

Analysis of Studies on the Extraction of Materials from Biosolids Through Bibliometric Networks

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Abstract – This study presents a literature review on the extraction of materials from biosolids, utilizing bibliometric tools to identify the most significant findings in this field. A database of documents was compiled from Scopus, and data analysis was conducted using VOSviewer, enabling the visualization of clusters and density maps related to scientific research on this topic. Subsequently, the database was uploaded to ScientoPy to identify key articles within each cluster and analyze the interrelations between these clusters. The main objective of the study was to evaluate the developed methods, identified gaps, and techniques, as well as to analyze potential future works for the extraction of materials from biosolids, with a particular focus on the application of engineering techniques in this area.

Key Words – Bibliometric Networks, Biosolids, Chemical Materials, Clusters, Heatmap, Organic Materials, Wastewater.

I. INTRODUCTION

In nature, each component of the ecosystem plays a crucial role, making the management of wastewater [1] and biosolids [2] a fundamental challenge. Wastewater, generated by daily human activities, contains a variety of substances that, if not properly treated, can pose a significant contamination risk. However, they can also serve as a potential source of nutrients for the soil. Therefore, the proper management of these waste materials is essential to protect the environment and to harness the resources they can offer, thus providing a new use for different compounds and elements that may be vital and essential for flora, fauna, and, of course, humanity itself [3].

Engineering fields, such as systems engineering and other related disciplines, play a key role in innovation, advancement in the treatment, and analysis of wastewater and biosolids. Systems engineering, in particular, stands out for its ability to integrate and optimize complex processes, which is essential for transforming this waste into valuable resources. By identifying critical points and key materials, advanced computational models can be developed and applied to analyze large environmental datasets, optimize extraction algorithms, and improve treatment and contaminant monitoring processes [4].

In this context, the present study aims to conduct an analysis using bibliometric tools to identify and evaluate the methods used in the extraction of elements from biosolids, as well as the elements present in these environments. This review is expected to provide an understanding of the techniques employed and facilitate progress in the management and optimization of resources derived from wastewater and biosolids, addressing questions such as: What are the most commonly used methods in the literature for the extraction and analysis of elements found in biosolids, and what techniques are identified for their collection or extraction?

II. METHODOLOGY

In this context, the study was conducted based on the PRISMA methodology [5], which is widely recognized for its approach to structuring literature reviews in scientific research. This methodology is grounded in principles of transparency and methodological rigor, providing a clear guide for the selection, evaluation, and synthesis of all previous studies presented below. Additionally, it aims to ensure that the systematic reviews included in this text are understandable, reproducible, and free from potential biases, offering a framework that correctly identifies relevant studies, their critical analysis, and the coherent presentation of results. While there are similar methodologies, such as the Cochrane systematic review [6] or the approach of the Agency for Healthcare Research and Quality (AHRQ) [7], PRISMA stands out for its general applicability across a wide range of disciplines. In this bibliometric study, PRISMA not only facilitates the organization of the literature on material extraction from biosolids but also helps identify patterns, trends, and gaps in current research, contributing to the advancement of knowledge in this area, as shown below.

A. Search in "Scopus" [8]

Scopus, one of the largest databases of scientific literature, was selected to conduct the state-of-the-art analysis of the bibliometric network. The following search strings were used for this task:

Table 1 Search Strings in Scopus

Search	Result
(TITLE-ABS-KEY(phosphorus extraction in biosolids) AND KEY(biosolids))	61
TITLE-ABS-KEY(extraction AND of AND materials AND in AND biosolids)	165

Table 1 demonstrates that the topic addressed in the search strings has not been widely studied, as reflected in the results obtained. However, this situation underscores the importance of its analysis to discover new findings in this field. For this reason, once the database was obtained from the search, an analysis was performed using the VOSviewer tool [9].

