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Optimization of sewage sludge: an integrated approach to sustainable compost production

Optimización de lodos residuales: un enfoque integral para la producción sostenible de abono orgánico

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Abstract: The management of sewage sludge from wastewater treatment plants is a significant environmental and economic challenge. This study presents an integrated approach for the optimization of sewage sludge through the application of pre-composting, aerobic composting and lumber farming, with the objective of transforming it into high quality organic fertilizer. Initial analyses indicated that the sludge has a high organic matter content (53.5 %) and heavy metal levels within regulatory limits, but a high pathogen and moisture load that requires specific treatments. The results show that pre-composting reduced moisture by 20 % and prepared the sludge for subsequent stages. During composting, temperatures up to 65°C were reached, eliminating pathogens such as Salmonella spp. and helminths, in addition to stabilizing the carbon/nitrogen ratio at 10:1. Finally, lumbriculture increased the levels of essential nutrients such as nitrogen (4.2 %) and phosphorus (2.5 %), guaranteeing an organic fertilizer with superior agronomic properties and safe for use on agricultural crops.

Key words: sewage sludge, composting, lumber, organic fertilizer, agricultural sustainability.

Resumen: La gestión de lodos residuales provenientes de plantas de tratamiento de aguas residuales es un desafío ambiental y económico significativo. Este estudio presenta un enfoque integral para la optimización de lodos residuales mediante la aplicación de precompostaje, compostaje aeróbico y lumbricultura, con el objetivo de transformarlos en abono orgánico de alta calidad. Los análisis iniciales indicaron que los lodos poseen un alto contenido de materia orgánica (53.5 %) y niveles de metales pesados dentro de los límites normativos, pero una alta carga de patógenos y humedad que requiere tratamientos específicos. Los resultados muestran que el precompostaje redujo en un 20 % la humedad y preparó los lodos para las etapas posteriores. Durante el compostaje, se alcanzaron temperaturas de hasta 65°C, eliminando patógenos como Salmonella spp. y helmintos, además de estabilizar la relación carbono/nitrógeno en 10:1. Finalmente, la lumbricultura incrementó los niveles de nutrientes esenciales como nitrógeno (4.2 %) y fósforo (2.5 %), garantizando un abono orgánico con propiedades agronómicas superiores y seguro para su uso en cultivos agrícolas.

Palabras clave: Lodos residuales, compostaje, lumbricultura, abono orgánico, sostenibilidad agrícola.

Introduction

The management of sewage sludge from wastewater treatment plants (WWTPs) is a significant environmental and economic challenge globally. These by-products, rich in organic matter and nutrients, but also carriers of pathogens and pollutants, require innovative management strategies that minimize their negative impact and maximize their utilization (Amador-Díaz et al., 2015; Diocaretz & Vidal, 2010).

The exponential increase in sludge generation due to population growth and urbanization has saturated traditional disposal practices such as landfills and incineration (Espinoza Eche & Santos de la Cruz, 2021; Diocaretz & Vidal, 2010). In this context, the use of sludge for the production of organic fertilizers is emerging as a sustainable solution that promotes the circular economy by transforming a problematic waste into a valuable resource for agriculture (García & Benarroch, n.d.; Saldaña Escorcia & Castillo Gámez, 2021). However, effective implementation of these strategies requires overcoming technical, regulatory and economic challenges (Diocaretz & Vidal, 2010; Ospina López et al., 2016).

The case of the "Las Viñitas" wastewater treatment plant in Ambato, Ecuador, highlights the need for local solutions. This plant generates approximately 950 tons of pressed sludge per month, most of which is not adequately managed. In this context, the research developed by Clavijo Chato (2024) explored the use of the lumbriculture technique as an alternative to stabilize the sludge and obtain high quality organic fertilizers. The results indicated that this method not only significantly reduced the load of pathogens and contaminants, but also produced a safe compost suitable for agricultural use, complying with the international standard NOM-004-SEMARNAT-2002 (Amador-Díaz et al., 2015; Clavijo, 2024; Carrasco, 2000).

