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Investigation of physicochemical and bacteriological properties of residual sewage sludge for sustainable agricultural valorization in Algeria

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Abstract

A significant amount of sewage sludge is generated by wastewater treatment plants. Its use in agriculture is a widely adopted method aimed to reducing the environmental impact associated with the accumulation of residual sludge. In this study, physicochemical and bacteriological characteristics of sewage sludge were analyzed. The sludge exhibited a significant composition of organic matter, nitrogen, phosphorus, and mineral elements, along with heavy metal concentrations well below regulatory limits, ensuring minimal environmental risk. Bacteriological analysis revealed significant mesophilic bacterial activity. Meanwhile, fecal coliform levels remained within acceptable limits for agricultural use, confirming compliance with standards for Class B biosolids but exceeding the threshold for Class A biosolids. However, high levels of total coliforms, fecal streptococci and sulfite-reducing anaerobic bacterial spores were observed, indicating significant microbial activity in the sludge. The sludge was free of pathogens such as *Vibrio cholerae* and *Salmonella*, confirming its microbiological safety under controlled conditions. Multivariate analysis highlighted significant interactions between organic matter, mineral elements, and microbial communities, underscoring the interconnected nature of these parameters. These findings emphasize the potential of sewage sludge as a sustainable resource for agricultural applications, provided that appropriate treatment and monitoring measures are in place to ensure safety and compliance with standards.

Keys words: agriculture, environment, residual sludge, physicochemical, bacteriological

Introduction

Sewage sludge, a by-product of wastewater treatment processes, has seen a notable global increase in volume over recent years (Salihoglu et al., 2007; Boudjabi et al., 2017). Once regarded primarily as waste destined for landfill disposal, sewage sludge is now increasingly viewed as a valuable resource for recycling (Lasheras, 2011). Its application in agriculture has emerged as a sustainable management strategy due to its richness in organic matter, nitrogen, phosphorus, and essential trace elements that support plant growth (Paganini et al., 2024; Tiruneh et al., 2024). These properties enhance soil characteristics such as water retention and cation exchange capacity, making sewage sludge a cost-effective alternative to commercial fertilizers (Tiruneh et al., 2024). Additionally, it contributes to circular economy principles by transforming waste into a valuable agricultural resource (Paganini et al., 2024).

Sewage sludge can supply nutrient levels similar to or exceeding those found in animal manure, with significant increases in soil organic matter and nutrient availability observed (Tiruneh et al., 2024; Rodrigues et al., 2024). Research indicates that crops treated with sewage sludge exhibit higher yields compared to those treated with conventional fertilizers, demonstrating its effectiveness as a soil amendment (El'shaeva et al., 2024; Rodrigues et al., 2024).

However, Sewage sludge contains various heavy metals, including chromium, copper, zinc, lead, cadmium, nickel, arsenic, iron, and manganese, alongside organic pollutants and microorganisms such as bacteria, posing significant environmental and health risks (Jumasheva et al., 2023; Islam et al., 2023; Xiao et al., 2023). These heavy metals contribute to moderate considerable ecological risks, largely attributed to anthropogenic activities. Additionally, the use of treated sludge as a soil amendment can lead to microbial contamination, as pathogens may persist in soil for extended periods (Hernández et al., 2018). Their survival is influenced by the sludge treatment methods and environmental factors such as moisture and temperature (Li et al., 2022; Hernández et al., 2018). These risks underscore the need for effective treatment and management strategies to mitigate potential environmental and health hazards associated with their application.

To further enhance its agricultural value, stabilization techniques like composting are employed to preserve nutrients, while additives such as zeolite can improve nitrogen retention (Gogina et al., 2024). Advances in treatment methods, like the integration of native microalgae for stabilization and pathogen removal also improve the safety and effectiveness of sewage sludge for agricultural use (Ben Hamed et al., 2024).

The objective of this study is to assess the quality of residual sludge through comprehensive physicochemical analyses focusing on nutrient elements and heavy metals, as well as bacteriological analyses, including fecal coliforms, fecal streptococci, sulfite-reducing anaerobic bacteria, and other indicator bacteria that may pose health risks to humans, animals, and the environment, to mitigate any risks associated with its agricultural use in Algeria.

