The Production of Biochar from Sewage Sludge Pyrolysis and its Use: A Mini Review

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Abstract. This mini-review, enhanced with a bibliometric analysis, explores biochar production via sewage sludge pyrolysis and its diverse applications, employing a bibliometric method to map the scientific landscape and key research impacts. It outlines the pyrolysis technique, a process converting sewage sludge into biochar by heating in an oxygen-free environment, which minimizes waste while producing valuable biochar. The review assesses biochar's characteristics-like its large surface area and porosity-beneficial for soil improvement, water filtration, carbon storage, and contaminant removal. It addresses production challenges and environmental benefits, urging further research to fine-tune pyrolysis and broaden biochar's uses across various sectors. ***Keywords.*** Biochar, Pyrolysis, Sewage sludge, Biochar utilization, Mini-review

1 Introduction

Sewage sludge management is a major environmental and economic challenge for municipalities and industries worldwide [1,2]. Produced in significant quantities in wastewater treatment plants, sludge is composed of solid residues from wastewater treatment, including organic and inorganic matter, microorganisms and various contaminants [3-5]. Historically, sludge management strategies have focused on landfill, incineration or use as agricultural fertilizer [6-12]. However, these traditional approaches are far from ideal (Figure 1).

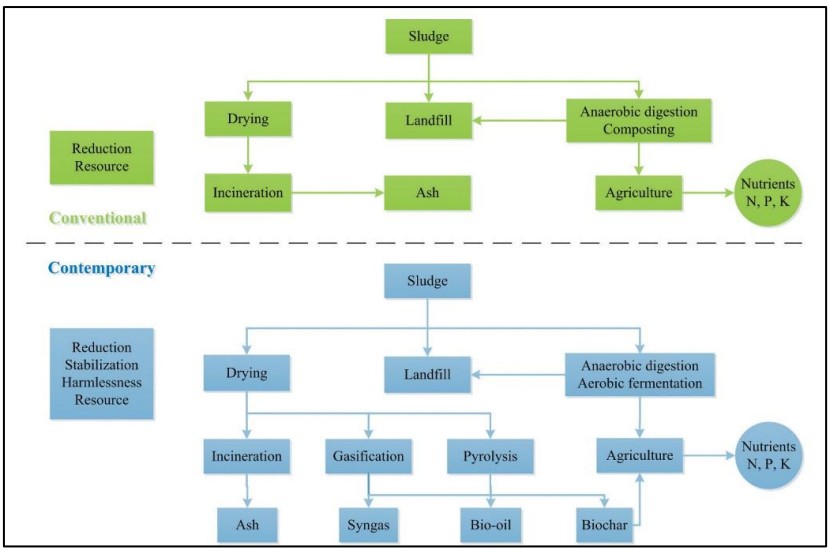

Fig. 1. Treatment processes of sludge

Landfill, though widespread, occupies vast tracts of land and risks soil and groundwater contamination, not to mention the production of methane, a greenhouse gas, during the anaerobic decomposition of organic matter [13-18]. On the other hand, incineration, despite its ability to reduce sludge volume and generate energy, brings with it major environmental concerns [19-23]. The release of atmospheric pollutants, such as dioxins and furans, and the management of bottom ash, potentially rich in heavy metals and toxins, are significant challenges [24-26]. As for the use of sludge as fertilizer, this raises concerns about food safety, given the risks of soil and crop contamination by heavy metals, pathogens and drug residues [27-29].

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In addition to their environmental impact, these traditional methods involve considerable economic costs and are no longer considered viable in the long term [30]. This situation has catalysed the search for more sustainable alternatives, such as pyrolysis for biochar production [31, 32]. This technology not only offers an environmentally-friendly approach to treating this waste [33-36], but also promises significant added value, transforming an environmental liability into a valuable resource with environmentally beneficial applications [37-41].

