresholds aim to guarantee the agronomic efficiency and environmental safety of sludge-derived inputs in agricultural production systems (MAPA, 2016).

More recently, IAT—a state-level environmental agency in Paraná, where the present study was conducted—introduced a classification system for hygienized sewage sludge as Class A or Class B. Class A sludge meets stricter standards and is suitable for broader agricultural applications, while Class B may be used under more limited conditions (IAT, 2025).

The regulatory thresholds established by CONAMA, MAPA, and IAT for metals parameters are summarized in Table 2.

Table 2: Summarizes the maximum permissible concentrations for metals parameters established by CONAMA, MAPA and IAT.

Parameter	Unit	CONAMA		MAPA		IAT	
		Class 1	Class 2	Plant Substrate	Organic Fertilizer / Soil Conditioner	Class 1	Class 2
As	mg kg^{-1} TS	41	75	20	20	41	75
Ba	mg kg^{-1} TS	1300	1300	–	–	1300	1300
Cd	mg kg^{-1} TS	39	85	8	3	39	85
Pb	mg kg^{-1} TS	300	840	300	150	300	840
Cu	mg kg^{-1} TS	1500	4300	–	–	1500	4300
Cr	mg kg^{-1} TS	1000	3000	500	–	1000	3000
Hg	mg kg^{-1} TS	17	57	2.5	1	17	57
Mo	mg kg^{-1} TS	50	75	–	–	50	75
Ni	mg kg^{-1} TS	420	420	175	70	420	420
Se	mg kg^{-1} TS	36	100	80	80	36	100
Zn	mg kg^{-1} TS	2800	7500	–	–	2800	7500

Sources: (CONAMA, 2020; IAT, 2025; MAPA, 2016)
TS: Total Solids.

3.2.1 Results of Metal Concentration Analyses

Table 3 presents the concentrations of regulated metals in DSS samples collected monthly throughout the monitoring period. The results show that the levels of As, Ba, Cd, Pb, Cu, Cr, Hg, Mo, Ni, Se, and Zn — all listed in CONAMA Resolution No. 498/2020 and IAT (2025) with defined maximum limits for land application—remained within the permissible thresholds in all samples analyzed (Table 2).

The only exception was observed for Zn in the January 2023 sample, which reached 8,800 mg kg^{-1}, exceeding the maximum limit of 7,500 mg kg^{-1} established for Class 2 (CONAMA, 2020) and Class B (IAT, 2025) sludge. This isolated exceedance is likely attributable to a localized contamination event. In contrast, the lowest Zn concentrations were recorded in the March (2,745 mg kg^{-1}) and May (2,765 mg kg^{-1}) 2023 samples, both falling below the 2,800 mg kg^{-1} threshold defined for Class 1 (CONAMA, 2020) and Class A (IAT, 2025).

All other samples exhibited concentrations compatible with the limits established for Class 2 and Class B sludge. Considering that the majority of results fall within the regulatory thresholds and only one isolated exceedance was observed during the 12-month monitoring period, the use of this biosolid for agricultural purposes remains permissible under current environmental regulations.

Table 3: Monthly concentrations of regulated heavy metals in DSS samples (mg kg⁻¹ TS) and comparison with legal thresholds for land application.

