WTP SLUDGE: A BIBLIOMETRIC AND SYSTEMATIC REVIEW ON THERMOCHEMICAL CONVERSION TO BIOPRODUCTS AND SUSTAINABILITY

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ABSTRACT

In this work, the challenges involved in the management of waste from water treatment plants (WTPs) were addressed, with a focus on the significant production of sludge. It was investigated on the conversion of these sludges into bioproducts by pyrolysis, highlighting the environmental and economic benefits, exploring its potential as a raw material for renewable energy, eliminating waste and mitigating greenhouse gas emissions. Through a bibliometric review carried out, which was governed by the laws of Lotka, Bradford and Zipf, and using the Web of Science and Scopus databases, the frequency of keywords, authors, articles and the most relevant journals in the area were identified. A systematic analysis was also carried out to deepen the findings around the theme. In this context of disseminated research, the geographic results indicate the leadership of Brazil in publications, followed by China. Among the most recurrent keywords around the theme are *biomass*, *pyrolysis, biochar*, *charcoal, biofuels*, *life cycle* and *waste water treatment* and *thermochemical conversion*. The journal that presents the most publications in this area was the Journal of Cleaner Production, with an impact factor of 9.8. Thus, this study offers a general understanding of the research on the use of WTP sludge, highlighting its environmental and energy importance. The topic involving the conversion of WTP sludge into bioproducts by pyrolysis fits with several Sustainable Development Goals (SDGs) and ESG (Environmental, Social and Governance) principles, namely, it is mainly related to SDG 6, which seeks to ensure the availability and sustainable management of water, and SDG 7, which promotes the use of clean and affordable energy. In addition, it supports SDG 11 by contributing to sustainable cities and communities, and SDG 12, by promoting sustainable consumption and production patterns. From an ESG point of view, the study addresses environmental issues, by encouraging the reduction of waste and emissions, and social issues, by promoting the improvement of public health and quality of life through proper waste management. It also aligns with the principles of governance, by fostering the implementation of sustainable management practices and transparency in environmental operations, promoting more responsible and sustainable development.

Keywords: Thermochemical processes. Pyrolysis. Mud. Water Treatment Plant (ETA). Bioproducts.

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INTRODUCTION

In recent years, the rapid economic development of countries has resulted in the significant production and accumulation of hazardous wastes such as sludge. These wastes, from hospital medical treatments, industrial manufacturing and other activities, pose serious risks to both the environment and human and animal health, due to their harmful characteristics. Unlike ordinary waste, hazardous waste cannot be treated in the same way, due to its corrosive, toxic, reactive and infectious properties. Thus, the proper treatment of hazardous waste constitutes a considerable challenge, and its improper handling can have serious consequences, awakening the urgency for advanced treatments such as the pyrolysis method.

Particularly, drinking water treatment plants are facing emerging challenges that affect raw water quality (De Marines et al., 2025). So much so that one of the most important contemporary environmental challenges in the world is the pollution and degradation of aquatic habitats. Many toxins reach aquatic streams as a result of human and natural activity, which poses a serious risk to both the environment and human health. As a consequence, addressing the challenges of water pollution and its monitoring is critical in terms of formulating management and protection measures, and has become a top priority for sustainable development (Kushwaha et al., 2025).

Among other factors, this is due to the strong influence of the advance of industrialization in world societies, which increasingly causes the release of pollutants into aquifers, causing great variability in water, thus imposing the need for treatments with a greater amount of chemical products. Achieving universal access to clean water, as mandated by SDG 6 – Clean Water and Sanitation, is crucial to supporting human health and environmental sustainability.

Solid waste from water treatment plants, or simply sludge, comes from conventional WTPs, encompassing the processes of coagulation, flocculation, decantation, filtration, disinfection, and fluoridation (Aquino et al., 2023). This by-product known as sludge, comprises organic and inorganic substances. Traditionally, the disposal of this type of sludge has presented environmental risks, including nutrient runoff and heavy metal contamination (Almeida et al., 2024).

In addition, the water remaining from sludge sedimentation in sedimentation tanks in drinking water WTPs contains significant amounts of dissolved organic matter and precursors of disinfection by-products, raising growing concerns about the safety of finished water after recycling. There is a marked presence of aromaticity and complexes containing nitrogen and sulfur heteroatoms, which are key precursors of the by-products used in the

water disinfection process (Wang et al., 2025), this fact indicates that the sedimented sludge also contains these pollutants.

The use of aluminum coagulants during drinking water treatment is crucial for the improved removal of particles and other impurities from raw water. However, this coagulation-sedimentation process generates a considerable amount of aluminum-rich drinking water treatment sludge as a typical municipal waste that requires proper treatment and disposal. This sludge is typically destined for landfills, wasting valuable urban land with potential environmental hazards (Li, P. et al., 2025). Wastewater sludges are also major reservoirs and sources of antibiotic resistance gene emission in cities. There is the presence of antimicrobial resistant host bacteria, which provides biological and ecological risks (Li, Y. et al., 2025).

There are several challenges to managing the sludge generated. The variability of waste, the options for beneficial use, the need to change the type of treatment, or the products used, to meet the requirements of a specific use, the need for differentiated dewatering to reduce transportation costs or to meet the requirements of final disposal, among other aspects, make decision-making complex and involve several interrelated processes. Given the various aspects involved, the decision on the disposal of sludge cannot be based solely on one criterion or another (Urban, Nakada, and Isaac, 2023). In addition, the generation of sludge in WTPs occurs constantly and in significant volumes. This scenario, combined with the high rate of population growth in large cities, demands the adoption of appropriate technologies that ensure the safe disposal of this type of waste, aiming to prevent or reduce the associated environmental impacts.

Discussions on sludge management in Brazil highlight the need for integration between Municipal Plans and the National Solid Waste Policy to ensure the environmentally appropriate disposal of this waste. However, an analysis of 24 Municipal Plans for Basic Sanitation (MPBS) and Integrated Solid Waste Management (ISWM) revealed significant flaws, such as the absence of data on the generation and characterization of sludge and filter washing water, in addition to the lack of proposals for the beneficial use of this waste. The lack of transparency and indicators in the National Sanitation Information System (SNIS), widely used in public reports, contributes to the lack of charges for efficient management, which accentuates environmental and operational challenges (Silva, Achon, and Isaac, 2019).

The SNIS data have limitations in offering a generalist and superficial view of the water supply system in the Brazilian scenario. There is a lack of a holistic analysis of the life cycle of the supply and specific indicators for waste management, such as the sludge

generated in WTPs. The absence of detailed data compromises the evaluation of municipal performance and the implementation of goals for improvement. In addition, the quantification of the waste generated, essential for decisions on dewatering and final disposal, is not a common practice in most Brazilian WTPs, in addition, few evaluate its characteristics, indicating a significant challenge for integrated waste management (Achon, Barroso and Cordeiro, 2013; Silva, Achon and Isaac, 2022). For example, a study involving 82 WTPs in the State of São Paulo concluded that 56% of them do not measure and/or estimate the amount of sludge generated (Silva, 2021).