Material and methods

Study area and sampling

15 samples were collected from residual sludge in accordance with Environmental Protection Agency (USEPA, 1978), these samples originated from a wastewater treatment plant (WWTP) located in Algeria, specifically about 18 km southeast of the province of Algiers. This plant treats urban and industrial wastewater. It is an activated sludge plant operating at medium load, with a capacity of 1,800,000 population equivalent. The sludge treatment process at this facility involves thickening, followed by anaerobic digestion and dewatering using belt filters. The annual sludge production amounts to approximately 10,676 tons.

Physical and chemical attributes of the samples

The moisture content was measured using the oven drying method at 105°C for 24 hours (APHA, 2017). The residual sludge samples were pre-dried and ground to obtain a homogeneous powder. After sieving to remove coarse particles, the samples were subjected to chemical analyses.

Total organic carbon (TOC) was determined by oxidation with potassium dichromate, according to the method of Nelson and Sommers (1996). Total organic nitrogen was analyzed using the Kjeldahl method, with titrimetric quantification involving sulfuric acid and a copper-based catalyst, in accordance with APHA (2017). The C/N ratio was also calculated.

Total and assimilable phosphorus was measured using a colorimetric method after chemically converting various forms of phosphorus into orthophosphate. This conversion was achieved through thermal digestion using concentrated sulfuric acid and ammonium persulfate. Quantification involved the adding ammonium molybdate, potassium antimonyl tartrate, and ascorbic acid, followed by spectrophotometric reading (USEPA, 1978).

Bicarbonate HCO_3^- content was measured by titration with hydrochloric acid (HCl), as described by Jackson (1973). Chloride content was determined by argentometric titration, according to APHA (2017).

Exchangeable bases (Ca, Mg, Na, K) and heavy metal (Zn, Mn, Cu, Fe) were analyzed by atomic absorption spectrometry after sample digestion in a mixture of nitric acid and hydrogen peroxide (H_2O_2) (USEPA, 1996).

Bacteriological Attributes of the Samples

For the research and enumeration of bacteria, dilutions were performed. A stock solution was prepared by mixing 10 g of sludge with 100 mL of sterile distilled water, followed by a series of decimal dilutions up to 10^{-5} (1/100000). Total mesophiles were enumerated on Plate Count Agar using the Spread Plate Method (APHA, 2017) while total coliforms were determined using the Most Probable Number (MPN) method in lactose broth with bromocresol purple (BCPL). Positive tubes were then subjected to a confirmation test in Schubert broth for the detection of fecal coliforms, with incubation at 44°C for 24 hours. The presence of fecal coliforms was confirmed by the appearance of a red ring on the surface of the medium after the addition of Kovacs reagent. The enumeration of total and fecal coliforms was performed using the MacGrady table, with results expressed as MPN/g (Rodier, 2009).

Fecal streptococci were also determined using the MPN method, initially in Rothe broth for presumptive testing, followed by confirmation in EVA-Litsky broth, characterized by the appearance of violet or whitish pellets at the bottom of the tube due to ethyl violet. Their enumeration was also performed using the MacGrady table, with results expressed as MPN/g. The research and enumeration of sulfite-reducing anaerobic bacterial spores were carried out by incorporation into meat-liver agar, where a positive result was indicated by the appearance of black colonies, expressed as UFC/g (Rodier, 2009). Finally, the detection of the pathogenic bacteria *Vibrio cholerae* and *Salmonella* was performed using enrichment in alkaline peptone water and selenite cystine broth, respectively, followed by isolation on selective media: alkaline bile nutrient agar (GNAB) for *Vibrio cholerae* and on xylose lysine deoxycholate agar (XLD) for *Salmonella* (Rodier, 2009).

Statistical analyses

A multivariate analysis was conducted on the physicochemical and bacteriological parameters using Principal Component Analysis (PCA) in R software (version 4.4.2). This process included the construction of a correlation matrix and the application of Bartlett's test to assess the significance of the correlations.

Results and discussion

Physico-chemical results

The results of the physico-chemical analysis are presented in Table 1, revealing characteristics that highlight the potential of sewage sludge for agricultural recovery. The sludge exhibits an average moisture content of 59.44% (±10.65), indicating a high water proportion typical of sewage sludge. Organic matter (OM) content has an average value of 40.56% (±10.65). The OM content in sewage sludge can vary widely, ranging from 25% to 90%, depending on the stabilization technology employed (Kacprzak, 2023). A systematic review has shown that the application of sewage sludge can substantially enhance soil organic matter, particularly at medium to high application rates (Paganini et al., 2024). The presence of OM in sewage sludge is essential for improving soil quality and nutrient availability, highlighting its value as a beneficial resource for agricultural practices (Paganini et al., 2024; Kacprzak, 2023).

