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Settleable Matter from the Parcona Pond as a Soil Amendment for Semi-Arid Soils of Ica-Peru
Materia Sedimentable de la Laguna de Oxidación de Parcona Como Enmienda para Suelos Semiáridos de Ica–Perú

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SUMMARY

Wastewater treatment in oxidation ponds primarily focuses on water purification, often overlooking the potential reuse of the accumulated sediments. The objective of this study was to describe the settleable matter from the oxidation pond in Parcona and assess its potential value for semiarid soils in Ica, Peru. A descriptive study design was applied in the oxidation pond, where five sampling lines (SL-1, SL-2, SL-3, SL-4, and SL-5) were established to ensure representative spatial sampling. In each sampling line, three sediment samples were collected and subsequently homogenized to form a composite sample, which was analyzed in duplicate to determine pH, organic matter content, texture, nitrogen, and phosphorus levels. The main results indicated neutral pH values ranging from 6.6 to 7.3. Organic matter content varied from moderate to very high (2.21%-13.87%). Textural analysis showed high clay content in SL-1 (11.3 g cm^{-3}) and SL-2 (12.3 g cm^{-3}), while SL-3 (73.8 g cm^{-3}) and SL-4 (65.8 g cm^{-3}) were predominantly silt. Nitrogen levels were elevated in SL-2 (1092 mg kg^{-1}) and SL-3 (1321 mg kg^{-1}), and phosphorus was consistently high across all sampling lines. The physicochemical variability of the sediment load reflects complex sedimentation processes that had not been previously characterized. The primary value of this finding lies in the potential use of this biosolid as an agricultural fertilizer; however, variability in pH, organic matter, and texture necessitates careful management to avoid adverse effects on agricultural soils. Overall, the sedimentable material from the oxidation pond exhibited exploitable nutrient properties, reinforcing its value as a fertilizer for semiarid soils within the framework of a circular economy.

Index words: *circular economy, fertilizer, physico-chemical property, sediments.*

RESUMEN

El tratamiento de aguas residuales en lagunas de oxidación consiste en la depuración del agua, aunque ignora la reutilización de los sedimentos acumulados. El objetivo del estudio fue describir la materia sedimentable de la laguna de oxidación de Parcona y valor para el suelo semidesértico de Ica, Perú. Se usó un diseño descriptivo en la laguna de oxidación, donde se establecieron cinco líneas de muestreo (LM-1, LM-2, LM-3, LM-4 y LM-5). En cada una de las líneas, se recolectaron tres muestras de materia sedimentaria y, luego, se mezclaron para formar una muestra volumen que se analizó por duplicado para determinar el pH, materia orgánica, textura, nitrógeno y fósforo. Los principales resultados señalaron que el pH estuvo en el rango neutro (6.6-7.3). La materia orgánica varió de rango medio a muy alto (2.21%-13.87%).

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La textura indicó altos contenidos de arcilla en la LM-1 (11.3 g cm^{-3}) y LM-2 (12.3 g cm^{-3}), mientras que LM-3 (73.8 g cm^{-3}) y LM-4 (65.8) tuvieron mayor limo. Los niveles de nitrógeno fueron elevados en LM-2 (1092 mg kg^{-1}) y LM-3 (1321 mg kg^{-1}), y el fósforo fue alto en todas las líneas de muestreo. Se desconoció la variabilidad físico-química de la carga sedimentaria como proceso complejo de sedimentación. El hallazgo descrito presenta como valor primario el potencial de este biosólido como fertilizante agrícola, pero las diferencias en pH, materia orgánica y textura requieren una gestión cuidadosa para evitar efectos adversos en suelos agrícolas. La materia sedimentable de la laguna de oxidación mostró propiedades nutritivas aprovechables, destacando su valor como fertilizante en suelos semidesérticos dentro de una economía circular.

Palabras clave: *economía circular, abono, propiedad físico-química, sedimentos*.