The amount of waste produced in the WTPs varies, depending on the type of treatment process used. It is estimated that the production of WTP sludge in the municipalities operated by Sabesp, for example, in the State of São Paulo, is approximately 90 tons per day, on a dry basis. There are significant variations in the amount of sludge generated in a WTP throughout the year. Sludge production is higher during the rainy season (from November to March), when there is a worsening in the quality of water from the springs, which requires greater use of chemicals, specifically coagulants, to treat it (Iwaki, 2018).

Studies at the Brazilian level report that the application of sludge can be made feasible in ceramic matrix, degraded areas, concrete matrix and civil construction. However, the number of disseminated scientific papers is low in the face of all the challenges of the sector to enable environmentally appropriate disposal and minimize the associated environmental impacts (Silva, Achon and Isaac, 2019).

The generation of sludge in WTPs in the Northeast of Brazil is a relevant environmental issue. During the treatment process, sludge is generated as a byproduct of removing impurities from the water. This waste is mainly composed of suspended particles, coagulants, organic and inorganic matter. In the State of Pernambuco, for example, a survey indicated that of the 246 operational WTPs, 75% dispose of their waste directly in water bodies and 22% in the soil, both without adequate treatment. Only 3% carry out dewatering processes, but the resulting solid mass continues to be discarded without adequate control in the soil (Sobrinho et al., 2019, p. 247).

But this is not only a reality in the Brazilian Northeast. For example, a study that considered three WTPs located in municipalities with good structure in Mato Grosso do Sul, of different sizes, consisting of public, private or mixed companies, whose treatment technology is conventional of complete cycle and whether or not the treatment of the waste exists, reported the lack of detailed information that compromises the proper use of the data produced by the WTPs,making it difficult to comply with Law 12.305/2010, which prioritizes

waste reduction, reuse and recycling. Two WTPs estimate the volume of sludge generated and one does not even have this information, reflecting a precarious management far from eco-efficient practices. The study highlights the importance of exchanging information with research institutions and the feasibility of employing multiple alternatives for destination. The idea that WTP waste comes from materials removed from water sources and that, therefore, must be returned to the source must be abolished, it is crucial to advance in the sustainable management of this waste.

The improper disposal of sludge can cause problems such as siltation of water bodies, changes in water quality, soil contamination and impact on aquatic biodiversity. Therefore, it is essential to seek sustainable alternatives for the management of this waste.

In the State of Paraíba, the Water and Sewage Company of Paraíba (Cagepa) plays an essential role in the management of water resources, operating several WTPs and being present in 224 locations (200 municipal headquarters cities and 24 districts and villages). The urban population served with water service is 2,789,463. Among them, the WTP of the Gramame System, which supplies the metropolitan region of João Pessoa, stands out. In addition, Cagepa also operates another important unit, the Campina Grande WTP, which plays a crucial role in supplying water to the second largest city in the state and neighboring municipalities (Cagepa, 2025). These WTPs are essential to ensure the supply of treated water, but they also face challenges related to the management of waste generated during the treatment process, such as sludge. The search for sustainable solutions for the final disposal of this waste is a priority for Cagepa, in line with sustainability and environmental protection goals.

Research indicates that WTP sludge can be reused sustainably. In Paraíba, for example, studies suggest that sludge can be used in the production of substrates for seedlings of native plants of the Caatinga, promoting the recovery of degraded areas (Souza, 2019). Another initiative practiced in PB since 2019 deals with a technology focused on meeting sustainability issues, combining development with practices to reduce damage to the environment, based on efforts to promote an advanced method for treating sludge by pyrolysis, providing complete sanitization and converting them into biochar, bio-oil and biogas. With the support of companies, public agencies and sludge generating concessionaires, this scenario can contribute to the State to stop landfilling rich raw materials, reducing the overload in landfills, and to encourage the use of bioproducts in a useful and safe way in agriculture, landscaping and gardening in the municipalities themselves, in addition to finding application in the chemical industry and energy sectors (G1,2024; ASN, 2025).

In Rio Grande do Norte, initiatives related to the management of sludge generated in WTPs have sought sustainable solutions to the challenges of the growing water supply, intensified by the increase in population demand. The need to meet the specific quality standards of treated water, combined with the degradation of water sources, has resulted in an increase in the use of chemicals in drinking water processes, resulting in a greater generation of sludge that needs to be properly treated for final disposal. According to ABNT, this waste can be reused, showing potential for use in civil construction, recovery of degraded areas and in the cultivation of plants. This scenario reflects the urgency of initiatives that promote the sustainable management of this waste in the State. Practices already developed in Brazil and around the world are presented as a reference to promote the application of WTP sludge in Rio Grande do Norte (Cunha et al., 2023).

In this context, the sustainable management of WTP sludge in the Northeast is an important environmental challenge. However, initiatives aimed at taking advantage of the potential of this waste as an input for agriculture, recovery of degraded areas or energy production, are promising ways to mitigate environmental impacts and promote sustainability.

The reuse of sludge is an inevitable path in times of greater commitment by companies to sustainable practices, already disseminated in developed countries such as Europe. The importance of sanitation, with access to clean water and sewage network, and the reuse of waste, generating energy or inputs for industries, cannot be ignored, as this way it is possible to solve various problems efficiently. In this way, initiatives by companies throughout Brazil explore reuse as raw material in the production of fertilizers, fertilizers and organic compounds for agriculture, or bricks, tiles and ceramics, which can open new business fronts. In addition to the generation of energy and fuel gas. Such applications contribute to soil recovery and the circular economy (Folha de Pernambuco, 2023).

On a global level, in the face of continuous urbanization and population growth, sludge management becomes a latent challenge faced by the water treatment industry and municipal governments. It is essential to explore innovative solutions to minimize the sludge problem with efficient resource recovery and reuse (Li, P. et al., 2025). For example, in municipal wastewater treatment plant, thermal treatment of sludge can be an efficient way to increase the ultimate dryness of the sludge cake and boost anaerobic digestion performance. On the other hand, these treatments generate refractory compounds that, once returned to the pipes, can affect the conformity of the quality of effluent discharges, especially with regard to organic nitrogen (Faixo et al., 2025). This reflects the real and

urgent need for more effective and efficient treatments, as well as a robust and sustainable management of this type of contaminating waste.

One of the circular economy business models is based on the recovery of by-products. In this model, the goal is to transform waste or by-products from one process into raw material for another or an alternative process. This approach has the dual benefit of reducing the amount of waste produced and significantly reducing the cost of obtaining natural resources (Goz w Praktyce, 2024a; Goz w Praktyce, 2024b). Adopting sustainable practices meets the vital need to preserve the environment and natural resources. In this context, the insertion of new techniques capable of transforming the production process, such as pyrolysis to generate bioproducts such as biochar, stand out as a strong ally to make this transformation feasible (Valença et al., 2023).