Month/	Concentration in mg kg^{-1} TS									
Year	As	Ba	Cd	Pb	Cr	Cu	Hg	Mo	Ni	Se	Zn
Nov/22	5,75 ± 0,16	426.67 ± 5.77	< 0,10	< 1,00	160.67 ± 1.15	317.67 ± 0.58	0.2 ± 0.01	< 1,00	< 0,50	< 0,10	4570.0 ± 17.32
Dec/22	5,59 ± 0,11	365.33 ± 3.51	< 0,10	< 1,00	183.33 ± 0.58	205.67 ± 1.53	0.29 ± 0.01	< 1,00	< 0,50	< 0,10	5673.33 ± 11.55
Jan/23	5,38 ± 0,03	482.0 ± 3.46	< 0,10	< 1,00	229.33 ± 1.15	277.33 ± 0.58	0.12 ± 0.01	< 1,00	< 0,50	< 0,10	8800.0 ± 17.32
Feb/23	5,37 ± 0,05	419.33 ± 3.06	< 0,10	< 1,00	199.33 ± 2.31	278.67 ± 2.31	0.22 ± 0.02	< 1,00	< 0,50	< 0,10	4796.67 ± 28.87
Mar/23	3,05 ± 0,01	353.67 ± 1.15	< 0,10	< 1,00	161.33 ± 0.58	295.0 ± 1.73	0.27 ± 0.01	< 1,00	< 0,50	< 0,10	2750.0 ± 17.32
Apr/23	3,29 ± 0,02	453.67 ± 5.51	< 0,10	< 1,00	176.33 ± 2.31	306.0 ± 3.61	0.34 ± 0.01	< 1,00	< 0,50	< 0,10	3116.67 ± 11.55
May/23	3,20 ± 0,03	340.67 ± 1.15	< 0,10	< 1,00	164.33 ± 1.15	283.0 ± 1.73	0.24 ± 0.01	< 1,00	< 0,50	< 0,10	2780.0 ± 51.96
Jun/23	3,26 ± 0,05	388.67 ± 2.89	< 0,10	< 1,00	196.67 ± 0.58	536.0 ± 2.65	0.31 ± 0.01	< 1,00	< 0,50	< 0,10	3896.67 ± 5.77
Jul/23	3,52 ± 0,04	312.33 ± 1.53	< 0,10	< 1,00	200.33 ± 1.15	426.67 ± 2.31	0.7 ± 0.01	< 1,00	< 0,50	< 0,10	4143.33 ± 5.77
Aug/23	3,87 ± 0,11	342.67 ± 1.15	< 0,10	< 1,00	207.67 ± 0.58	348.33 ± 2.08	0.36 ± 0.01	< 1,00	< 0,50	< 0,10	2820.0 ± 17.32
Sep/23	4,35 ± 0,06	358.0 ± 1.73	< 0,10	< 1,00	244.67 ± 0.58	269.67 ± 1.15	0.33 ± 0.04	< 1,00	< 0,50	< 0,10	3526.67 ± 5.77
Oct/23	3,46 ± 0,04	404.67 ± 8.14	< 0,10	< 1,00	192.33 ± 1.53	325.67 ± 2.52	0.34 ± 0.01	< 1,00	< 0,50	< 0,10	3270.0 ± 262.11

Values are presented as mean ± standard deviation (SD). The table includes concentrations of arsenic (As), barium (Ba), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn).

A targeted investigation was conducted to identify the cause of elevated Zn concentrations in sewage sludge samples from WWTPs in the Metropolitan Region of Curitiba during 2022 and 2023.

The results revealed Zn levels exceeding the thresholds established by CONAMA Resolution No. 498/2020. This anomaly was traced to the use of ferric chloride with elevated Zn content during the physicochemical treatment stage.

The study demonstrated that, in addition to being directly influenced by the characteristics of the wastewater source, sludge composition is significantly affected by the chemical inputs used during treatment. Samples collected from the thermal dryer — at the same point as DSS sampling — on November 7, 2022, showed Zn concentrations of 5,240.1 mg kg^{-1} (Bittencourt, 2024), a value comparable to that found in the DSS sample from November 4, 2022, which measured 4,570.0 mg kg^{-1}.

The average concentrations of metals in dewatered sewage sludge (DSS) samples analyzed over a 12-month period followed the descending order: Zn > Cu > Ba > Cr > As > Mo > Ni > Hg > Cd ≈ Pb ≈ Se. Zinc was the most abundant element among those analyzed, a trend also reported by Alvarez et al. (2015), Chan and Wang (2016), Sava et al. (2024), and Petryk et al. (2024), with values ranging from 1,256.10 mg kg^{-1} to 4,660.00 mg kg^{-1}, consistent with the mean concentration of 4,472.20 mg kg^{-1} observed in the present study. Similarly, Ignatowicz (2017) identified a comparable pattern in sewage sludge composts, with metal concentrations ordered as Zn > Cr > Cu > Ni > Pb > Cd. This distribution is influenced by the origin of the effluents, the treatment processes applied, and the presence of industrial and domestic inputs.

No evidence of soil contamination by copper, cadmium, lead, or zinc was found, despite a noticeable increase in the concentrations of these metals following the incorporation of sewage sludge into the soil. Even under multiple application scenarios, the concentrations of these elements remained below the permissible limits for agricultural soils, as previously reported by Petryk et al. (2024).

Among the metals evaluated, Zn and Ni exhibit the highest mobility in soils, followed by Cd and Cu, with Pb and Cr showing lower mobility. The application of sewage sludge to soil can increase the total concentration of metals and induce short-term changes in their dominant chemical forms. However, the speciation of sludge-associated metals evolves over time, driven by interactions with plant roots, soil minerals, and the mineralization of organic matter facilitated by rhizospheric microbiota (Feng et al., 2023).