INTRODUCTION

Ica is one of the 24 departments of Peru (INEI, 2017), where one of its major challenges for agricultural productivity is its semi-desert environment. In this context, the traditional management of soil fertility to maintain crop yields under climatic stress continues to rely on the use of organic fertilizers (Singh *et al*., 2024).

Among the technological systems that enable the generation of substantial quantities of sedimentary organic matter are the oxidation lagoons designed for treating domestic-urban wastewater. This type of system operates through controlled oxidation and biological decomposition processes, facilitated by the action of aerobic and anaerobic microorganisms that break down organic compounds present in the wastewater, resulting in nutrient-rich sediments containing nitrogen, phosphorus, and potassium (Sabliy, Kuzminskiy, Zhukova, Kozar, and Sobczuk, 2019; Skopina, Demin, Kostomakhin, and Kovaleva, 2023). These sediments can be recycled as fertilizers, offering the advantage of containing essential elements for plant growth and the potential to enhance soil structure by increasing moisture retention and promoting microbial activity (Gmitrowicz, Ligęza, Pranagal, Smal, and Wójcikowska-Kapusta, 2023). The use of raw wastewater increases the values of organic matter, electrical conductivity and pH in the upper soil layer (García-Carrillo *et al*., 2020).

Some authors, such as Jafarov (2023), demonstrate that these sediments can be applied directly to agricultural soils or alternatively subjected to composting processes to enhance their physicochemical properties and reduce the presence of pathogens, thereby increasing their safety and effectiveness as fertilizers. Similarly, other researchers emphasize the importance of this sediment load as a valuable resource for agriculture. For instance, recent studies have shown that this sediment is rich in essential nutrients, such as nitrogen and phosphorus, which are crucial for the healthy growth of crops and offer a sustainable alternative (Wang *et al*., 2024; Sharma *et al*., 2024). Additionally, it has been observed that the physicochemical properties of these sediments, such as their texture and water retention capacity, can significantly improve soil structure, thereby enhancing nutrient availability for plants (Gmitrowicz-Iwan *et al*., 2023; Braga *et al*., 2024).

In the context of circular economy, studies suggest that the use of sediments from oxidation ponds not only reduces the quantity of these waste materials but also transforms them into valuable agricultural inputs, promoting a closed resource cycle (Yang *et al*., 2021; Witzgall *et al*., 2021), and aligning with the principles of sustainability and efficiency of the circular economy (Abraham, D'Angelo, Ramírez, Camargo, and Altamirano, 2023; Abel, Eriksson, Gorokhova, and Sobek, 2024). Despite the potential benefits, it is essential to conduct further research to adequately characterize the physicochemical quality of these sediments and assess their applicability in the semiarid agricultural soils of Ica. Although the province of Ica has seven oxidation ponds designated for the treatment of domestic wastewater (García-Gonzalez and Tam-Málaga, 2023; Castillo-Valencia, Condori-Calapuja, and Pérez-Pacheco, 2024), the scientific literature shows a significant lack of studies in Peru that examine the potential of the sediment load from these ponds as an agricultural resource.

The facultative oxidation pond of Parcona, originally designed for the treatment of domestic wastewater, operated through biological processes that regulated organic matter degradation and sediment stabilization. However, the interruption of the domestic influent altered its functionality, modifying the physicochemical and microbiological conditions of the sedimentable material. In this context, the accumulated sediment load is assumed to undergo transformations that may affect its viability as an agricultural amendment, since the reduction of microbial activity and prolonged exposure to arid conditions and high solar radiation can alter its composition and stability. Therefore, its characterization is essential to determine its current properties and assess its potential application in the semi-arid soils of Ica.

The objective of the study was to characterize the settleable material from the Parcona oxidation pond for its potential application as a soil amendment in semi-arid soils under agricultural use in Ica, Peru.