In this study, it focused on investigating the use of WTP sludge through the pyrolysis process for use in the production of value-added bioproducts such as biochar, bio-oil and biogas, depending on their composition. In this sense, pyrolysis emerges as a viable technology aligned with sustainable waste management practices and circular economy principles. In Brazil, water treatment is carried out through the conventional full-cycle process, involving the phases of capture, coagulation, flocculation, decantation, filtration and chlorination, and the sludge is generated from these stages of the treatment process (Oliveira and Rondon, 2016).

Bioproducts produced from WTP sludge can be a promising alternative to traditional fossil fuels. Sludge, which is a waste generated during the water treatment process and contains a mixture of organic and inorganic materials, can be converted by pyrolysis into bioproducts, offering various environmental and economic advantages. The production of bioproducts helps to reduce the amount of waste that needs to be disposed of in landfills, which can reduce the emission of greenhouse gases and other pollutants, in addition, they can act as a renewable source of energy, contributing to replacing fossil fuels and reducing dependence on these resources. This approach aligns with the "zero emissions" initiative, which responds to policies to reduce emissions and carbon footprints.

The organic matter fed to the pyrolytic reactor can be converted into several by-products [gases (H_2, CH4, CO); liquid fuels (HC, alcohols, bio-oil); solid waste (slag, char)], allowing energy recovery with an always positive energy balance (Leme, Fernandes and Lopes, 2017).

The bibliometric study developed in this work took into account the survey of statistical techniques to analyze and understand the global production of research in the field of biochar, bio-oil and biogas production through pyrolysis of WTP sludge, based on

recovered publications. The perspective was to highlight pyrolysis as an advanced sanitization process that induces the conversion of environmental liabilities into bioproducts, contributing to a sustainable approach to managing waste and producing valuable resources.

METHODOLOGY

METHOD OF REVISION

A review research approach was employed by the method of bibliometrics and systematic analysis, integrating tools such as VOSviewer, RStudio and Bibliometrix to identify the premises that permeate the pyrolysis process of sludge from water treatment plants (WTP sludge), promoting a management of information about authors, institutions and keywords, presenting the findings and evaluation of the theme by quantitative and statistical methods.

To this end, in bibliometrics, Lotka's law was taken as a basis to approach the scientific productivity of researchers; Bradford's law, to encompass the relevance of journals in the area of the topic under study; and Zipf's law, to verify the frequency of keywords most used in the texts of the analyzed documents.

In the systematic analysis, the probable shortcomings of the use of water treatment sludge as an alternative raw material for the pyrolysis process were explored, promoting a holistic understanding of the topic considered, and highlighting the importance of the pyrolysis mechanism as an advanced solution for its sanitization and conversion into sustainable bioproducts, enabling the extraction of relevant conclusions about the current applications given for this type of solid contaminant,through classification, categorization and analysis of the aspects of the theme.

DATA COLLECTION

The data collection process was carried out through the Web of Science and Scopus databases. to identify articles with scientific relevance and that address the pyrolysis of WTP sludge.

The search in the databases was carried out with the construction of two research axes, namely, (I) Pyrolysis and (II) Water treatment plant. Keywords were defined for each axis, namely, thermochemical process, pyrolysis and bioproducts for the first axis; sludge, water treatment plant and Brazil for the second axis. The association of the keywords established in axes I and II of the research, together with the Boolean indicators AND and

OR, generated thesearch string in English "thermochemical process" AND "pyrolysis" AND "sludge" OR "water treatment station" AND "bioproducts" AND "Brazil".

DATA ANALYSIS

The data previously obtained were worked inthe RStudio software and in the Bibliometrix tool that uses the R language, thus making it possible to obtain statistical calculations and graphs, consequently, originating a coupling network with a measure of similarity determined between the information, thus inducing a more accurate and statistically reliable understanding of the theme

44 articles were identified in the Web of Science databaseand 109 in Scopus, totaling 153 articles. Through the use of RStudio, the presence of duplicate articles was not found.

For the categorization of the data found, criteria for analyzing the documents using Bibliometrix were delimited. Thus, for the total of 153 articles, filters were considered whose criteria considered retaining only scientific and review articles, published between the years 2021 and 2024, disseminated in English and Spanish.

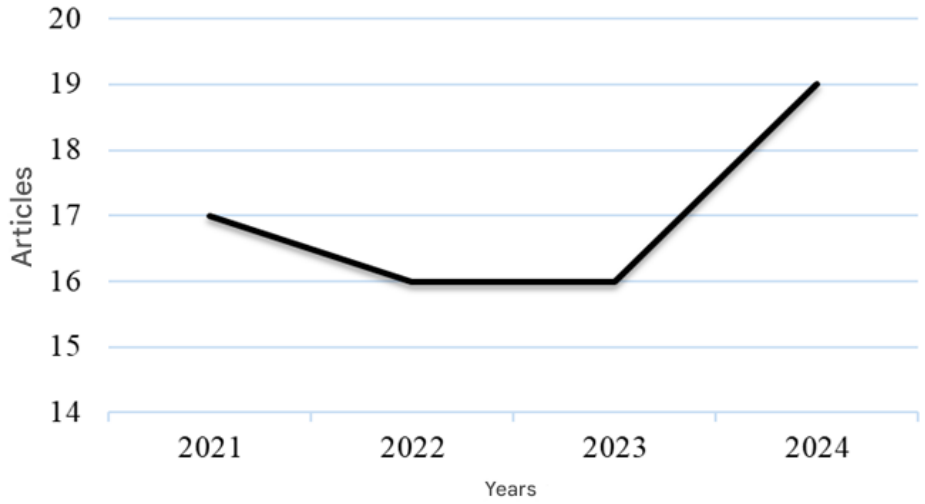
The filtration process resulted in 68 publications aligned with the theme pyrolysis of WTP sludge and its aspects, which were analyzed in terms of scientific production per year, scientific production by country, the relevance of journals, most cited authors, the occurrence of keywords and authors who work together on the theme.

The systematic analysis was carried out considering the 10 most cited articles in the portfolio containing the 68 publications. The articles were read in full and analyzed in order to identify the presence of keywords and important nuances that permeate the theme. In addition, it also seeks to identify the bioproducts that are produced through the pyrolysis process of WTP sludge, and their applications.

DATA ANALYSIS

Initially, Figure 1 illustrates a time frame of the last 4 years of scientific production that addresses the pyrolysis of WTP sludge. In general, the data presented highlight both the relevance and the trends of this research area. Considering the adopted timeline, the scientific production on the pyrolysis of WTP sludge has shown consistent growth. This trend reflects the increased interest in sustainable and innovative solutions for waste reuse, in line with global sustainability goals.

Figure 1. Scientific Production by year addressing the pyrolysis of water treatment plant sludge between the years 2021 – 2024.



Source: Prepared by the authors (2025).

For the year 2021, 17 articles were identified, a factor that represents 25% of the bibliographic portfolio analyzed. possibly motivated by advances in pyrolysis techniques or by encouraging environmental policies. For the years 2022 and 2023, the number of publications remained stable, with 16 articles for each year. This suggests a consolidation of the area, with the continuity of relevant research, but without significant expansion.