Cu, Ba, and Cr were the most concentrated metals in the DSS samples after Zn. The average Cu concentration was 358.00 mg kg^{-1}, lower than the 1,384.00 mg kg^{-1} reported by Alvarez et al. (2015), yet consistent with values from Chan and Wang (2016) (565.00 mg kg^{-1}) and Sava et al.

(2024) (406.00 mg kg^{-1}). Ba concentrations ranged from 311 to 483 mg kg^{-1}, with a mean of 327.00 mg kg^{-1}, comparable to Chan and Wang (2016) (277.00 mg kg^{-1}) and substantially below the 1,144.00 mg kg^{-1} observed by Alvarez et al. (2015). Cr was detected at an average of 201.80 mg kg^{-1}, within the range reported by Alvarez et al. (2015) (637.00 mg kg^{-1}) and Chan and Wang (2016) (167.00 mg kg^{-1}). Although present in moderate to elevated concentrations, all values remained below regulatory thresholds for agricultural application.

Arsenic concentrations ranged from 3.05 to 5.75 mg·kg^{-1} TS, remaining well below the legal threshold of 41 mg·kg^{-1} established by CONAMA for Class 1 biosolids. Comparable values have been reported by Chan and Wang (2016) (11.00 mg·kg^{-1}), Raveendravarrier et al. (2020) (4.60 mg·kg^{-1}), and Ragonezi et al. (2022) (0.60 mg·kg^{-1}), indicating low environmental risk. Molybdenum was consistently below 1.00 mg·kg^{-1}, in contrast to higher levels documented by Chan and Wang (2016) (10.00 mg·kg^{-1}) and Ragonezi et al. (2022) (24.00 mg·kg^{-1}). Nickel remained at trace concentrations (<0.50 mg·kg^{-1}), substantially lower than those reported by Alvarez et al. (2015) (410.00 mg·kg^{-1}) and Cristina et al. (2019) (137.00 mg·kg^{-1}).

Trace concentrations of Hg, Cd, Pb, and Se were observed in DSS samples. Mercury ranged from 0.12 to 0.70 mg kg^{-1} TS, which is consistent with values reported by Ragonezi et al. (2022) (0.30 mg kg^{-1}), Sava et al. (2024) (0.50 mg kg^{-1}), and Petryk et al. (2024) (0.67 mg kg^{-1}), indicating minimal contamination risk. Cadmium and lead were consistently below detection limits (<0.10 mg kg^{-1} and <1.00 mg kg^{-1}, respectively), remaining far below concentrations documented by Onofre et al. (2015) (Cd: 5.10 mg kg^{-1}; Pb: 143.10 mg kg^{-1}) and Alvarez et al. (2015) (Pb: 323.00 mg kg^{-1}). Selenium was also detected at levels below 0.10 mg kg^{-1}, with no significant temporal variation, suggesting negligible environmental concern.

Studies have demonstrated that seasonal variations in parameters such as pH, temperature, and dissolved organic matter significantly influence the mobility and solubility of metals like Pb, Cd, and Ni in industrial effluents. These fluctuations can lead to concentration peaks during transitional climatic periods, particularly in months such as September and October (Maphanga et al., 2024). Valle et al. (2012) further emphasize that such parameters may vary seasonally or in response to specific industrial discharges. For instance, elevated Cr concentrations (31,570 mg kg^{-1}) were detected in sewage sludge due to industrial residues from sectors including tanning, textiles, wood processing, metallurgy, and pigment manufacturing (Ronda et al., 2019).

From a scientific and environmental management perspective, this study strengthens the evidence base supporting the use of thermally dried DSS in agriculture, not only for its agronomic potential, but also for its regulatory compliance over time. The results highlight the importance of continuous elemental monitoring and the traceability of treatment inputs, contributing to safer and more efficient circular economy strategies.

4. Conclusions and recommendations

4.1 Conclusions

This study presents the first comprehensive, longitudinal dataset on thermally dried sewage sludge (DSS) in Brazil, bridging a significant knowledge gap in national and international literature. By conducting a 12-month monitoring campaign with systematic chemical evaluations, this work establishes a robust scientific baseline for assessing the safety and agronomic potential of DSS as a soil amendment.

Beyond technical validation, this research contributes strategically to the advancement of circular economy practices in Brazil's sanitation sector. By demonstrating the feasibility of safely reintegrating treated sludge into agricultural systems, it supports a shift away from landfill dependency toward resource recovery and nutrient recycling. Such an approach aligns with international sustainability goals, including those outlined in the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation) and SDG 12 (responsible consumption and production).