The total organic carbon (TOC) content averages 20.72% (±8.84), indicating a high organic matter concentration, which is beneficial for application such as composting. In comparison, sewage sludge from the wastewater treatment plant in Jijel Province, Algeria, has a slightly higher TOC content of 26.4% (Boumalek et al.,2019). This elevated organic carbon level plays a crucial role in soil health by enhancing structure, improving moisture retention, and supplying essential nutrients for plant growth. Rich in TOC, sewage sludge can be repurposed in agriculture, contributing nitrogen, phosphorus, and organic compounds like proteins and fats, which further enhance soil fertility and support sustainable farming practices (Carvalho et al., 2015). The total nitrogen (TN) content of 2.64% (±0.50) indicates potential for soil enrichment, although it lies at the lower limit of the range reported by Zhao et al. (2024), which varies from 2.5% to 9.0% depending on treatment processes and environmental conditions. While, it is higher than the one reported by Meghari et al. (2017) who found an average total Kjeldahl nitrogen (TKN) concentration of 5440 mg/kg equivalent to 0.544 %, highlighting its rich nitrogen content and its value as a fertilizer and soil conditioner. However, sewage sludge application in agriculture enhances soil fertility, improper management can result in nitrogen pollution risks (Paganini et al., 2024). Nevertheless, seasonal variations significantly affect nitrogen forms, with colder months reducing efficiency due to disrupted nitrification and denitrification processes (Młyńska & Chmielowski, 2024).

The C/N ratio in this study averages 8.30 (±4.34), suitable for rapid degradation of organic matter. Sloot et al. (2022) showed that a low C/N ratio (~10) promotes nitrogen mineralization, enhancing nutrient availability, while higher ratios (>20) could lead to nitrogen immobilization. Sewage sludge applications can improve soil carbon and nitrogen dynamics, aiding the recovery of degraded soils (Hoffmann et al., 2024).

The total phosphorus (TP) content of 0.13% (±0.038). In comparison, Wang et al. (2018) found an average TP concentration of 17.3 ± 5.1 $g \cdot kg^{-1}$ in sewage sludge, equivalent to 1.73% ± 0.51%. Additionally, Xu et al. (2012) reported that TP levels in sewage sludge typically range from 0.97% to 1.74%, highlighting the variation in phosphorus content across different studies. While, phosphorus pentoxide (P_2O_5) content in our study is 3028 ppm (±875) equivalent to 0.30% (±0.0875), which is notably lower than the P_2O_5 concentrations reported by Romanos et al. (2019) (1.84–3.93%). Phosphorus pentoxide in sewage sludge is essential for plant growth, contributing to soil fertility and productivity, as highlighted by (Haouas et al., 2021; Ongun et al., 2023).

Mineral element analysis confirms the agronomic value of sewage sludge. Potassium was measured at 0.998 meq/100g (±0.27), corresponding to potassium oxide (K_2O) levels of 468.5 ppm (±128.3). Calcium and magnesium concentrations averaged 15.65 meq/100g (±11.01) and 4.83 meq/100g (±3.35), respectively, while sodium was measured at 1.66 meq/100g (±0.88). Compared to other studies, the calcium levels observed in this study are significantly lower than those reported by Ionescu and Ionescu (2014), which ranged from 2.1% to 4.2% equivalent to 52.4 to 104.8 meq/100g. Similarly, the magnesium content recorded in this study is below the range of 0.2% to 0.5% equivalent to 8.23 to 20.6 meq/100g reported by Dusza et al. (2009), showing a notable difference in the mineral composition of sewage sludge across studies. Potassium concentrations in our study are notable and contribute positively to the nutrient profile of the sludge, supporting soil fertility, consistent with findings by Dusza et al. (2009). Sodium and potassium levels are acknowledged to vary depending on the type of wastewater treatment plant and processes used (Alonso et al., 2023). While the nutrient profile of sewage sludge offers significant benefits, careful management is essential to prevent potential issues such as soil acidification or nutrient imbalances due to excessive organic matter inputs (Ionescu & Ionescu, 2014).