In 2024, the increase to 19 publications, representing 27.9% of the total portfolio, shows renewed momentum and greater maturity of research. This growth may be associated with the implementation of new environmental regulations, advances in pyrolysis techniques or encouraging environmental policies, as well as greater academic and industrial engagement.

Although when compared to sewage treatment plant (STP) sludge, this number of publications per year is significantly lower, reflecting a still significant gap in the use of WTP sludge as raw material for pyrolysis, the results suggest the emergence of interest in this solution in search of environmentally correct disposal encompassing the pyrolysis process.mainly focused on the production of biochar and/or biogas, contributing to more sustainable solutions. In other words, this process goes beyond the use of this type of waste as an agricultural fertilizer or its treatment by densification, which are practices used in WTPs in the State of São Paulo, (Saneamento, 2021; Andooz et al., 2023; Hu et al., 2022).

Regarding the most relevant journals and considering the years 2021 to 2024, Table 1 describes the 10 main sources that explore the pyrolysis of WTP sludge and their respective impact factors. The impact factor is a metric for scientific evaluation, helping to

identify sources that are being widely read, cited, and used, regardless of geographic location (Salomão and Santos, 2025).

Table 1. Relevance of journals and their respective impact factors in articles that address the pyrolysis of WTP sludge.

Newspapers	Articles	Impact Factor
Journal of cleaner production	5	9.8
Science of the total environment	4	8.2
Environmental science and pollution research	3	5.8
Biofuels, bioproducts and biorefining	2	3.2
Biomass conversion and biorefinery	2	3.5
Bioresource technology	2	9.7
Chemosphere	2	8.1
Energies	2	3.0
Energy conversion and management	2	9.9
Journal of analytical and applied pyrolysis	2	5.8

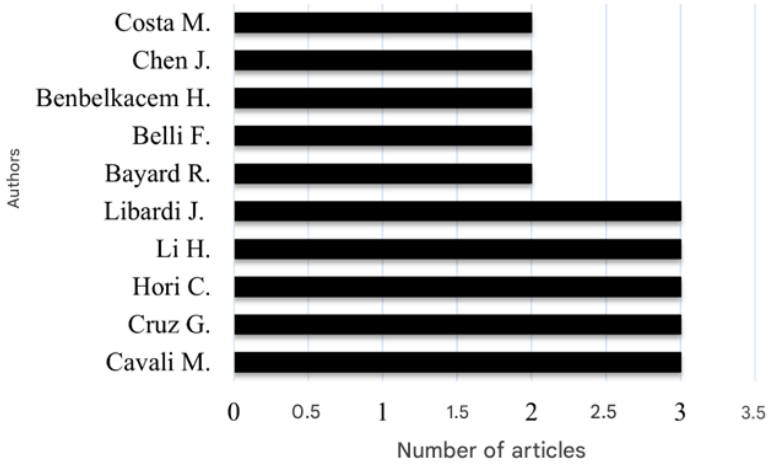
Source: Prepared by the authors (2025).

The journals Journal of Cleaner Production, Science of the Total Environment and Environmental Science and Pollution Research presented the highest number of publications, in relation to the total, with 5, 4 and 3 articles. In addition, these sources exhibited the highest impact factors, 9.8, 8.2 and 5.8, respectively, since they are recognized for disseminating topics such as sustainable development, technical processes, water quality and safety, environmental impacts of waste or wastewater treatment.

In addition, although the journals Bioresource Technology and Chemosphere account for only two articles each, their high impact factors, 9.7 and 8.1, respectively, reinforce the importance of these sources for the dissemination of high-quality research on the subject. This disparity between the number of publications and impact highlights the diversity of approaches and prestige within the scientific sources related to WTP sludge pyrolysis.

The following analysis prioritized the identification of the main authors who contributed to the dissemination of knowledge about the pyrolysis of WTP sludge between 2021 and 2024. As shown in Figure 2, authors such as Cavali M., Cruz G., Horii C., Li H. and Libardi J. stood out for publishing the largest number of articles, totaling 3 each, in a universe of 68 publications analyzed. It is important to note that the other authors recorded productions equal to or less than 2 articles, evidencing a more limited number of individual contributions.

Figure 2. Top authors by number of articles published between the years 2021-2024.

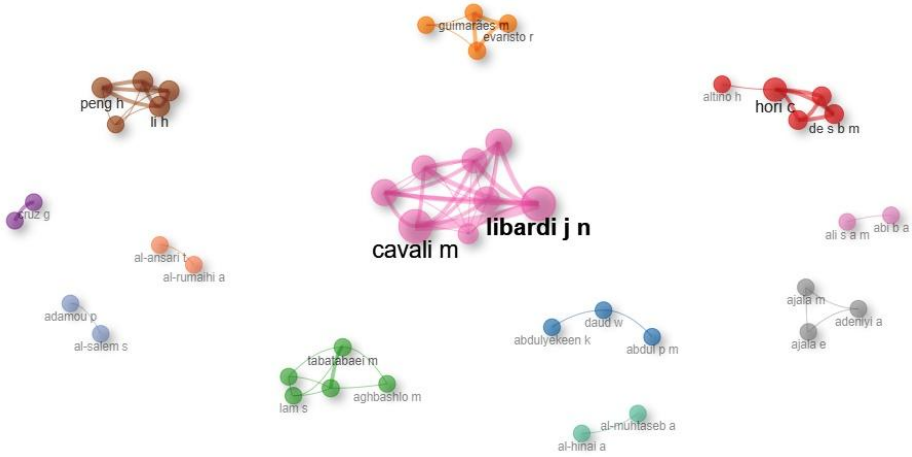


Source: Prepared by the authors (2025).

By correlating the thematic aspects of the publications, it is observed that the authors Cavali M. and Li H. produce outstanding works that explore the application of pyrolysis of organic waste in the generation of biogas and biochar, demonstrating the potential of the process in sustainable energy solutions. On the other hand, the authors Costa G., Chen J. and Belli F. are recognized for their research in the field of thermochemical processes, aimed at the use of sludge from water treatment plants. These studies emphasize innovative approaches to waste management and the promotion of environmentally responsible practices.

Figure 3 illustrates the co-authorship relationship between the authors of the analyzed bibliographic portfolio. From the Bibliometrix it is observed the presence of 12 clusters expressed by the colors orange, brown, purple, blue, pink, green, red, gray and cyan.

Figure 3. Correlation between authors in the co-authorship analysis performed using Bibliometrix.



Source: Prepared by the authors (2025).

The absence of links linking the groups indicates that the authors did not contribute jointly on the pyrolysis theme of WTP sludge, a factor that highlights the theme being researched in particular by some research groups around the world. In addition, this aspect can be confirmed by observing that the authors Li H., Cavali M. and Cruz G. appear in separate groups and have already been highlighted previously by the number of contributions on the subject.