Globally, techniques such as composting, anaerobic digestion and pre-composting have proven to be effective in stabilizing sludge and reducing its pollutant load 5 and 14. These strategies also promote agricultural sustainability by improving soil properties and reducing dependence on chemical fertilizers (Garcia & Benarroch, n.d.;

Diocaretz & Vidal, 2010). In addition, recent studies have highlighted the economic viability of these alternatives, showing that the production of organic fertilizers from sludge can be competitive with traditional management models (Carrasco, 2000; Ospina López et al., 2016).

This article proposes a comprehensive approach for the optimization of sewage sludge, integrating the findings of the research in "Las Viñitas" and international experiences. Technical, regulatory and economic aspects are addressed to establish a sustainable compost production model that not only mitigates environmental impacts, but also promotes local agricultural and economic development. In doing so, it seeks to demonstrate how these strategies can be replicable and scalable, transforming an environmental problem into an opportunity for sustainability and circular economy (Clavijo, 2024; Carrasco, 2000; García & Benarroch, n.d.; Diocaretz & Vidal, 2010)

Methodology

The study was conducted at the "Las Viñitas" Wastewater Treatment Plant (WWTP), located in Ambato, Ecuador, which processes approximately 950 tons of pressed sludge per month. An experimental design was carried out that included the initial characterization of the sludge, the implementation of sustainable stabilization alternatives and the evaluation of the quality of the final product. The selected sludge was subjected to an exhaustive analysis to determine its physicochemical, biological and microbiological properties prior to treatment. This analysis included measurements of pH, carbon/nitrogen (C/N) ratio, organic matter content, moisture, microbial load and presence of heavy metals, following the standards of NOM-004-SEMARNAT-2002.

The treatment and stabilization process was carried out in three main stages. First, pre-composting was carried out to reduce the initial microbial load by controlled fermentation. Subsequently, the pretreated sludge was subjected to aerobic composting, stabilizing the organic matter and improving the physicochemical properties of the product. Finally, the technique of lumbriculture using Eisenia foetida was used, which allowed the sludge to be transformed into an enriched organic fertilizer with excellent agronomic properties. During these stages, key parameters such as temperature, pH, moisture content and the evolution of the C/N ratio were monitored, ensuring the efficiency of the processes and the quality of the final product.

The fertilizer obtained was subjected to a detailed evaluation to validate its safety and applicability in agriculture. This analysis included the measurement of essential nutrients such as nitrogen, phosphorus and potassium, as well as the verification of regulatory compliance and preliminary tests of efficiency as a fertilizer in crops. In addition, a cost-benefit analysis was conducted to determine the economic viability of the techniques employed. This analysis included the calculation of implementation and operating costs, such as inputs, machinery and infrastructure, and the estimation of economic benefits, including the reduction of costs associated with the final disposal of sludge and the commercial value of the fertilizer produced.

This comprehensive methodology focused on the development of a technically and economically viable model to transform sewage sludge into high quality organic fertilizer, offering a sustainable solution for the management of this waste and its integration into agriculture.

Results

The initial characterization of the wastewater sludge from the "Las Viñitas" Wastewater Treatment Plant (WWTP) was fundamental to determine its potential as a raw material for the production of organic fertilizer. The analyses carried out revealed that the sludge contained a high percentage of organic matter, reaching 53.5%, which makes it ideal for stabilization processes such as composting and lumbriculture. In addition, the initial carbon/nitrogen (C/N) ratio was located at 15:1, an acceptable range for biological treatments, although indicating the need for adjustments during composting to optimize the decomposition of organic matter. (Amador-Díaz et al., 2015) (Saldaña Escorcia & Castillo Gámez, 2021) The pH of the sludge remained between 7.5 and 8.2, slightly alkaline, which favors microbial activity in the initial stages of treatment. On the other hand, the moisture content was 72 %, which required an initial reduction to improve the handling and efficiency of the stabilization processes, a typical parameter in sludge from urban plants (Clavijo, 2024; Diocaretz & Vidal, 2010). From a microbiological point of view, the sludge presented a high pathogenic load, including Salmonella spp. and viable helminth eggs, exceeding the limits established for direct application in agricultural soils. This