MATERIALS AND METHODS

Study and Sampling Period

The study was conducted in the facultative oxidation pond of Parcona (Ica, Peru) between January and June 2024 (dry period). According to communications from health authorities, the pond had ceased receiving effluent discharges for a period exceeding four months, allowing access to its interior. Additionally, the presence of vegetation suggested favorable substrate conditions (sedimentary load) for its growth. Sampling was conducted between 06:15 and 07:35 hours to mitigate the effects of evaporation and thermal fluctuations, ensuring stable environmental conditions and minimizing external interferences. Five sampling lines (SL) were established, and three sediment sampling points (a, b, and c) were defined within each line (Figure 1). This technique increases representativeness by considering the heterogeneity of the sedimentary load at each sampling location (Charry *et al*., 2020; de Morais, Nicolodelli, Mitsuyuki, Mounier, and Milori, 2021). Subsequently, the three samples collected per sampling line were homogenized to form a composite sample, which was analyzed in duplicate for the determination of pH, organic matter, texture, nitrogen, and phosphorus.

Analysis of Physicochemical Parameters

The pH was determined using the potentiometric method with a glass-electrode pH meter, following the reference standards: EPA 9045D (Soil and Waste pH) and ISO 10390:2005 (Soil quality - Determination of pH). Organic matter was measured using the wet oxidation method with potassium dichromate (Walkley-Black), following the reference standards: ISO 14235:1998 (Soil quality - Determination of organic carbon by sulfochromic oxidation) and ASTM D2974-14 (Moisture, Ash, and Organic Matter of Peat and Organic Soils). The sediment texture was analyzed through granulometric assessment by sieving and sedimentation, following the reference standard: ISO 11277:2020 (Soil quality - Determination of particle size distribution in mineral soil material Method by sieving and sedimentation). Total nitrogen was determined using the Kjeldahl method, following the reference standard: ISO 11261:1995 (Soil quality - Determination of total nitrogen - Modified Kjeldahl method). Total phosphorus was measured using the acid digestion method and molecular absorption spectrophotometry with molybdate blue, following the reference standard: ISO 11263:1994 (Soil quality - Determination of phosphorus - Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution).

The sediment load of the facultative oxidation lagoon, upon losing its active biogeochemical function as an organic substrate, transitions into a residual material with prolonged persistence, whose composition may differ from that of treated sludge. From the perspective of circular economy and its reuse potential, the evaluation was based on the principle of residual functionality, classifying it as a nutrient residual for substrate application, aimed at enhancing and increasing soil fertility. In this context, the physicochemical parameters of the nutrient residual were analyzed concerning soil quality through tests conducted at the Accredited Testing Laboratory Envirotest S.A.C. (Registration No. LE-056, Lima).

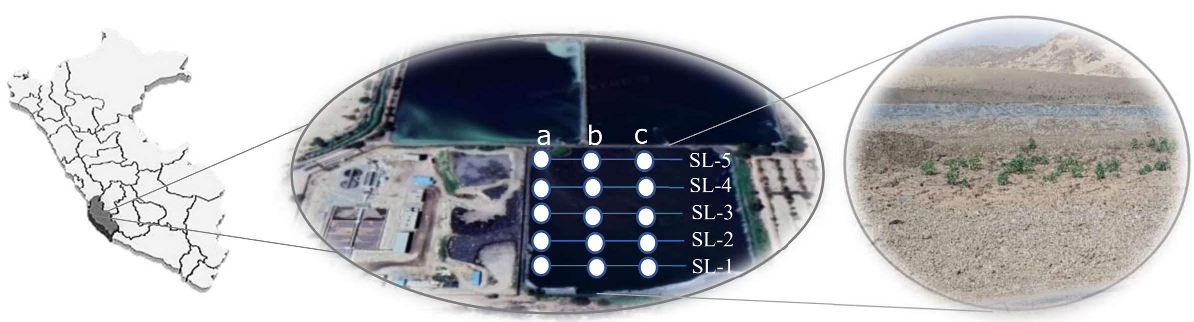

Figure 1. Sampling lines and sampling points in the Parcona oxidation pond, Ica-Peru.