B. Clusters and Density Map: Their Acquisition and Analysis

With the database present and exported in "RIS" format [10] from Scopus, it was then uploaded into the VOSviewer tool or application. Once uploaded, the corresponding configuration was carried out to generate the map based on bibliographic data, and the database was imported, thus obtaining the bibliometric network (Figure 1) and four clusters, which were named in order as "Biodegradation" (Figure 2), "Contaminants and Wastewater" (Figure 3), and "Soils" (Figure 4). Additionally, a density map (Figure 5) was obtained for subsequent individual analysis, resulting in the following:

2) Density Map

The density map provides a clear visualization of the frequency and relevance of key terms found in the clusters, such as "biosolids," "contaminants," and "wastewater treatment," and shows how they are interconnected. The areas of research include the analysis of contaminants using advanced techniques, the optimization of wastewater treatment processes, and the application of biosolids as soil amendments.

a) *Biosolids and Biological Materials*

This section is represented with a highlighted color in the center of the map, where terms such as "biosolids," "biosolid," and "biological material" are observed. This suggests that a large portion of the research focuses on the management, treatment, and reuse of biosolids, similar to what was observed in the analysis of the main cluster. The high density of these terms underscores their central importance in the field of study, reflecting the number of works dedicated to understanding and optimizing the use of these materials.

b) *Contaminants and Analysis Techniques*

The terms "mass spectrometry," "liquid chromatography," and "solvent extraction" indicate significant research in advanced chemical analysis techniques used to detect and quantify contaminants in biosolids and wastewater. These include heavy metals such as cadmium, lead, and zinc, as well as persistent organic compounds like triclosan.

c) *Wastewater Treatment*

Terms such as "wastewater treatment," "anaerobic digestion," and "sludge" are found in the green area of the map, suggesting a considerable focus on wastewater treatment processes. The research focuses on improving the efficiency and sustainability of sludge and wastewater management through techniques such as anaerobic digestion.

d) *Soil Amendments and Fertilizers*

The terms "soils," "soil amendment," and "fertilizers" show notable density, indicating a focus on how biosolids can be used to improve the quality of agricultural soil. The research investigates the incorporation of essential nutrients such as nitrogen and phosphorus to enhance soil structure and its water retention capacity.

e) *Contaminants in Soils*

The presence of terms such as "soil pollutants," "cadmium," and "zinc" in areas of lower, yet still significant, density indicates research focused on the behavior and mitigation of specific contaminants in soils treated with biosolids. Although this area has lower density, its study is crucial for understanding the long-term effects on soil quality.

sludge. By analyzing samples from various treatment plants, the study found that two compounds in particular, Galaxolide and Tonalide, are the most predominant. Additionally, the study evaluated how different wastewater treatment technologies impact the accumulation of these compounds in sludge, concluding that current technologies have a limited effect on reducing these contaminants.

- Articles [22], [23], [24], and [25] analyze the fate of triclosan and triclocarban compounds during wastewater and biosolids treatment processes. These compounds, common in personal care products, are persistent in the environment.

Studies [26], [27] and [28] discuss the persistence and removal of antimicrobial compounds such as triclocarban and triclosan during the production of municipal biosolids. Despite the fact that anaerobic and aerobic digestion systems show different levels of removal, there is a clear need to improve the efficiency of these processes to reduce the concentration of these emerging contaminants in biosolids.