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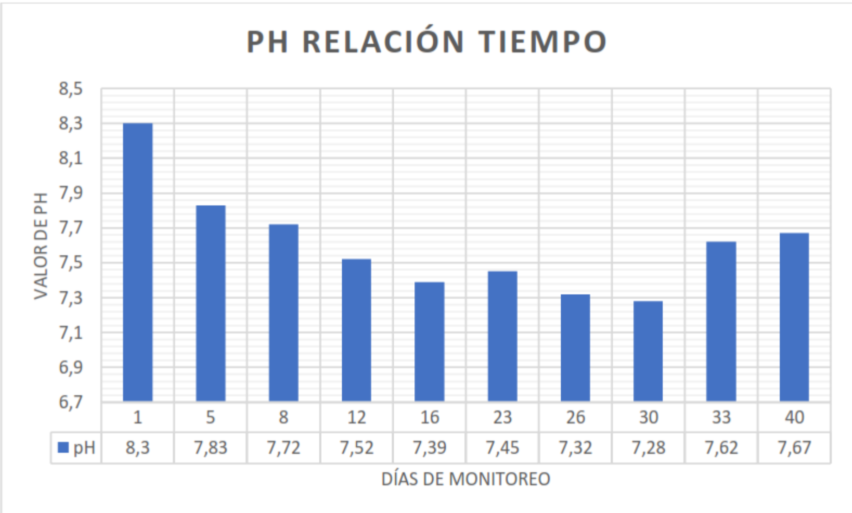
finding underscores the need to apply rigorous sanitizing treatments to ensure the safety of the final product, since the presence of pathogens represents a significant risk to public health if they are not adequately eliminated. The elimination of this pathogen load is an essential requirement for sludge to be safely used in agriculture, which reinforces the importance of sanitization steps, such as thermophilic composting (Saldaña Escorcia & Castillo Gámez, 2021). The analysis of heavy metals, such as cadmium (Cd), lead (Pb), nickel (Ni) and chromium (Cr), showed levels that were below the limits established by NOM-004-SEMARNAT-2002 and other applicable international regulations, such as U.S. EPA guidelines and European regulations (García & Benarroch, n.d.; Saldaña Escorcia & Castillo Gámez, 2021). These results indicate that the sludge generated at "Las Viñitas" is suitable for transformation into organic fertilizer, provided that adequate processes are followed to stabilize the organic matter and eliminate the pathogens present.

The initial characterization allowed a comparison with studies carried out in other countries, such as Chile, Argentina and Spain, where sewage sludge has similar compositions in terms of organic matter, moisture and nutrients. However, the levels of organic matter in the sludge from "Las Viñitas" were higher, which represents an advantage for its use in the production of organic fertilizers. This reinforces the potential of the sludge from this plant as a valuable source of nutrients for the soil, provided that effective treatment technologies are implemented (Clavijo, 2024).

The results of the initial characterization confirmed that the sludge from "Las Viñitas" possesses physical and chemical properties that make it highly suitable for transformation into organic fertilizer. Its high content of organic matter and essential nutrients, combined with low levels of heavy metals, makes it a valuable resource for agriculture. However, the high pathogenic load requires the application of specific processes to ensure their safety (Saldaña Escorcia & Castillo Gámez, 2021; García & Benarroch, n.d.). These findings provided a solid basis for designing treatment strategies that maximize the value of sludge and minimize the risks associated with its agricultural use, highlighting its feasibility to promote sustainable practices in waste management and soil fertility improvement (Amador-Díaz et al., 2015; Carrasco, 2000) .