Chloride and bicarbonate levels were 5.499 meq/100g (±0.86) and 10.79 meq/100g (±7.19), respectively. He et al. (2010) reported chloride concentrations in sewage sludge ranging from 0.63 to 3.6 mg/g, equivalent to 1.78 to 10.71 meq/100g, comparable to our findings. The study by Pérez-Gimeno et al. (2016) underscores the importance of monitoring chlorides and bicarbonates in leachates when using sewage sludge for soil rehabilitation. These compounds significantly impact salinity, water quality, and soil health, making them critical factors in evaluating the environmental effects of such practices. Elevated chloride levels can lead to soil salinization, impairing plant growth and soil structure (Maiti et al., 1992; Pérez-Gimeno et al., 2016). Similarly, high bicarbonate levels can alter soil pH and reduce nutrient availability, affecting agricultural productivity (Lamastra et al., 2018). Proper management of these elements is critical to ensure sustainable agricultural practices and mitigate environmental risks.

Table 1 physicochemical results

Parameters	Minimum	Maximum	Average	Standard deviation
Moisture %	39.64	72.52	59.44	± 10.65
OM %	27.48	60.36	40.56	± 10.65
TOC %	11.5	36	20.72	± 8.84
TN %	2.18	3.58	2.64	± 0.50
C/N	3.84	15.75	8.30	± 4.34
TP%	0.09	0.2	0.13	± 0.038
P_2O_5 ppm	2084	4580	3028	± 875
K_2O ppm	219.3	656.7	468.5	± 128.3
Ca meq/100g	4.41	39.3	15.65	± 11.01
Mg meq/100g	1.57	11.9	4.83	± 3.35
Na meq/100g	0.8	3.74	1.66	± 0.88
K meq/100g	0.47	1.399	0.998	± 0.27
Cl^- meq/100g	3.83	7	5.499	± 0.86
HCO_3^{--} meq/100g	0.664	19.92	10.79	± 7.19

Regarding heavy metals table 2, the average concentrations of iron, zinc, manganese, and copper in the sewage sludge are 1.74 ppm (±1.10), 45.60 ppm (±18.37), 3.20 ppm (±1.598), and 14.38 ppm (±22.00), respectively. These levels are well below regulatory limits, ensuring compliance with standards for safe agricultural use. Specifically, they fall within the threshold limits recommended by the Council of the European Communities (CEC, 1986) and the Environmental Protection Agency (USEPA, 1993), confirming the sludge's suitability for farming. In contrast, a study by Singh et al. (2022) reported significantly higher concentrations of iron (490.27 ppm), zinc (184.27 ppm), manganese (246.08 ppm), and copper (240.63 ppm), underscoring the comparatively lower metal content observed in our study. Similarly, Boumalek et al. (2019) reported elevated levels of iron (11.6 ppm) and manganese (360 ppm) in sewage sludge from Algeria, further emphasizing the comparatively lower metal concentrations in our findings.

Table 2 Heavy metal results

Parameters	Minimum	Maximum	Average	Standard deviation	The limit value US EPA Section 503.13	The limit value [Directive 86/278/EEC]
Fe ppm	0.5	4.3	1.74	± 1.10	-	-
Zn ppm	18.00	76.49	45.60	± 18.37	2800	2500-4000
Mn ppm	0.19	5.85	3.20	± 1.598	-	-
Cu ppm	1.35	79.20	14.38	± 22.00	1500	1000-1750

Bacteriological results

Table 3 presents the results of bacteriological analysis of sewage sludge, focusing on various bacterial indicators. The results indicate significant concentration of mesophiles, with an average of 3.47×10^4 CFU/g. reflecting strong bacterial activity typical at moderate temperatures. The microbial communities in sewage sludge are diverse and play a crucial role in the degradation of organic matter, with mesophiles being particularly important for pollutant breakdown (Cai et al., 2024; Dregulo et al., 2021). Total mesophilic bacteria in sewage sludge reported in the study of Farian et al., 2022 ranged from 1.6×10^3 to 5.7×10^8 CFU/g, highlight significant microbial activity (Farian et al., 2022). Higher levels of mesophilic bacteria correlate with increased sewage contamination, indicating a greater likelihood of pathogenic bacteria being present (Gunjyal et al., 2023).

The analysis of fecal contamination indicators revealed that total coliform levels ranged between 18×10^4 and 24×10^5 MPN/g, while fecal coliforms were detected in concentrations ranging from 1×10^4 to 14×10^4 MPN/g. These fecal coliform levels exceed the threshold for Class A biosolids ($< 1 \times 10^3$ MPN/g) but remain within the acceptable limits for Class B biosolids ($< 2 \times 10^6$ MPN/g), indicating compliance with the standards recommended by USEPA (2003). Class B biosolids may contain microbial pathogens, primarily enteric, which can pose health risks. However, with appropriate management practices, the risk of direct exposure is considered minimal (Toze & Sidhu, 2011; Pepper et al., 2008).