In Peru, Supreme Decree No. 003-2014-MINAM establishes Soil Quality Standards; however, its scope is primarily focused on the regulation of soil contaminants and does not address general physicochemical parameters. Likewise, Supreme Decree No. 015-2017-VIVIENDA approves the regulation for the reuse of sludge generated in wastewater treatment plants, defining biosolids as a byproduct derived from an organic matter stabilization process for specific purposes, such as agricultural, forestry, and industrial applications, among others. Nevertheless, this decree does not establish permissible limits for physicochemical parameters. Given this regulatory gap, the results of the present study were compared against the reference values established in the Official Mexican Standard NOM-021-RECNAT-2000 (2002).

Heavy metals were not analyzed because previous wastewater discharges were of domestic origin and limited in volume. Historically, metal concentrations in reservoir sediments have consistently remained below toxic thresholds (Walter, Gunkel, and Gamboa, 2013). Similarly, microbiological analysis was not considered, as the prolonged absence of wastewater discharges and exposure to high temperatures significantly reduce microbial proliferation and parasite egg viability, as documented in the literature (Obuch-Woszczatyńska, Bylińska, Krzyżowska, Korzekwa, and Bąska, 2025). The lack of favorable conditions for the survival of pathogenic organisms in the sediment eliminates the need for additional analyses, such as the detection of helminth eggs, fecal coliforms, or Salmonella (Mohammad, Khalil, and Hussein, 2022; Otene, Chukwu, and Pepple, 2022).

Data Analysis and Processing

For data analysis, Statgraphics v19 software was used (Statgraphics Technologies, 2019). A multivariate cluster analysis was conducted to describe the similarity among the sampling lines. The method employed was the nearest neighbor, with the distance metric corresponding to squared Euclidean distance and clustering based on observations. The graphical visualization was represented by a dendrogram of groups produced by hierarchical clustering analysis.

RESULTS AND DISCUSSION

Physical-Chemical Evaluation

There is variability in the physicochemical composition of the sediment load among the sampling lines in relation to the reference values (Table 1). All sampling lines (SL-1 through SL-5) exhibited pH values within the neutral range (6.6-7.3), with SL-4 (7.24) approaching the upper threshold. Neutral pH conditions are generally conducive to microbial activity and the bioavailability of essential nutrients. According to Barrow and Hartemink (2023), a neutral to slightly alkaline pH optimizes organic nitrogen mineralization and phosphorus solubility processes critical to soil fertility. Nonetheless, even minor deviations from neutrality, as observed in SL-4 and SL-5, can alter nutrient dynamics, particularly under soils with low buffering capacity. Liu *et al*. (2023) reported that pH fluctuations influence phosphorus speciation and microbial nitrogen transformations, thereby affecting the agronomic efficacy of sediment-based amendments.

Organic matter (OM) content exhibited considerable heterogeneity across the sampling lines. SL-1 showed an exceptionally high OM content (13.87%), substantially exceeding that of the other lines. SL-2 (4.13%) was classified as high, while SL-3 (2.96%), SL-4 (3.44%), and SL-5 (2.21%) fell within the medium range. Elevated OM enhances soil structure, moisture retention, and microbial proliferation, serving as a proxy for soil fertility potential (Voltr *et al*., 2021). However, the marked disparities in OM among lines may hinder uniform field application, especially in mechanized or large-scale agricultural systems. Buttar and Sharma (2023) emphasized that such inconsistencies can lead to spatially heterogeneous nutrient distribution, compromising crop uniformity and fertilization efficiency.