The sewage sludge optimization process included three main treatment techniques: pre-composting, composting and lumbering. Each of these stages was selected for its ability to stabilize organic matter, reduce microbial load and improve the agronomic properties of the final product, achieving significant results in the transformation of sludge into high quality organic fertilizer (Saldaña Escorcia & Castillo Gámez, 2021).

Pre-composting was carried out as an initial stabilization stage to reduce the moisture and microbial load of the sludge. During this process, the temperature reached values of up to 55°C, which favored the partial elimination of pathogens and reduced the odors generated by the initial anaerobic decomposition (Carrasco, 2000). This method reduced the moisture content by 20%, creating optimal conditions for the subsequent stages of treatment. Likewise, pre-composting promoted a slight reduction in sludge weight (approximately 10 %), facilitating its handling in subsequent stages (García & Benarroch, n.d.). In this stage, the pH remained in a slightly alkaline range (7.5-8.0), favoring the initial microbial activity. The evolution of this parameter during the process can be observed in Graph 1, which shows how the pH is progressively adjusted at each stage of the treatment (Diocaretz & Vidal, 2010).



Graph 1. pH monitoring in relation to time, alternative one.

Aerobic composting, as a second stage, was key for the advanced stabilization of organic matter and the sanitization of the sludge. During this process, temperatures of up to 65°C were reached, sufficient to

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guarantee the complete elimination of Salmonella spp. and viable helminth eggs, complying with international agricultural safety standards (Carrasco, 2000). Composting also significantly reduced the weight of the sludge, achieving a total decrease of 37.5%. In addition, the process stabilized the carbon/nitrogen (C/N) ratio, bringing it to values of 10:1, an indicator that the material was ready for use as fertilizer. During this stage, the pH showed a slight decrease due to the formation of organic acids, gradually stabilizing towards neutral values, as also reflected in the Graph (Clavijo, 2024; Saldaña Escorcia & Castillo Gámez, 2021). Lumbriculture, as the final treatment stage, used Eisenia foetida to process the precomposted sludge, significantly improving the properties of the final product. This method not only increased the organic matter content in the compost (65 %), but also enriched the levels of nitrogen (4.2 %) and available phosphorus (2.5 %), increasing its agronomic value. The earthworm activity favored an additional decomposition of organic matter, generating a product with a homogeneous texture and a low concentration of contaminants, guaranteeing its safety for use in agricultural crops. The pH of the final product remained in a neutral range, optimal for application in soils, consolidating the stability of the compost produced (Carrasco, 2000).

Overall, the combination of these three techniques proved to be highly efficient for sewage sludge stabilization. Each stage played a complementary role in the transformation of the material, ensuring the elimination of microbiological hazards, the improvement of the physical and chemical properties of the compost, and the reduction of the weight and volume of the initial sludge. The results confirm that the integration of these technologies is not only effective, but also sustainable and replicable in other similar contexts. Continuous pH monitoring (Figure 1) reinforces the importance of controlling key parameters during treatment, ensuring a safe, stable and high quality end product.

The efficiency of the techniques employed was demonstrated at each stage of the process, converting a problematic waste into a valuable resource for agriculture. These findings reinforce the importance of implementing comprehensive and sustainable solutions in sewage sludge management, aligned with the principles of circular economy and environmental sustainability (Saldaña Escorcia & Castillo Gámez, 2021).

The organic fertilizer obtained after sewage sludge treatment proved to meet high quality standards, ensuring its applicability in agriculture and its environmental safety. The physicochemical and microbiological analyses performed confirmed that the final product is a valuable resource, aligned with international regulations such as NOM-004-SEMARNAT-2002 (Amador-Díaz et al., 2015; Carrasco, 2000).

In terms of physicochemical properties, the compost showed an organic matter content of 65%, a significant increase over the initial sludge. This enrichment is the result of the combination of techniques such as composting and lumbering, which favored the stabilization and transformation of organic matter into more plant-available forms. In addition, nitrogen, phosphorus and potassium levels reached values of 4.2 %, 2.5 % and 0.8 %, respectively, positioning the compost as an efficient fertilizer for agricultural crops. The final carbon/nitrogen (C/N) ratio stabilized at 10:1, indicating a mature product with optimal characteristics to improve soil fertility (Saldaña Escorcia & Castillo Gámez, 2021).