Comparing these findings with previous studies, Pillai et al. (2011) reported fecal coliform levels of approximately 10^8 MPN/g in untreated sewage, which is significantly higher than the average concentration of 7.6×10^4 MPN/g observed in our study. This notable reduction emphasizes the effectiveness of the treatment processes in substantially lowering fecal bacteria levels, as highlighted by Lee et al. (2010). Nevertheless, the presence of fecal indicators in biosolids raises concerns regarding their agricultural application. Pinilla et al. (2015) stressed the need for continuous monitoring to mitigate potential health risks associated with land application of biosolids. Furthermore, elevated coliform bacteria levels in sludge-amended soils can disrupt soil biodiversity and health, adversely impacting crop productivity and long-term sustainability (Suarez et al., 2023).
Additional microbial indicators were assessed, revealing fecal streptococci levels between 3×10^4 and 43×10^4 MPN/g, while sulfite-reducing anaerobic bacterial spores ranged from 49×10^4 to 10.2×10^5 UFC/g. Although no specific regulatory limits exist for these parameters, they serve as valuable indicators for further evaluation. The presence of fecal streptococci in sewage sludge indicates fecal pollution, serving as a biological indicator for tracking fecal waste sources and assessing potential health risks associated with pathogens, as highlighted in the review on fecal pollution detection (Li et al., 2021). High concentrations of sulfite-reducing anaerobic bacteria may suggest the presence of pathogenic microorganisms, which could pose potential health risks to humans and animals (Vitenko et al., 2023). While the presence of these spores indicates effective anaerobic processes, it may also raise concerns regarding the potential for pathogen regrowth, as seen with clostridia, which could complicate sludge hygienization efforts (Martín-Díaz et al., 2017). The presence of sulfite-reducing clostridia indicates past human pollution, as these bacteria thrive in environments influenced by fecal matter (Robles et al., 2000).

Notably, the analysis confirmed the absence of *Vibrio cholerae* and *Salmonella* in all samples, thus meeting the regulatory standard for Salmonella (< 3 MPN/4 g). This finding supports the suitability of the biosolids for limited land application under Class B conditions, provided that all site-specific management practices are rigorously implemented. Although the sludge meets Class B standards, current regulations do not fully monitor emerging pollutants, underscoring the need for more rigorous testing to protect public health (Pozzebon & Seifert, 2023). Advancing research and strengthening regulatory frameworks are crucial to tackling the ongoing challenges of biosolid management and application.

Table 3 Bacteriological results

Parameters	Minimum	Maximum	Average	Standard deviation	The limit value US EPA Section 503.32
Total mesophile (UFC/g)	9×10^3	7.2×10^4	3.47×10^4	$\pm 2.18 \times 10^4$	-
Total coliforms (MPN/g)	18×10^4	24×10^5	13.6×10^5	$\pm 7.88 \times 10^5$	-
Fecal coliforms (MPN/g)	1×10^4	14×10^4	7.6×10^4	$\pm 3.62 \times 10^4$	$< 1 \times 10^3$ MPN/g for class A $< 2 \times 10^6$ MPN/g for class B
Fecal streptococci (MPN/g)	3×10^4	43×10^4	2.42×10^5	$\pm 1.05 \times 10^5$	-
Sulfite-reducing anaerobic bacterial spores (UFC/g)	49×10^4	10.2×10^5	7.78×10^5	$\pm 1.55 \times 10^5$	-
Vibrio cholerae	0.0	0.0	0.0	± 0.0	-
Salmonella	0.0	0.0	0.0	± 0.0	< 3 MPN/ 4 g

Statistical Analysis of Physicochemical and Bacteriological Parameters

Multivariate analysis of physicochemical and bacteriological parameters reveals significant relationships, validated by Bartlett's test. This analysis is performed through principal component analysis (PCA) and hierarchical clustering. Figures 1,2,3 and 4 display the outcomes of PCA and hierarchical clustering applied to the physicochemical and bacteriological parameters of sewage sludge following multivariate analysis. The PCA provides insight into the relationships among the studied variables by projecting them onto two main axes: Dim 1 (47.03%) and Dim 2 (26.31%), which together explain approximately 73% of the total variance in the data. This representation helps to identify several significant associations between the variables.