Textural composition also varied significantly among the sampling lines. Clay content was elevated in SL-1 (11.3 g cm^{-3}) and SL-2 (12.3 g cm^{-3}), both exceeding typical reference values. SL-3 (3.1 g cm^{-3}), SL-4 (8.4 g cm^{-3}), and SL-5 (0.9 g cm^{-3}) showed lower clay contents. In contrast, silt dominated SL-3 (73.8 g cm^{-3}) and SL-4 (65.8 g cm^{-3}), while sand was more prevalent in SL-1 (42.4 g cm^{-3}) and SL-2 (38.5 g cm^{-3}). These textural profiles significantly influence bulk density, aeration, porosity, and infiltration rates. Carvalho, Brosinsky, Foerster, Texeira, and Medeiros (2022) noted that clay-rich soils often exhibit reduced porosity and increased susceptibility to compaction under mechanical stress, which may limit root penetration and water movement. Conversely, high-silt matrices, as described by Usaborisut and Ampanmanee (2015) and Oluyemi and Akinleye (2019), are prone to structural instability, especially under high moisture regimes, leading to crusting and sealing phenomena. As such, sediment application must be adapted to site-specific edaphic conditions to avoid structural degradation and preserve soil functionality. Furthermore, Renella (2021) and Zhang *et al*. (2024) underscore the role of phosphate-solubilizing microorganisms in mitigating compaction risks and improving nutrient mobilization in fine-textured soils.

Table 1. Concentration of physicochemical parameters in the sedimentary load of the Parcona oxidation lagoon, Ica-Peru.

Parameters		Unit of measurement	SL-1	SL-2	SL-3	SL-4	SL-5
pH		[-$\log_{10}$(H+)]	7.06	7.05	7.01	7.24	7.16
Organic matter		%	13.87	4.13	2.96	3.44	2.21
Texture	clay	g cm^{-3}	11.3	12.3	3.1	8.4	0.9
	sand		42.4	38.5	23.1	25.8	37.5
	silt		46.3	49.2	73.8	65.8	61.6
Nitrogen		mg kg^{-1}	639.28	1092	1321	594.67	214.21
Phosphorus			754.62	748.06	706.39	767.61	265.68

Reference: SL (sampling lines). pH (strongly acidic: <5.0; moderately acidic: 5.1-6.5; neutral: 6.6-7.3; moderately alkaline: 7.4-8.5; strongly alkaline: >8.5). OM (very low: <0.5; low: 0.6-1.5; medium: 1.6-3.5; high: 3.6-6.0; very high: >6.0). Texture (clay: 1.0-1.19; sand: 1.20-1.32; silt: >1.32). Nitrogen (very low: 0-10; low: 10-20; medium: 20-40; high: 40-60; very high: >60). Phosphorus (low: <5.5; medium: 5.5-11; high: >11).

Total nitrogen concentrations were markedly elevated across the sediment samples, all exceeding the "very high" reference threshold (>60 mg kg^{-1}). SL-2 (1092 mg kg^{-1}) and SL-3 (1321 mg kg^{-1}) registered the highest concentrations, followed by SL-1 (639.28 mg kg^{-1}) and SL-4 (594.67 mg kg^{-1}). SL-5, although lowest (214.21 mg kg^{-1}), still remained within the upper classification. These data indicate significant potential for the use of these sediments as nitrogen-enriched soil amendments. However, excessive nitrogen input is associated with substantial environmental risks, including nitrate leaching and surface water eutrophication. Ferrans *et al*. (2022) and Kiani *et al*. (2023) highlight the need for nutrient balancing and application control to mitigate such impacts. Strategies such as split applications, soil nutrient testing, and the use of controlled-release formulations can enhance nitrogen use efficiency while minimizing environmental losses.

Phosphorus concentrations were also consistently high, surpassing the agronomic threshold (>11 mg kg^{-1}) in all samples. SL-4 (767.61 mg kg^{-1}) showed the highest value, followed closely by SL-1 (754.62 mg kg^{-1}), SL-2 (748.06 mg kg^{-1}), and SL-3 (706.39 mg kg^{-1}). Although SL-5 had the lowest phosphorus level (265.68 mg kg^{-1}), it remained significantly above the threshold for high fertility classification. These elevated P levels suggest strong fertilizing potential but raise concerns regarding phosphorus accumulation, particularly in erosion-prone environments such as the Ica region. Djodjic and Markensten (2019) emphasize that phosphorus runoff is a major contributor to eutrophication in fragile agroecosystems with minimal vegetative cover. The integration of phosphate-solubilizing bacteria, as suggested by Zhang *et al*. (2024), may enhance phosphorus bioavailability while reducing fixation and residual accumulation.