In sum, this study not only reinforces the environmental and agronomic viability of DSS but also provides a replicable analytical framework for future assessments across diverse geographic and operational contexts. Future research should expand on this foundation by evaluating long-term impacts on soil health and crop productivity, testing field-scale applications, and refining sludge treatment technologies to maximize both safety and utility.

4.2 Recommendations

To enhance the safe and effective use of thermally dried sewage sludge (DSS) in agriculture, the following actions are recommended:

i. Implement continuous monitoring programs for the chemical composition and heavy metals in DSS, ensuring compliance with environmental standards and traceability of treatment inputs.
ii. Conduct long-term studies on the effects of DSS on soil health, agricultural productivity, and potential environmental risks, including trials with different crops and soil-climate conditions.

iii. Develop training programs for farmers on the correct use of DSS, safe handling practices, and agronomic benefits, as well as awareness campaigns on circular economy and sustainability.

iv. Recommend complementary potassium fertilization in areas receiving DSS, due to the low potassium content observed in the samples, ensuring balanced crop nutrition.

References

ABNT, 2004. NBR 10007: Amostragem de resíduos sólidos., 2nd ed, ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT, Rio de Janeiro.

APHA (American Public Health Association), 2005. Standard Methods for the Examination of Water and Wastewater. APHA.

Barros, A.J.M., Santos, J.C.O., Prasad, S., Leite, V.D., Souza, A.G., Soledade, L.E.B., Duarte, M.S.B., Santos, V.D., 2006. Thermal decomposition study of sewage sludge and of organic waste used in the sorption of metals. Journal ofThermal Analysis and Calorimetry 83, 291–295. https://doi.org/https://doi.org/10.1007/s10973-005-6599-6

Batista, M.A., Neto, M.E., Batista, M.A., Inoue, T.T., Esper, M., Saraiva, A., 2018. Capítulo 4 - Princípios de fertilidade do solo, adubação e nutrição mineral. EDUEM, Maringá.

Chan, W.P., Wang, J.Y., 2016. Comprehensive characterisation of sewage sludge for thermochemical conversion processes - Based on Singapore survey. Waste Management 54, 131–142. https://doi.org/10.1016/j.wasman.2016.04.038

Comineti, C. da S.S., Schlindwein, M.M., Hoeckel, P.H. de O., Mateus, T.H. de A., Kalache, N., 2025. Sewage waste management in Brazil: A sustainable development perspective. Util Policy 97, 102070. https://doi.org/10.1016/j.jup.2025.102070

Cristina, G., Camelin, E., Pugliese, M., Tommasi, T., Fino, D., 2019. Evaluation of anaerobic digestates from sewage sludge as a potential solution for improvement of soil fertility. Waste Management 99, 122–134. https://doi.org/10.1016/j.wasman.2019.08.018

Giannopoulos, G., Tzanakakis, V.A., Duelli, G., Anastopoulos, I., Aschonitis, V.G., Arampatzis, G., Barouchas, P.E., 2025. Municipal sewage sludge treatment and soil pH conclusively affect the nitrogen dynamics of amended soils. Environmental Advances 19, 100618. https://doi.org/10.1016/j.envadv.2025.100618

Gusiatin, M.Z., Kulikowska, D., Bernat, K., 2024. Municipal Sewage Sludge as a Resource in the Circular Economy. Energies 17. https://doi.org/10.3390/en17112474

IDR-Paraná, 2024. Boletim Agrometereológico - Instituto de Desenvolvimento Rural do Paraná.

Ignatowicz, K., 2017. The impact of sewage sludge treatment on the content of selected heavy metals and their fractions. Environ Res 156, 19–22. https://doi.org/10.1016/j.envres.2017.02.035

Menezes, L.N.B., 2022. Proposta de gerenciamento de lodos de esgotos por processo termoquímico (Trabalho de conclusão de curso (Pós-graduação em tecnologias químicas e biológicas)). Universidade de Brasília, Brasília, DF.