- The authors of the articles [29], [30], [31] and [32] provide a foundation for the research by [33], offering a comprehensive view of how soil management practices can influence food security and environmental health in specific soils. They investigated how the application of biosolids and farm manure on calcareous soils affects the availability and speciation of heavy metals, such as copper, nickel, lead, and zinc, in wheat plants, three years after the initial application. The main idea is that, although these organic amendments improve soil fertility and physical properties, they can also increase the bioaccessibility of certain heavy metals, which could have implications for environmental and human health. The results show that while lead and nickel concentrations in wheat were lower in soils treated with biosolids and manure compared to untreated soils, zinc and copper concentrations were higher in amended soils. Additionally, most of the metals were found in less bioavailable forms, suggesting a lower environmental risk, although the authors warn that the long-term effect of organic matter degradation could change this dynamic.
- Articles [34], [35], [36], and [37] are relevant for those interested in sustainability and environmental management, as they address the reuse of industrial waste as fertilizers, evaluating both their benefits and potential risks. Essentially, study [34] explores how the use of fly ash and biosolids, in pellet form, affects the availability and mobility of nutrients and potentially toxic elements in the soil, and how this impacts plant growth. In general, the article highlights that while fertilizing with these pellets may increase the concentration of certain elements in the soil, this does not always translate into higher absorption by plants. In fact, plants grown in soils fertilized with municipal incineration fly ash showed greater growth compared to other soils, but also a higher accumulation of toxic elements such as arsenic (As) and cadmium (Cd). The study emphasizes the importance of not exceeding the amount of elements added to the soil to avoid accumulation in the surface layers, which could have negative long-term implications. Furthermore, it suggests that the acid-neutralizing capacity of industrial waste is a key factor in maintaining soil pH levels, which influences nutrient availability and the toxicity of elements.
- Study [38] focuses on developing an analytical method to detect pharmaceutical residues in biosolids, using techniques such as supported liquid extraction (SLE) and tandem mass spectrometry coupled with gas chromatography (GC-MS/MS). The main objective of the article is to establish a rapid and sensitive method for identifying 16 common pharmaceuticals in biosolid samples, which are the organic remnants resulting from wastewater treatment. These compounds range from anti-inflammatory drugs to antidepressants. The article emphasizes the importance of monitoring these residues due to their potential environmental impact, especially since conventional wastewater treatments do not completely eliminate these contaminants.
- In summary, article [38] details, based on articles [39], [40], and [41], how they optimized and applied this method to biosolid samples in Madrid and Catalonia, detecting several pharmaceuticals in low but significant concentrations, highlighting the persistence of these compounds in the environment even after wastewater treatment processes.

- The article [42] addresses the development and optimization of a microwave-assisted extraction method for the determination of selected phenols (alkyl, aryl, and halogenated) in sewage sludge and biosolids. The authors describe how different factors, such as solvent, temperature, time, moisture content, acid, and the number of extractions, affect the recovery of these compounds. This method has been successfully applied to the measurement of phenolic compounds in over 150 samples since 2009, making it an effective tool for the environmental monitoring and assessment of contaminants in sludge and biosolids.
- Author [43] based his work on several articles such as [44], [45], [46], [47], and [48], with the main idea being that, although wastewater treatment plants remove a large amount of microplastics (MPs), a considerable amount still remains, accumulating in the residual sludge. This sludge is then used or disposed of in various ways, such as in landfills, incineration, or applied to agricultural lands. These processes allow microplastics to enter the natural environment, posing risks to both human and ecological health. The article also highlights the need for further research to better understand how these microplastics are transported and persist in the environment, as well as the importance of standardizing methods for their study and reporting.

In summary, the reviewed articles provide a detailed overview of the multiple aspects involved in the management and reuse of biosolids and wastewater. They highlight the persistence of contaminants such as PFAS, microplastics, nitro musks, triclosan, phosphorus, and zinc, emphasizing the need for effective mitigation and monitoring strategies.

IV. FINDINGS AND METHODOLOGIES USED

Table 2 presents a simplified summary of the previously selected articles. Although a summary or analysis of these articles has already been provided, the table below offers a synthesis of the most relevant and objective data.