Table 2 shows the analysis of scientific production by country on the subject of pyrolysis of WTP sludge in the period from 2021 to 2024. The countries with the most prominence were Brazil, with 20 articles and 874 citations, followed by China, with 12 articles and 259 citations, and India, with 9 articles and 362 citations. These numbers reflect the leadership of these nations in research on the subject, probably supported by factors such as economic conditions, strict environmental legislation and technological advances. These elements stimulate the exploration of sustainable alternatives for the reuse of sludge, which, in the absence of adequate treatment, is usually disposed of in landfills or water bodies.

Table 2. Number of publications by countries that most concentrated studies focused on pyrolysis of water treatment plant sludge between the years 2021-2024.

Countries	Articles	Quotes
Brazil	20	874
China	12	259
India	9	362
United States	5	67
Malaysia	4	141
Iran	3	61
Oman	3	504
Portugal	2	19
Vietnam	3	21
South Africa	1	22

Source: Prepared by the authors (2025).

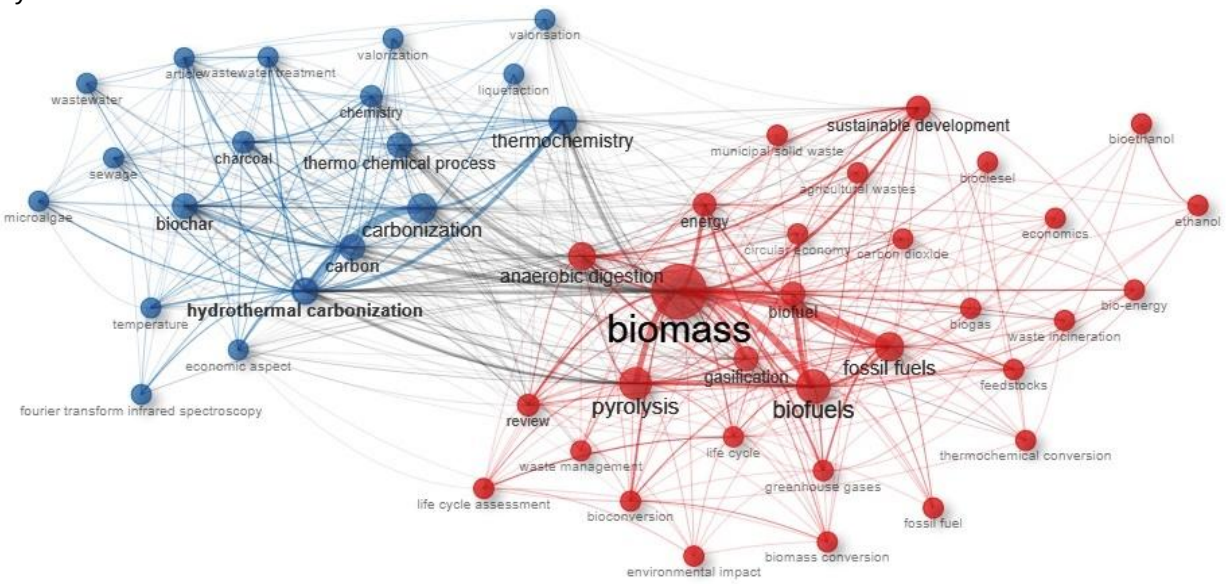
Brazil leads both in number of publications and citations, indicating a combination of robust academic efforts and high scientific visibility. China, in turn, maintains prominence in volume of articles, probably influenced by its rapid industrialization and search for technological solutions for waste management. India, on the other hand, with significant numbers of citations in relation to publications, shows the significant impact of its scientific contributions, especially in areas that explore the economic and environmental potential of sludge pyrolysis.

Other countries also contributed to the scientific literature, although with less intensity. In the cases of Oman and Malaysia, for example, there is a small number of articles published (3 and 4, respectively), but with an expressive 504 and 141 citations,

which may suggest the qualitative relevance of their research. Such studies reinforce the global importance of pyrolysis as a strategic solution for the management of waste from WTPs.

Figure 4 illustrates the analysis of the occurrence of the keywords, expressing the terms that were most cited in the analyzed studies portraying the pyrolysis of WTP sludge. The cluster represented in red concentrates the main terms associated with the theme, such as biomass, pyrolysis, biogas and thermochemical conversion, among others. This analysis is corroborated by the literature, which emphasizes the proximity in the arrangement of the terms as a crucial characteristic to identify their relevance and recurrence in related scientific research (Peixe and Pinto**,** 2021).

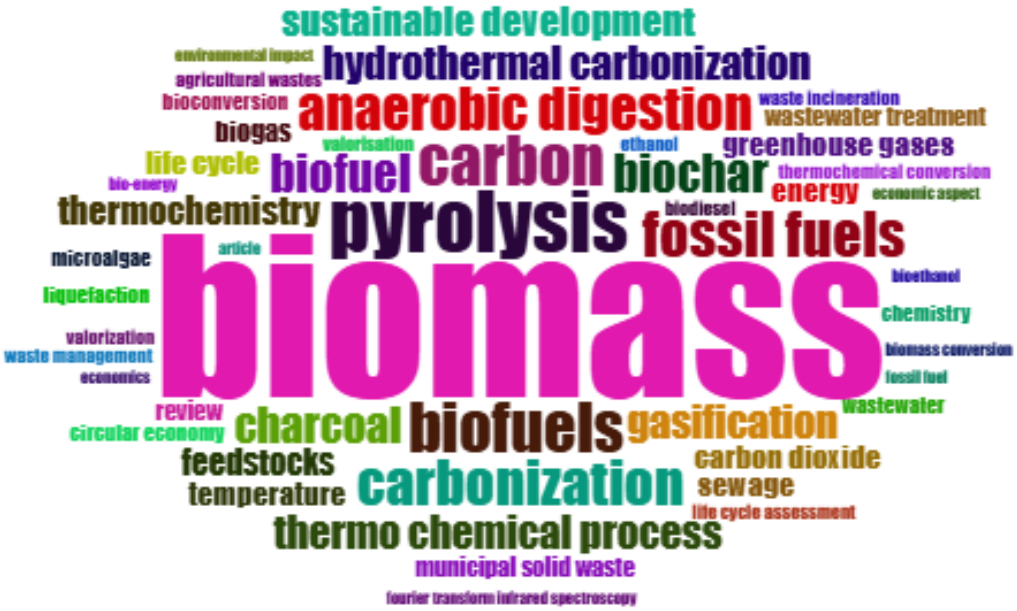
Figure 4. Analysis of the occurrence of keywords to identify the clusters with the most cited terms in the analyzed studies.



Source: Prepared by the authors (2025).

These results are in line with the terms observed in the keyword cloud illustrated in Figure 5, in which the size of the words proportionally reflects their frequency of occurrence in the analyzed texts. Among the most prominent expressions are biochar, biofuels, life cycle and waste water treatment, evidencing the emphasis of studies on the sustainable production of bioproducts and the management of waste from WTPs.

Figure 5. Word cloud of the analyzed bibliographic portfolio regarding the pyrolysis of WTP sludge.



Source: Prepared by the authors (2025).