Mlaiki, F., Dridi, I., Tlili, A., Ben Hadj Mbarek, S., Dridi, S., Attia, R., 2025. Medium-Term Effects of Sewage Sludge Application on the Physicochemical Properties of Agricultural Soil and Crop Productivity in the Semi-Arid to Arid Region of Central-Western Tunisia. Earth Systems and Environment 9, 1773–1791. https://doi.org/10.1007/s41748-025-00745-5

Nahar, N., Shahadat Hossen, M., 2021. Influence of sewage sludge application on soil properties, carrot growth and heavy metal uptake. Commun Soil Sci Plant Anal 52, 1–10. https://doi.org/10.1080/00103624.2020.1836201

Nang, S., Mercl, F., Košnář, Z., Pierdonà, L., Doležal, P., Paul, C.S., Tlustoš, P., 2025. Torrefaction of sewage sludge: An approach to nutrient recycling and contaminant reduction in agriculture. Environ Res 275. https://doi.org/10.1016/j.envres.2025.121409

Naqvi, S.R., Tariq, R., Hameed, Z., Ali, I., Taqvi, S.A., Naqvi, M., Niazi, M.B.K., Noor, T., Farooq, W., 2018. Pyrolysis of high-ash sewage sludge: Thermo-kinetic study using TGA and artificial neural networks. Fuel 233, 529–538. https://doi.org/10.1016/j.fuel.2018.06.089

Onofre, S.B., Abatti, D., Tessaro, A.A., 2015. Propriedades Físico-Químicas E Microbiológicas Do Lodo De Esgoto Produzido Pela Estação De Tratamento De Esgoto (Ete) De Toledo – Paraná - Brasil. VI Congresso Brasileiro de Gestão Ambiental 1–6.

Petryk, A., Ryczek, M., Guzdek, S., 2024. Evaluation of the Effect of Using Sewage Sludge As a Fertilizer on the Concentration of Heavy Metals in Soil and the Economic Implications of Its Application. Economics and Environment 88, 647–666. https://doi.org/10.34659/eis.2024.88.1.647

Ragonezi, C., Nunes, N., Oliveira, M.C.O., de Freitas, J.G.R., Ganança, J.F.T., de Carvalho, M.Â.A.P., 2022. Sewage Sludge Fertilization—A Case Study of Sweet Potato Yield and Heavy Metal Accumulation. Agronomy 12, 1–18. https://doi.org/10.3390/agronomy12081902

Raveendravarrier, B., Palatel, A., Chandrasekharan, M., 2020. Physico-chemical Characterization of sewage sludge for thermochemical conversion processes. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. https://doi.org/10.1080/15567036.2020.1841858

Rietow, J.C., Possetti, G.R., Carneiro, C., Gervasoni, R., Aisse, M.M., Noyola, A.R., 2022.

Aproveitamento do biogás produzido em reatores anaeróbios de fluxo ascendente de manta de lodo para a secagem térmica de lodos de estações de tratamento de esgoto. Engenharia Sanitaria e Ambiental 27, 347–356. https://doi.org/10.1590/s1413-415220200286

Rodrigues, M.Â., Sawimbo, A., da Silva, J.M., Correia, C.M., Arrobas, M., 2024. Sewage Sludge Increased Lettuce Yields by Releasing Valuable Nutrients While Keeping Heavy Metals in Soil and Plants at Levels Well below International Legislative Limits. Horticulturae 10, 1–17. https://doi.org/10.3390/horticulturae10070706

Shan, Y., Lv, M., Zuo, W., Tang, Z., Ding, C., Yu, Z., Shen, Z., 2021. Sewage sludge application enhances soil properties and rice growth in a salt - affected mudflat soil. Sci Rep 1–7. https://doi.org/10.1038/s41598-020-80358-2

SINISA, 2024. Relatório dos Serviços de Esgotamento Sanitário - Planilha - Ano de Referência 2023. Sistema Nacional de Informações em Saneamento Básico.

Syed-Hassan, S.S.A., Wang, Y., Hu, S., Su, S., Xiang, J., 2017. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. Renewable and Sustainable Energy Reviews 80, 888–913. https://doi.org/10.1016/j.rser.2017.05.262

Uddin, S., Zaman, M., Martínez-Guijarro, K., Al-Murad, M., Behbehani, M., Habibi, N., Al-Mutairi, A., 2025. Sewage sludge as soil amendment in arid soils - A trace metal, nutrient and trace organics perspective. Emerg Contam 11, 100420. https://doi.org/10.1016/j.emcon.2024.100420

Zhu, Ya, Zhai, Y., Li, S., Liu, Xiangmin, Wang, B., Liu, Xiaoping, Fan, Y., Shi, H., Li, C., Zhu, Yun, 2022. Thermal treatment of sewage sludge: A comparative review of the conversion principle, recovery methods and bioavailability-predicting of phosphorus. Chemosphere 291, 133053. https://doi.org/10.1016/j.chemosphere.2021.133053