Table 2 Comparative Summary of Articles

PAPERS	TOPIC DEVELOPED	GAPS FOUND	TECHNIQUES / METHODS / TOOLS	FUTURE WORK
[12]	Study of Temporal Trends of Perfluoroalkyl Substances (PFAS) in Lime-Treated Biosolids from a Water Resource Recovery Facility.	No significant decrease in PFAS concentrations was observed over time, indicating the persistence of these compounds in consumer products and a potential continuous source of contamination.	Analysis of biosolid samples using high-performance liquid chromatography [49] coupled with tandem mass spectrometry [50] (HPLC-MS/MS) to measure PFAS levels in the samples. Comparison of storage methods to ensure the accuracy of the results.	It is suggested to further study the impact of regulation and the elimination of PFAS in consumer products and their persistence in the environment, as well as the evaluation of new technologies for the treatment of these compounds in wastewater treatment plants.
[21]	Analysis of the presence of synthetic musk compounds in sludge from municipal wastewater treatment plants, with a focus on their accumulation and the technological factors that influence their persistence.	Se identifica la limitada capacidad de las tecnologías actuales de plantas de tratamiento para reducir la acumulación de compuestos de almizcle sintético en los lodos. También, la falta de correlación clara entre ciertas condiciones operativas de las plantas y la concentración de estos compuestos.	Collection and analysis of sludge samples using gas chromatography coupled with mass spectrometry (GC-MS/MS) techniques to identify and quantify specific musk compounds. Statistical analysis to evaluate the correlation between operational parameters.	The need to investigate innovative sludge treatment technologies that may be more effective in reducing synthetic musk compounds is suggested. Additionally, further studies are recommended to better understand the influence of different technological factors on the accumulation of these compounds.
[22]	Behavior and Persistence of Triclosan and Triclorcarban During Wastewater and Biosolid Treatment	Need for strategies to eliminate or reduce these compounds during treatment	Solvent extraction techniques, gas chromatography coupled with mass spectrometry (GC-MS)	Research on advanced treatment technologies for the removal of antimicrobial compounds
[26]	Removal of Triclorcarban (TCC) and Triclosan (TCS) During the Production of Municipal Biosolids	Need to improve the efficiency of TCC and TCS removal during sludge treatment	Heated solvent extraction, liquid chromatography coupled with mass spectrometry (LC-MS)	Development of more effective methods for the removal of TCC and TCS, and evaluation of their transformation byproducts
[33]	Investigate the residual effects of applying biosolids and farm manure on calcareous soils, focusing on the speciation and absorption of heavy metals (Cu, Ni, Pb, Zn) in wheat plants.	Lack of information on the long-term effects of organic matter degradation on the mobility and bioavailability of heavy metals in soils treated with biosolids and	- Chemical speciation through sequential extraction of metals. -Analysis of pH, electrical conductivity (EC), and organic carbon (OC) in the soil.	It is suggested to investigate the long-term effects of biosolid application, especially considering the degradation of organic matter and its impact on the mobility and

PAPERS	TOPIC DEVELOPED	GAPS FOUND	TECHNIQUES / METHODS / TOOLS	FUTURE WORK
		manure.	-Atomic absorption spectroscopy (AAS) for metal quantification.	bioaccessibility of heavy metals in the soil.
[34]	Assessment of the availability and mobility of nutrients and potentially toxic elements in soils fertilized with fly ash pellets and biosolids.	The relationship between the total elemental content in the soil and its absorption by plants is not always proportional, indicating a gap in the understanding of the mechanisms that influence the bioavailability of toxic elements.	- Plant pot experiments. -Sequential extraction of elements. -Analysis by inductively coupled plasma optical emission spectroscopy (ICP-OES). -Measurement of pH and acid neutralization capacity.	Long-term investigation of the impact of toxic element accumulation in the surface layer of soil and its effect on the food chain.
[38]	Development of an analytical method for the detection of pharmaceutical compounds in biosolids using supported liquid extraction (SLE) and gas chromatography coupled with tandem mass spectrometry (GC-MS/MS).	Lack of adequate analytical methods to detect a wide range of pharmaceuticals in complex solid matrices such as biosolids; most previous studies have focused on a limited number of compounds.	Lack of adequate analytical methods to detect a wide range of pharmaceuticals in complex solid matrices such as biosolids; most previous studies have focused on a limited number of compounds.	Expand the applicability of the method to other compounds and environmental matrices, as well as optimize it for greater efficiency in detecting emerging contaminants.
[42]	Development and optimization of a microwave-assisted extraction method for the determination of phenols in sludge and biosolids.	Limited information on organic contaminants in sludge and biosolids, along with a lack of efficient analytical methods.	Microwave-assisted extraction, gas chromatography with mass spectrometry (GC-MS), in situ acetylation, silica gel column cleanup.	Application of the method to a broader range of compounds and more environmental samples, improving sensitivity and accuracy in the detection of phenolic compounds.
[43]	The study addresses the presence and persistence of microplastics in sludge from municipal wastewater treatment plants and their impact on the environment. It focuses on how this sludge, when reused or disposed of, can be a significant source of microplastics in terrestrial and aquatic ecosystems.	Several gaps in knowledge are identified, including the lack of standardization in the quantification and analysis methods for microplastics, as well as insufficient understanding of how microplastics are transported and persist in different environments following their application to agricultural soils or disposal in landfills.	Literature review techniques were used to quantify microplastics in sludge, including extraction and analysis methods such as density separation, vacuum filtration, and Fourier-transform infrared spectroscopy (FTIR) for the identification of microplastics.	Future work should focus on improving the standardization of analysis methods, gaining a better understanding of the transport and persistence of microplastics in different environments, and exploring new technologies to reduce the release of microplastics from treated sludge.