The systematic analysis of the 10 most cited articles, detailed in Table 3, among the bibliographic portfolio of the 68 filtered articles, presents important contributions to the understanding of the thermochemical processes associated with the pyrolysis of WTP sludge, as well as to the identification of the resulting bioproducts and their possible applications.

From the articles analyzed, it can be seen that biochar (or biochar) is the most frequently explored bioproduct, with emphasis on the pyrolysis process as the main technique employed. Approximately 70% of the selected studies focused on the production of biochar from WTP sludge or sewage sludge, demonstrating the great potential of this material as a source for the generation of high value-added products. In addition, 20% of the articles addressed the achievement of hydrochar through hydrothermal carbonization, while a smaller fraction examined hybrid processes, such as the combination of incineration, pyrolysis, and hydrothermal carbonization.

Regarding the type of waste used, it is observed that 60% of the articles worked specifically with WTP sludge, while the remaining 40% used sewage sludge or additional waste, such as rice husk and crop residues. This data suggests a trend of diversification in the raw materials used to improve the efficiency and economic viability of thermochemical technologies.

The studies identified several applications for the derived bioproducts. Biochar has been widely highlighted as a promising component for agriculture, due to its soil-improving properties, and for environmental remediation. On the other hand, hydrocoal has potential applications as a source of renewable energy and in the production of biofuels.

Table 3. Set of most cited articles used in the systematic analysis addressing the pyrolysis of WTP sludge between the years 2021-2024.

Bioproducts	Thermochemical process	Residue	Reference
Hydrocoal	Liquefaction Hydrothermal	WTP mud	Act, Liu and Sketch (2024)
Biochar	Pyrolysis	WTP mud	Medeiros, Chelme-Ayala and El-Din (2023)
Biochar	Pyrolysis	WTP mud	Gomes et al. (2022)
Biochar	Pyrolysis	Award from WTP	Jiang et al. (2021)
Biochar	Pyrolysis	Award from WTP	Luo et al. (2021)
Biochar	Pyrolysis	Sludge of Sludge	Jellali et al. (2021)
Biochar	Pyrolysis	Sludge of Sludge	Constantinescu-Aruzandei and Oancea (2023)
Biochar	Pyrolysis	Sludge of Sludge	Sun et al. (2024)
Hydrocoal	Hydrothermal Carbonization	Sludge of Sludge Crop residues	Cavali et al. (2023)
Biochar	Incineration Pyrolysis Hydrothermal Carbonization	Sludge of Sludge Rice husks	Hu et al. (2022)

Source: Prepared by the authors (2025).

A notable aspect is the high representativeness of recent papers, such as the work of Aktas, Liu, and Eskicioglu (2024) and Medeiros, Chelme-Ayala, and El-Din (2023), indicating that research on pyrolysis of WTP sludge is an emerging and dynamic field. The selection of studies with a large number of citations reinforces the scientific relevance of these publications, as well as the impact that their results have had on the academic community and on the development of sustainable technologies.

The statistical analysis of the portfolio also highlights the centrality of biochar and hydrochar in the most cited studies, reflecting the interest in practical applications and the ability of these materials to contribute to a circular economy. These results offer a solid basis for future research and for the implementation of innovative solutions in the use of WTP sludge.

So, in detail, the 10 most cited articles within the universe of the portfolio of 68 publications analyzed, highlight relevant themes and practical applications related to the pyrolysis of WTP sludge, evidencing the scientific importance of this field of study.

Jiang et al. (2021) explored the potential of WTP sludge in biochar production. Pyrolysis, employed at temperatures between 400 and 800 °C, proved to be an efficient thermochemical process, resulting in a highly porous material, with a fixed carbon content between 40% and 60%. However, the high mineral content in the sludge was associated with high ash levels, reducing its calorific value. At the same time, Luo et al. (2021) highlighted the versatility of biochar from WTP sludge as an alternative fuel for heat and electricity generation, and also as an adsorbent, fertilizer and soil amendment.

Gomes et al. (2022) pyrolysis of WTP sludge in a fixed-bed reactor at 700 °C for 2 hours, injecting nitrogen gas at a flow rate of 220 mL/min to maintain an atmosphere with low oxygen content. The biochar obtained by pyrolysis was used as a supplementary cementitious material, improving the heat and hydration properties in cement composites when compared to the use of raw sludge. Similarly, Medeiros, Chelme-Ayala, and El-Din (2023) investigated WTP sludge in the pyrolysis production of raw and zinc chloride activated biochar, showing that activated biochar has a greater surface area and efficiency in the adsorption of pollutants due to the abundance of mesopores (89% of the pore volume).

In addition to pyrolysis, alternative thermochemical processes have also been explored. Aktas, Liu, and Eskicioglu (2024) studied the hydrothermal liquefaction of WTP sludge in a 1-liter capacity Parr reactor at 350 °C for 15 minutes, producing hydrochar with a higher moisture content (7.4%), as well as lower surface area and pore volume. In this case, the superiority of the pyrolysis process in the production of bioproducts with better properties is evidenced, such as those found in the work of Medeiros, Chelme-Ayala and El-Din (2023). Cavali et al. (2023) reported the production of hydrochar using lignocellulosic biomass and sewage sludge, verifying its efficiency in removing aquatic and atmospheric pollutants.

With regard to sewage sludge, Constantinescu-Aruzandei and Oancea (2023) highlighted methods for nutrient recovery, such as the thermochemical separation of phosphorus and recovery of nitrogen, sulfur, and phosphorus by anaerobic digestion. Sun et al. (2024) corroborated the viability of sewage sludge as a feedstock for biochar production, noting its ability to reduce carbon emissions by up to 3.9 t CO_2 per 1 ton of biomass equivalent (Lehmann et al. (2021). By contrast, Hu et al. (2022) highlighted the formation of persistent free radicals during thermochemical processes of incineration, pyrolysis and hydrothermal carbonization of biochars produced with sewage sludge and rice husks. Regarding pyrolysis, evidencing temperature as a determining factor in the generation of contaminants.

Jellali et al. (2021) explored the production of biochar through sewage sludge from wastewater treatment plants, considering this a new alternative to the production of this bioproduct through lignocellulosic waste. They demonstrated that the physicochemical properties of biochar, including its ability to adsorpt pollutants, depend on the nature of the treated sludge. The biochar produced with dewatered digested sludge showed better porosity and greater surface area, being effective in the removal of lead (Pb II) and phosphorus (P) from aqueous solutions.

The results obtained demonstrate that, although the 10 most cited articles do not exclusively discuss the pyrolysis of WTP sludge, the production of biochar is a recurring theme in all publications. The breadth of methodological approaches reflects the global character of the issues analyzed, with significant contributions to the circular economy and environmentally responsible practices. In this way, the dissemination of these studies strengthens the scientific basis for future technological advances and practical applications in areas of high environmental and social impact.