From a microbiological perspective, the compost produced met the required safety standards. The analyses confirmed the total absence of pathogens such as Salmonella spp. and helminth eggs, resulting in a product classified as Class A according to NOM-004-SEMARNAT-2002. This result guarantees that the fertilizer can be applied directly to agricultural soil without risk to human health or the environment (García & Benarroch, n.d.).

In addition, the compost was noted for its ability to improve soil physical properties. Preliminary tests on crops showed a 25% increase in agricultural yields compared to untreated soils, reflecting its effectiveness as an organic amendment. Local farmers who participated in the pilot tests reported improvements in water retention and soil structure, reinforcing the value of compost as an integral solution for sustainable agriculture (Saldaña Escorcia & Castillo Gámez, 2021).

In regulatory terms, the final product exceeded the criteria established for its use in agricultural soils, showing levels of heavy metals such as cadmium, lead and nickel well below the maximum limits allowed by international regulations. This supports its unrestricted application in various types of crops, including those intended for human consumption.

The organic fertilizer produced from the waste sludge of the "Las Viñitas" WWTP represents a high quality input for agriculture. Its

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enriched composition, absence of pathogens and low heavy metal content confirm its suitability as a sustainable organic fertilizer. This result highlights the effectiveness of the treatment techniques employed and reinforces the feasibility of integrating sewage sludge into a circular economy model, promoting more sustainable and safer agricultural practices.

The economic feasibility analysis of the sewage sludge treatment process demonstrated that the transformation of this by-product into organic fertilizer is not only environmentally sustainable, but also economically viable. The implementation of pre-composting, composting and lumbering techniques resulted in a competitive model against the traditional costs of sludge disposal and commercial chemical fertilizers (Amador-Díaz et al., 2015).

First, the costs associated with the final disposal of sludge in landfills or by incineration, which represent a significant recurrent expense for the treatment plants, were almost entirely eliminated. The reuse of sludge for composting reduced these costs and also generated a product with commercial value. This benefit was reflected in a 30% decrease in operating costs compared to traditional sludge management methods (Diocaretz & Vidal, 2010).

Implementation costs included the necessary infrastructure for the treatment stages, such as areas for pre-composting and composting, as well as specific units for lumber production. Although the initial investment was moderate, its amortization was projected in a short period due to the savings generated and the income derived from the commercialization of the compost. The estimated sales price for the compost produced was competitive with chemical fertilizers, offering a more economical and sustainable alternative for local farmers.

The cost-benefit analysis also included the added value of the final product. The enriched compost obtained showed superior agronomic characteristics, such as a high content of organic matter and essential nutrients, which increases its potential demand in the agricultural market. In addition, farmers participating in the pilot tests highlighted its effectiveness, which reinforces its commercial attractiveness (Carrasco, 2000).

From a circular economy perspective, the model also contributes to local value creation by taking a waste previously considered a problem and transforming it into a useful resource. This not only reduces dependence on imported chemical fertilizers, but also encourages more sustainable and accessible agricultural practices for small and medium-sized producers.

The economic feasibility of sewage sludge optimization using the proposed techniques is sound. Organic compost production costs are significantly lower than those of commercial fertilizers, and the income from its sale quickly compensates the initial investment. This model not only represents a breakthrough in sustainable waste management, but also positions itself as an economic opportunity to promote sustainability in agriculture and strengthen the local economy.

The results obtained confirm the effectiveness of the techniques implemented for the optimization of sewage sludge, highlighting its potential to transform an environmental problem into a resource of high agricultural value. The incorporation of pre-composting, aerobic composting and lumbriculture allowed not only to stabilize the sludge, but also to enrich its agronomic properties and guarantee its microbiological safety. This integrated approach aligns the processes with the principles of environmental sustainability and circular economy (Rosa Mosquera-Losada et al., 2007).