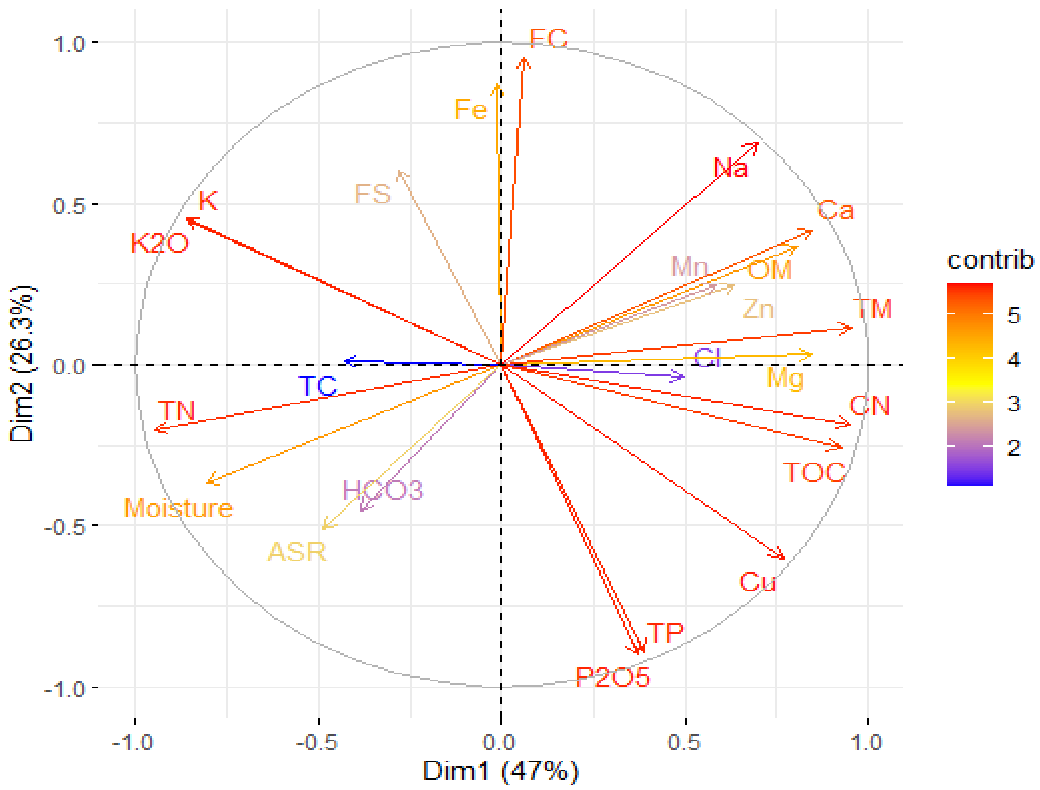

Figure 1. Circle correlation

The correlation circle indicates that certain variables, such as Na, Ca, Cu, TOC, OM, TM, Zn, and Mg, are strongly correlated and contribute positively to Dim 1. In contrast, variables such as Moisture, TN, K, and K2O are oriented in the opposite direction, suggesting inverse relationships. These latter parameters are strongly associated with Dim 2. Furthermore, FC, Fe, and FS are primarily aligned with Dim 2.