CONCLUSIONS

This study presented a bibliometric review and systematic analysis on the pyrolysis of water treatment plant sludge (WTP), addressing key aspects related to scientific production, authors and prominent journals, geographic distribution of research and analysis of recurrent keywords. The bibliometric approach made it possible to identify trends and gaps in the theme, while the systematic analysis deepened the understanding of the products generated by pyrolysis and their applications.

The bibliometric review revealed that Brazil, China and India lead in the number of publications on the pyrolysis of WTP sludge, reflecting the impact of probable factors such as economic contexts, environmental legislation and technological advances. The journals Journal of Cleaner Production, Science of the Total Environment, and Environmental Science and Pollution Research were the most highlighted, showing significant impact factors of 9.8, 8.2, and 5.8, respectively. These data reinforce the relevance of these sources for the dissemination of knowledge in the field. The analysis also indicated that the research groups operate mostly in isolation, without extensive interaction between the main authors.

The correlation of keywords highlighted terms such as biochar, biofuels, biomass, pyrolysis, biogas and waste water treatment, highlighting the main lines of research and the technological potential of bioproducts derived from WTP sludge.

Within the scope of the systematic analysis, it was identified that the production of biochar is recurrent in the studies analyzed. This bioproduct was widely highlighted for its adsorbent potential, being applied in technological fields such as the removal of pollutants and the improvement of properties of cementitious materials. In addition, it was found that there was a growing interest in the use of sewage sludge, expanding the possibilities of generating value-added products from organic waste.

Finally, the conclusions of this study reinforce the importance of pyrolysis as a sustainable solution for the reuse of sludge generated in water treatment plants (WTP) and sewage treatment plants (STP), contributing to circular economy practices and environmentally responsible management. The expansion and deepening of this research can foster technological innovations and strengthen the global relevance of the theme, aligning with the contemporary challenges of sustainability and efficiency in waste management.

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REFERENCES

1. Achon, C. L., Barroso, M. M., & Cordeiro, J. S. (2013). Resíduos de estações de tratamento de água e ISO 24512: Desafio do saneamento brasileiro. Engenharia Sanitária e Ambiental, 18(2), 115–122.

2. Aktas, K., Liu, H., & Eskicioglu, C. (2024). Treatment of aqueous phase from hydrothermal liquefaction of municipal sludge by adsorption: Comparison of biochar, hydrochar, and granular activated carbon. Journal of Environmental Management, 356, Article 120619.

3. Al Duhailib, Z., Granholm, A., Alhazzani, W., Oczkowski, S., Belley-Cote, E., Moller, M. H., & outros. (2024). Grade pearls and pitfalls—Part 1: Systematic reviews and meta-analyses. Acta Anaesthesiologica Scandinavica, 68(5), 584–592.

4. Almeida, M. B. G., Jesus, A. M. D., Pereira, A. S., & Fiore, F. A. (2024). Evaluating centrifuged water treatment plant sludge as an adsorbent for nutrients, microorganisms, and heavy metals removal from wastewater. Journal of Cleaner Production, 468, Article 142975.

5. Aquino, G. P., Pereira, C. R. B., Motta, M. F. B., & Mülle, M. (2023). Caracterização física de lodo de ETA pós desaguamento em bolsa geotêxtil. In Anais do 10º Congresso Brasileiro de Geotecnia Ambiental (pp. XX–XX). Salvador: IGS-Brasil/ABMS.

6. ASN. (2025, 10 de fevereiro). Engenheira se destaca como empreendedora em projeto que transforma rejeito de esgoto em fertilizante (V. Costa, Autor). Agência Sebrae de Notícias, Inovação & Tecnologia. Recuperado em 18 de março de 2025, de https://pb.agenciasebrae.com.br/inovacao-e-tecnologia/engenheira-se-destaca-como-empreendedora-em-projeto-que-transforma-rejeito-de-esgoto-em-fertilizante/

7. CAGEPA. (s.d.). Apresentação. João Pessoa: Companhia de Água e Esgotos da Paraíba. Recuperado em 18 de março de 2025, de https://www.cagepa.pb.gov.br/institucional/apresentacao/

8. Cavali, M., Libardi, J. N., Sena, J. D., Woiciechowski, A. L., Soccol, C. R., Belli, F. P., Bayard, R., Benbelkacem, H., & Castilhos Júnior, A. B. (2023). A review on hydrothermal carbonization of potential biomass wastes, characterization and environmental applications of hydrochar, and biorefinery perspectives of the process. Science of the Total Environment, 857, Article 159627.

9. Constantinescu-Aruxandei, D., & Oancea, F. (2023). Closing the nutrient loop—the new approaches to recovering biomass minerals during the biorefinery processes. International Journal of Environmental Research and Public Health, 20(3), Article 2096.

10. Cunha, M. C. B., Torres, D. M., Ferreira, D. M., & Lopes, R. L. (2023). Gerenciamento de lodos em estações de tratamento de água: Sludge management in water treatment plants. Revista Brasileira de Meio Ambiente & Sustentabilidade, 3(2), 64–74. Recuperado de https://rbmaes.emnuvens.com.br/revista/article/view/298

11. Faixo, S., Garrigues, J.-C., Haddad, M., Mazeghrane, S., Gaval, G., Benoit-Marquié, F., & Paul, E. (2025). Thermal treatment of sewage sludge: Impact of the sludge type and origin on the formation of recalcitrant compounds. Water Research, 271, Article 122868.

12. G1. (2024, 13 de maio). Empreendedoras criam startup que melhora a fertilidade e recupera o solo. Sebrae Paraíba. Recuperado em 18 de março de 2025, de https://g1.globo.com/pb/paraiba/especial-publicitario/sebrae-paraiba/neon/noticia/2024/05/13/empreendedoras-criam-startup-que-melhora-a-fertilidade-e-recupera-o-solo.ghtml

13. Gomes, S. C., Zhou, J. L., Zeng, X., & Long, G. (2022). Water treatment sludge conversion to biochar as cementitious material in cement composite. Journal of Environmental Management, 306, Article 114463.

14. GOZ w Praktyce. (2024a). Circular business models. [S.l.]. Recuperado em 13 de maio de 2024, de https://gozwpraktyce.pl/modele-biznesowe/

15. GOZ w Praktyce. (2024b). Recovery of by-products. [S.l.]. Recuperado em 13 de maio de 2024, de https://gozwpraktyce.pl/odzysk-produktow/

16. Gregorio-Chaviano, O., López Mesa, E. K., & Limaymanta, C. H. (2022). Web of Science as a research tool and support for scientific activity: Lights and shadows of their collections, products and indicators. E-Ciencias de la Información, 12(1), 134–157.

17. Hu, Y., Zhang, B., Guo, Q., Wang, S., & Lu, S. (2022). Characterization into environmentally persistent free radicals formed in incineration fly ash and pyrolysis biochar of sewage sludge and biomass. Journal of Cleaner Production, 373, Article 133666.