The consistently high concentrations of nitrogen and phosphorus across all sampling lines underscore the agronomic potential of these sediments as biosolids. Nonetheless, their physicochemical heterogeneity presents significant challenges to uniform and safe large-scale application. Agronomic efficacy is contingent not only upon nutrient content but also upon compatibility with target soil types. For instance, while SL-1 may improve structure due to its high organic matter and clay content, SL-3 and SL-4, rich in silt, may increase susceptibility to compaction and reduced drainage if misapplied. In addition, uncontrolled nutrient inputs pose environmental threats. Ferrans *et al*. (2022) and Kiani (2023) caution that excessive use of nutrient-dense biosolids may lead to nutrient runoff, groundwater contamination, and eutrophication of downstream aquatic systems. Therefore, effective nutrient management plans incorporating pre-application soil testing, crop-based dosing, and the use of microbial bioinoculants are essential to optimize benefits and minimize adverse impacts (Zhang *et al*., 2024).

From a circular economy perspective, the reuse of sediments from oxidation lagoons as agricultural amendments aligns with sustainable resource recovery goals. Nevertheless, their safe and effective application requires a comprehensive regulatory framework that ensures quality control, environmental risk assessment, and long-term soil monitoring (Brils, de Boer, Mulder, and Boer, 2014; Beljin *et al*., 2023). The findings of this study confirm the feasibility of such reuse while emphasizing the need for adaptive management strategies tailored to sediment variability and site-specific soil conditions.

Evaluation of Multivariate Analysis

To further interpret the interrelationships among sampling lines, a hierarchical cluster analysis (HCA) was conducted based on their complete physicochemical profiles. The resulting dendrogram (Figure 2) revealed a maximum linkage distance of 0.63, indicating moderate dissimilarity and suggesting that the sediment composition, although heterogeneous, did not exhibit extreme divergence among the five lines.

A distinct cluster was observed between SL-1 and SL-4, which exhibited congruent pH values and intermediate nitrogen levels. Their consistently elevated phosphorus concentrations further support a degree of functional similarity, even in the presence of contrasting textural attributes. This pattern is indicative of convergent geochemical behavior rather than spatial or depositional uniformity, consistent with findings from Li *et al*. (2024), who argue that such clustering often reflects analogous nutrient cycling and retention dynamics within distinct sediment matrices.

SL-5 showed partial association with this cluster. Despite its comparatively low nitrogen and organic matter levels, SL-5's neutral pH and substantial sand fraction aligned it structurally with SL-1. Its inclusion within the cluster may thus be justified by textural and pH similarities, while its divergence in nutrient content underscores a degree of chemical distinction. As suggested by Anschutz *et al*. (2019), cluster formation in sediment analysis is often sensitive to minor shifts in redox state, microbial assemblages, and sedimentation dynamics, which may obscure spatial or physical continuity.

In contrast, SL-2 and SL-3 formed a separate, well-defined cluster, primarily driven by their markedly elevated nitrogen concentrations and dominant silt fractions. The comparatively lower sand content further delineates their grouping, implying enhanced nutrient retention and reduced percolation potential. This association may reflect areas of intensified organic loading or zones with prolonged particle residence time. Zhang *et al*. (2024) describe such configurations as typical in facultative lagoons, where hydraulic flow patterns, settling velocities, and microbial decomposition rates create localized nutrient accumulation zones.

Notably, the cluster configuration did not exhibit a spatially linear progression from SL-1 (proximal to the influent) to SL-5 (near the effluent zone). This non-sequential distribution suggests that sediment deposition within the lagoon is not strictly governed by distance from the inlet but rather by more complex and heterogeneous processes. These may include variable turbulence, episodic wind-driven resuspension, temperature stratification, or differential microbial activity factors previously identified by Anschutz *et al*. (2019) as influential in disrupting spatial sediment gradients.