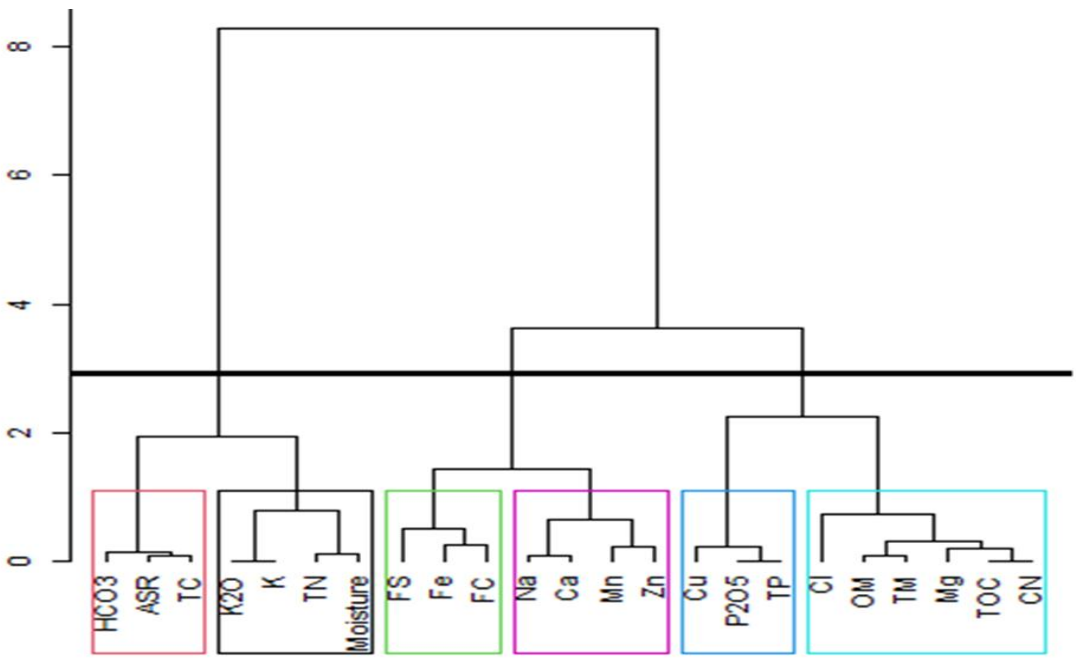

Figure 2. Hierarchical clustering

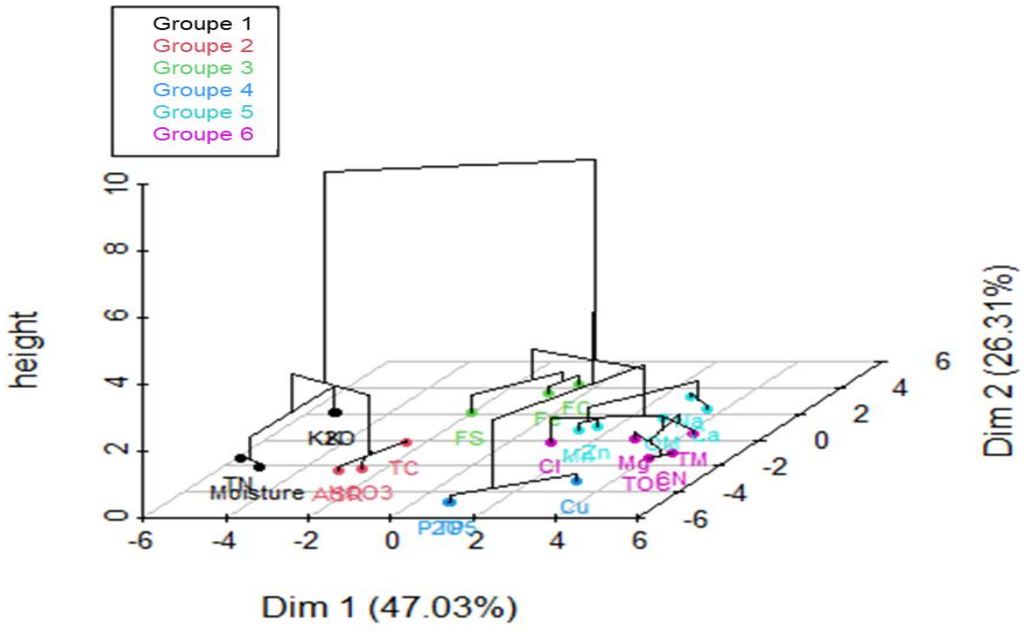

Figure 3. Hierarchical clustering on the factor map

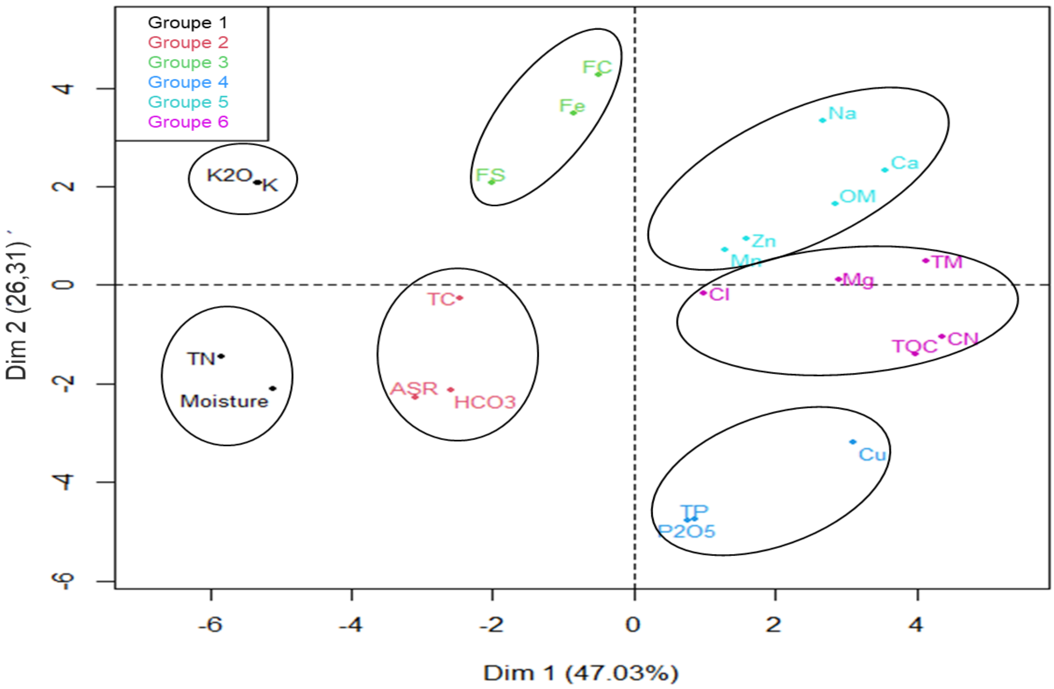

Figure 4. Factor map (Bottom plot)

The hierarchical grouping, shown by the dendrogram and bottom plot, reveals six distinct groups based on similar variability and proximity, illustrating the parameter structuring. The first group associates nutrients and moisture (K, K2O, TN, Moisture) and is separated from other variables. The second group includes variables such as HCO_3^-, ASR, and TC, indicating a strong relationship between sulfate-reducing anaerobic spores and HCO_3^-, with a correlation coefficient of r = 0.59. This suggests that conditions favorable to anaerobic bacteria are linked to the alkalinity of the medium. A third cluster groups parameters like FC, FS, and Fe, where FC and FS show moderate correlations with Fe (r = 0.39 and r = 0.32, respectively). However, FC shows a moderate positive correlation with Na (r = 0.59). The fourth group is composed of phosphorus compounds (P_2O_5, TP, and Cu), while the fifth includes mineral elements and metals (Ca, Na, OM, Zn, Mn). The sixth cluster gathers mesophilic bacteria and organic matter (TM, Mg, TOC, C/N, Cl-). The latter two groups are closely related, highlighting an interdependence between organic matter, minerals, and total microbiological load. Notably, a strong correlation is observed between: total mesophilic bacteria and OM (r = 0.68); TOC, C/N, Ca, Mg, and Na, with correlation coefficients of r = 0.75, r = 0.78, r = 0.55, r = 0.67, and r = 0.66, respectively. This indicates that their development is favored by the presence of organic matter and certain minerals. The results of Oneț, (2014) suggest that elevated organic carbon levels play a key role in promoting bacterial growth. Furthermore, Jin et