18. Iwaki, G. (2018, 19 de maio). Destinação final de lodos de ETAs e ETEs. Portal Tratamento de Água. Recuperado em 11 de março de 2025, de https://tratamentodeagua.com.br/artigo/destinacao-final-de-lodos-de-etas-e-etes/

19. Jellali, S., Khiari, B., Usman, M., Hamdi, H., Charabi, Y., & Jeguirim, M. (2021). Sludge-derived biochars: A review on the influence of synthesis conditions on pollutants removal efficiency from wastewaters. Renewable and Sustainable Energy Reviews, 144, Article 111068.

20. Jiang, G., Xu, D., Hao, B., Liu, L., Wang, S., & Wu, Z. (2021). Thermochemical methods for the treatment of municipal sludge. Journal of Cleaner Production, 311, Article 127811.

21. Krymskaya, A. S. (2023). The bibliometrics of bibliometrics as a new area of research. Scientific and Technical Information Processing, 50(4), 286–291.

22. Kudaybayeva, K., Tleumagambetoya, B., Bazargaliyev, Y., Kosmuratova, R., & Zhylkybekova, A. (2024). Global trends in LADA type diabetes research: A bibliometric analysis of publications from Web of Science and Scopus, 1994–2024. Journal of Diabetes Research, 2024(1), Article 4960075.

23. Kushwah, A., Shanka, R., Goeloel, D., Singhingh, S., & Chaurasia, P. K. (2025). Role of plants as bioindicators of water pollution and treatment of water contaminations. In Biotechnologies for wastewater treatment and resource recovery: Current trends and future scope (pp. 187–201). [S.l.: s.n.].

24. Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. Nature Geoscience, 14(12), 883–892.

25. Leme, G. R., Fernandes, D. M., & Lopes, C. L. (2017). Utilização da pirólise para o tratamento de resíduos no Brasil. In Anais do 8º Fórum Internacional de Resíduos Sólidos (pp. XX–XX). Curitiba: [s.n.].

26. Li, P., Sun, F., Dong, Y., Wen, L., Lin, L., & Li, X.-Y. (2025). Utilization of drinking water treatment sludge with coal fly ash to make permeable bricks for low impact development. Resources, Conservation and Recycling, 212, Article 107932.

27. Li, Y., Tao, C., Li, S., Chen, W., Fu, D., Jafvert, C. T., & Zhu, T. (2025). Feasibility study of machine learning to explore relationships between antimicrobial resistance and microbial community structure in global wastewater treatment plant sludges. Bioresource Technology, 417, Article 131878.

28. Luo, H., Cheng, F., Yu, B., Hu, L., Zhang, J., Qu, X., Yang, H., & Luo, Z. (2021). Full-scale municipal sludge pyrolysis in China: Design fundamentals, environmental and economic assessments, and future perspectives. Science of the Total Environment, 795, Article 148832.

29. Marines, F., Corsino, S. F., Cosenza, A., Capodici, M., Torregrossa, M., & Viviani, G. (2025). A modified robustness index for assessing operational performance of drinking water treatment plants: A comparative study within a new regulatory framework. Water Research, 268(Part B), Article 122668.

30. Medeiros, D. C. C. S., Chelme-Ayala, P., & El-Din, M. G. (2023). Sludge-based activated biochar for adsorption treatment of real oil sands process water: Selectivity of naphthenic acids, reusability of spent biochar, leaching potential, and acute toxicity removal. Chemical Engineering Journal, 463, Article 142329.

31. Mezquita, B., Afonso-Arias, C., Martínez-Jaimez, P., & Borrego, Á. (2024). The use of bibliometrics in nursing science: Topics, data sources and contributions to research and practice. Nursing Open, 11(9), Article e70036.

32. Oliveira, I. Y. Q., & Rondon, O. C. (2016). Diagnóstico da gestão de lodo de estação de tratamento de água em Mato Grosso do Sul. Interações, 17(4), 687–698.

33. Peixe, A. M. M., & Pinto, J. S. P. (2021). Infometria nas bases Web of Science e Scopus: Governança corporativa, informação e tecnologia da informação; precificação de ações e riscos de mercado. Research, Society and Development, 10(5), Article e56110515433.

34. Salomão, P. E. A., & Santos, A. T. O. (2025). Evolução e desafios na avaliação científica: Da classificação de periódicos à qualidade intrínseca dos artigos. Revista Multidisciplinar do Nordeste Mineiro, 1(1), 1–18.

35. Saneamento. (s.d.). Destinação de lodo resultante do tratamento de água é desafio para o saneamento. Saneamento Já. Recuperado em 10 de março de 2025, de http://www.saneamentoja.com.br/melhores-praticas/destinacao-de-lodo-resultante-do-tratamento-de-agua-e-desafio-para-o-saneamento/

36. Silva, L. R., Achon, C. L., & Isaac, R. L. (2019). Lodo gerado em estações de tratamento de água: Planos municipais de resíduos sólidos e pesquisas acadêmicas no Brasil. In Anais do 30º Congresso Brasileiro de Engenharia Sanitária e Ambiental (pp. XX–XX). [S.l.]: ABES.

37. Silva, L. R., Achon, C. L., & Isaac, R. L. (2022). Análise crítica da gestão do lodo gerado em estações de tratamento de água – cenário brasileiro. In Anais do International Workshop for Innovation in Safe Drinking Water (pp. XX–XX). [S.l.: s.n.].

38. Sun, H., Chen, T., Ji, L., Tian, D., Li, X., & Sun, C. (2024). Waste derived biochar for water purification: The roles of redox properties. Waste Disposal & Sustainable Energy, 1–23. Advance online publication.

39. Tan, C., Xiao, Y., Chen, S., Liu, T., Zhou, J., Zhang, S., Hu, Y., Zhou, J., She, Z., Tian, B., Wu, A., & Li, C. (2024). Bibliometrics analysis and knowledge mapping of pertussis vaccine research: Trends from 1994 to 2023. Infection, 1–12. Advance online publication.

40. Urban, R. C., Nakada, L. Y. K., & Isaac, R. L. (2023). A system dynamics approach for large-scale water treatment plant sludge management: A case study in Brazil. Journal of Cleaner Production, 419, Article 138105.

41. Valença, A. K. A., Dantas, J., Silva, K. C. G., & Almeida, T. O. (2023). Análise bibliométrica da evolução da pesquisa científica sobre biochar do lodo de esgoto: Revisão dos últimos 10 anos (2012-2022). In Anais do 25º Encontro Internacional sobre Gestão Empresarial e Meio Ambiente (pp. XX–XX). São Paulo: FEA/USP.

42. Vieira, L. J. C., & Silva, I. C. O. (2023). Scientific production about bibliometric studies in Brazil: An analysis from Brapci. Em Questão, 29, Article e-128160.

43. Wang, Y., Tong, Z., Jiang, L., Peng, F., Liu, W., Chen, J., Rao, X., Feng, G., Kang, C., & Fang, L. (2025). Molecular-level insights into the synergistic activation of peracetic acid by ultraviolet and ferrous ions for the degradation of sedimentation sludge water in drinking water treatment plants based on Fourier transform-ion cyclotron resonance mass spectrometry. Separation and Purification Technology, 355(Part B), Article 129708.