The absence of a clear spatial pattern in the clustering reinforces the hypothesis of a relatively balanced treatment performance throughout the lagoon, but it also highlights the need for higher-resolution spatial and temporal monitoring. Understanding these dynamic processes is essential for optimizing lagoon management and improving biosolid quality for subsequent agricultural reuse (Watson *et al*., 2020).

However, it is essential to apply these results in broader contexts, such as the reuse of such sediment loads in agriculture, where the risks of their immediate use and their potential long-term influence on the physicochemical and microbiological properties of the soil are taken into account.

A limitation of the study was the lack of knowledge regarding the duration of the absence of domestic wastewater discharges. Under the conditions in which the sampling was conducted, certain climatic factors, such as wind and humidity, may have influenced the dispersion and variability of the physicochemical composition of the sediment load.

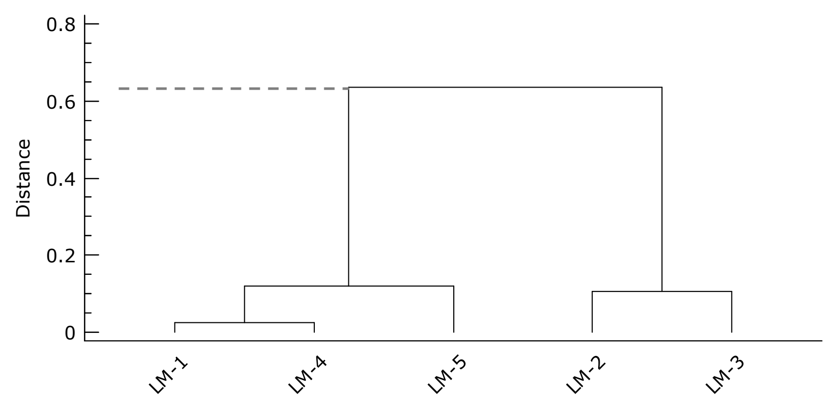

Figure 2. Dendrogram of sampling lines for sediment load in the Parcona oxidation lagoon, Ica-Peru.

CONCLUSIONS

The characterization of the settleable material from the Parcona oxidation pond revealed that its neutral pH, combined with elevated nitrogen and phosphorus concentrations, supports its potential use as a soil amendment in semi-arid agricultural soils. The organic matter content ranged from moderate to very high, indicating viability as an organic fertilizer. However, the sediment's texture, with significant proportions of clay, sand, and silt, requires preliminary treatment to prevent negative impacts on soil structure and the efficiency of water and nutrient retention. Significant physicochemical variability among sampling lines suggests heterogeneous sedimentation and degradation processes. Considering the cessation of effluent inflow and extended exposure to arid conditions, further studies are necessary to evaluate the long-term stability and nutrient bioavailability. Agronomic trials at an experimental scale are recommended to confirm its effectiveness and to assess risks related to persistent contaminants.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The data set shown in the results and received by the accredited laboratory Accredited Testing Laboratory Envirotest S.A.C. is available upon request to the author.

COMPETING INTERESTS

The authors declare no competing interests.

FINANCING

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AUTHORS' CONTRIBUTIONS

Conceptualization, G.A.P., R.F.B.C., and R.A.D.C.; methodology, G.A.P., R.F.B.C., and R.A.D.C.; software, G.A.P.; validation, R.F.B.C., R.A.D.C., and J.A.C.G.; formal analysis, and.; investigation, R.F.B.C., and R.A.D.C.; resources, R.F.B.C., R.A.D.C., and J.A.C.G.; data curation, G.A.P., R.F.B.C., R.A.D.C., and J.A.C.G.; writing-original draft preparation, G.A.P.; writing-review and editing, G.A.P., R.F.B.C., R.A.D.C., and J.A.C.G.; visualization, R.F.B.C., R.A.D.C. and J.A.C.G.; supervision, G.A.P., R.F.B.C., R.A.D.C., and J.A.C.G.; project administration, R.F.B.C., R.A.D.C., and J.A.C.G.

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