al. (2007) provides strong evidence that nutrient availability, particularly total nitrogen and organic carbon, is crucial for microbial proliferation in soils. These results reveal significant correlations between physicochemical and bacteriological parameters, highlighting key relationships between organic matter, minerals, and microbial populations, which provide valuable insights for optimizing sewage sludge treatment, and valorization processes, considering the strong interactions between different components.

Conclusion

The analyzed residual sewage sludge proves to be a valuable resource due to its richness in organic matter, total organic carbon, nitrogen, and mineral element as well as its concentrations of heavy metals (Mn, Zn, Fe, Cu), which comply with European and American (USEPA) standards. However, its use requires careful attention due to the significant presence of microorganisms indicative of fecal contamination. Although the level of fecal coliforms remains within the limits of Class B as defined by the USEPA, additional treatments could be considered to improve its hygienic quality and ensure its safe utilization, particularly in agricultural or environmental applications. These characteristics make this sludge a promising material for agricultural or biological reclamation, subject to compliance with environmental standards. Future research could focus on optimizing treatment processes to further reduce microbiological risks while maintaining the nutrient content of the sludge. Exploring innovative technologies such as advanced thermal treatments, composting, or chemical stabilization could enhance its safety and environmental benefits. Furthermore, long-term studies on the impact of sludge application on soil health and crop productivity would provide valuable insights for sustainable agricultural practices.

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