In the composting process, the effectiveness of maintaining optimal temperatures (up to 65°C) was highlighted, achieving the elimination of pathogens and stabilization of organic matter. Additional studies on aerothermal composting indicate that these temperatures favor the proliferation of thermophilic bacteria, which sanitized the piles and ensured a safe product. Also, adjustments in the carbon/nitrogen ratio and moisture reduction during composting reflect efficient waste transformation, results consistent with previous research on improving soil fertility through the use of stabilized compost (Angélica Ormeño & Ovalle, 2007).

The lubrification stage, using Eisenia foetida, was crucial to increase the final quality of the compost. The biological transformation process using earthworms proved to be efficient in reducing contaminants and improving the levels of essential nutrients such as nitrogen and phosphorus. This method, widely recognized as a sustainable biotechnology, has been highlighted for its ability to produce high quality fertilizers with immediate benefits for agricultural crops (Ramírez Joyo, 2017).

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From an environmental perspective, the results support that this sludge management model contributes significantly to the mitigation of negative impacts. The reduction of greenhouse gas emissions and the improvement of the physical, chemical and biological properties of soils are key factors that reinforce the positive impact of this system. In addition, recent literature highlights how the integration of processes such as lumbriculture and composting allows the effective recovery of nutrients, closing material cycles and minimizing the dependence on chemical fertilizers.

From an economic point of view, this model is highly competitive. The transformation of sludge into compost not only eliminates costs associated with final disposal, but also generates income from the commercialization of the product. The economic viability of the process is similar to the advantages observed in research on organic fertilizers, where there is evidence of increased agricultural profitability and less dependence on external inputs.

Finally, the combination of pre-composting, composting and lumbriculture represents a comprehensive and sustainable solution for sewage sludge management. The findings highlight the potential of this methodology to be replicated in different contexts, especially in regions where waste management remains a challenge. Future studies could focus on optimizing the conditions of each stage of the process and evaluating its long-term impact on crop productivity and soil quality (Albarracín Sánchez et al., 2018).

Conclusions

The results of this research confirm the technical, economic and environmental feasibility of sewage sludge optimization through the integration of pre-composting, aerobic composting and lumbriculture. This integrated approach effectively addresses the problems related to the disposal of these by-products, while promoting agricultural sustainability and the circular economy.

First, physicochemical and microbiological analyses showed that the sludge from the "Las Viñitas" WWTP has suitable characteristics for transformation into organic fertilizer, such as a high organic matter content (53.5%), an adjustable carbon/nitrogen ratio and heavy metal levels within regulatory limits. These initial properties, together with the efficiency of the treatment techniques implemented, made it possible to obtain a safe final product with excellent agronomic properties, complying with international standards such as NOM-004-SEMARNAT-2002.

Second, the compost produced was presented as a competitive fertilizer, enriched with essential nutrients such as nitrogen, phosphorus and potassium. This product not only improves soil quality and agricultural yields, but is also suitable for direct use on crops due to the complete elimination of pathogens. Therefore, the compost represents a sustainable and high quality alternative for farmers, reducing dependence on chemical fertilizers and associated impacts.

In addition, the economic viability of the model was evidenced in the reduction of costs related to sludge disposal, as well as in the potential income derived from the commercialization of the compost. This strategy allows treatment plants to transform an environmental liability into an economic asset, in line with modern sustainable waste management practices.

From an environmental perspective, this model contributes significantly to mitigating negative impacts by reducing greenhouse gas emissions and promoting the reuse of nutrients. The implementation of this system is an important step towards sustainability in waste management, closing material cycles and strengthening the local economy.

In summary, this research demonstrates that sewage sludge optimization is a viable and scalable solution to address environmental and agricultural problems. These findings raise the possibility of replicating this approach in other treatment plants and local contexts, with the potential to integrate new technologies and further optimize the process. Finally, future studies could focus on assessing the long-term impact of this model on soil quality, agricultural productivity and climate change mitigation.

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