V. CONCLUSIÓN

The bibliographic analysis provides a comprehensive view of the multiple aspects involved in the management and reuse of biosolids and wastewater. The studies highlight the persistence of contaminants and underscore the need for effective strategies for their mitigation and monitoring. Engineering plays a fundamental role in the extraction and treatment of chemical compounds, developing sustainable and effective solutions. This bibliometric study is crucial for understanding the trends and challenges in the treatment of wastewater and biosolids, providing a basis for the search for new solutions.

The essence of the study lies in the identification of multiple research themes, knowledge gaps, employed techniques, and directions for future work, thus facilitating a more complete understanding of the current state of knowledge in a specific field. By studying the management of biosolids and wastewater treatment, the bibliometric analysis has provided valuable information on predominant areas of focus, the most commonly used methods, and emerging needs in everyday practice. It assists future researchers in the field by guiding their efforts toward areas that require more attention and developing more effective and sustainable strategies, fostering collaboration and knowledge exchange among the various researchers who have contributed to these topics.

However, studies on the presence and removal of organic contaminants such as perfluoroalkyl substances (PFAS), triclocarban (TCC), triclosan (TCS), and nitro musks have highlighted the persistence of these compounds in biosolids throughout the treatment processes. For example, the research by Ogunyoku and Young on the removal of TCC and TCS during the production of municipal biosolids emphasizes the need to improve the efficiency of current treatment methods to reduce the concentration of these emerging contaminants. This issue is critical, as the persistence of these compounds poses long-term environmental and human health risks.

The presence of microplastics in wastewater sludge is an emerging concern due to their ubiquity and potential to enter the food chain. Furthermore, heavy metals, as discussed in the article on the influence of these metals on anaerobic digestion, can inhibit biological processes and reduce sludge treatment efficiency. These findings accentuate the urgent need to develop advanced treatment technologies and mitigation strategies to address these contaminants.

Composting and anaerobic digestion are key processes in biosolid management, providing sustainable solutions for transforming waste into useful resources. Studies on composting presented in the articles have demonstrated its effectiveness in the biodegradation of organic contaminants and the improvement of the quality of the resulting fertilizer. On the other hand, research on anaerobic digestion highlights how the addition of certain additives can significantly increase methane production, offering a valuable source of renewable energy. However, it is crucial to continue optimizing these processes to maximize their efficiency and sustainability.

The application of biosolids to agricultural soils can improve soil fertility and physical structure, providing essential nutrients such as nitrogen and phosphorus. Nevertheless, studies have pointed out the need to better understand the long-term effects of this practice, including monitoring residual contaminants that could affect soil and plant health. Future research should focus on developing management strategies that ensure the sustainability and safety of biosolid application in agriculture.

The generated tables have identified several knowledge gaps that need to be addressed in future research. Among them is the need to develop more effective methods for the removal of organic contaminants and heavy metals, the mitigation of microplastics in sludge, and the optimization of composting and anaerobic digestion processes. The authors of the reviewed articles have proposed various areas for future research, including the evaluation of transformation byproducts of contaminants and the development of advanced treatment technologies. These directions are fundamental for advancing the sustainable management of biosolids and wastewater treatment, contributing to the protection of the environment and public health.

Finally, this study demonstrates the importance of the applicability of multiple engineering disciplines or expert fields in the subject, as they are necessary to carry out each of the processes or procedures required in the analyzed articles; since, even if one does not act as a developer of the presented methods, their analysis facilitates the understanding and search for these methods for future developments or to improve the accessibility of the knowledge presented.

VI. REFERENCES

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