This review aims to provide a concise and structured analysis of recent advances in biochar production via sewage sludge pyrolysis. It focuses on an in-depth examination of the various pyrolysis methods and operating conditions, such as temperature, retention time and atmosphere, essential for the transformation of sludge into biochar. The review also explores the various uses of biochar, notably in soil fertility improvement, carbon sequestration and water treatment. Finally, it addresses current challenges and future prospects in this field, aiming to fill existing research gaps and stimulate innovation for sustainable sewage sludge management.

2 Bibliometric analysis

Bibliometric analysis, a quantitative method for assessing scientific publications and citations, begins by collecting bibliographic data, typically comprising article titles, author names, affiliations, publication venues, abstracts, keywords, and citation counts [42].
To gather this data, databases like Web of Science, Scopus, PubMed, or Google Scholar are often utilized. The focus on terms such as "Biochar", "Sewage", "Sludge", and "Pyrolysis" reflects their rising prominence in recent research literature, prompting a multi-stage literature search strategy. This study, conducted on January 29, 2024, specifically targeted articles from 2013 to 2023 that included these terms in their titles, abstracts, or keywords and were published in English. To analyze and visually represent the bibliographic data, the study employed two software tools, VOSviewer and Bibliometrix, both of which are widely recognized in bibliometric and scientometric research for their analytical capabilities. Table 1 presents main informations about this bibliometric study.

Table 1. Main informations of the bibliometric study

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2013:2023
Sources (Journals, Books, etc)	188
Documents	739
Annual Growth Rate %	33,7
Document Average Age	3,71
Average citations per doc	38,7
References	34646
DOCUMENT CONTENTS	
Keywords Plus (ID)	5210
Author's Keywords (DE)	1653
AUTHORS	
Authors	2286
Authors of single-authored docs	5
AUTHORS COLLABORATION	
Single-authored docs	7
Co-Authors per Doc	5,81
International co-authorships %	31,26
DOCUMENT TYPES	
article	650
book chapter	18
conference paper	25
conference review	3
data paper	2
review	41

2.1 Publication and citation trends by year

Table 2 reveals an interesting dynamic in scientific production concerning sewage sludge pyrolysis for biochar production over an 11-year period (2013-2023).

Table 2. Tendency of publications and citations per year

Year	Mean TC Per Article	Articles	Mean TC Per Year	Citable Years
2013	221.12	8	18.43	12
2014	131.8	15	11.98	11
2015	96.07	29	9.61	10
2016	103.36	25	11.48	9
2017	71.3	27	8.91	8
2018	63.24	55	9.03	7
2019	66.64	70	11.11	6
2020	43.75	91	8.75	5
2021	24.82	117	6.2	4
2022	13.83	156	4.61	3
2023	2.55	146	1.27	2

The table shows a significant increase in the number of articles published per year, starting with 8 in 2013 and peaking at 156 in 2022, before decreasing slightly to 146 in 2023. However, looking at "Mean Total Citations (TC) Per Article", there is a notable decrease from 221.12 in 2013 to just 2.55 in 2023, suggesting that although more and more articles are being published, the average impact per article, as measured by citations, is decreasing. Similarly, the "Mean TC Per Year" decreases over time, indicating that more recent articles are cited less than those from earlier years. This may suggest either saturation of the field or a lower propensity for more recent publications to have been cited due to their novelty. Citable Years also decrease over time, which is natural since more recent articles have had fewer opportunities to be cited.

2.2 Countries and Affiliations with the highest productivity

Looking at Figures 2 and 3, we can see that China largely dominates scientific output in the field of sewage sludge pyrolysis for biochar production, with an impressive total of 410 papers. This may reflect a strategic focus on environmental and waste management technologies, as well as substantial support for research

in this field. Australia and the USA follow with 49 and 48 articles respectively, suggesting significant interest and participation in this research, albeit to a lesser degree than China. The contributions of countries such as Poland, Brazil, Germany and India, which produce between 30 and 44 articles, show that interest in biochar is widespread and represents a global environmental concern. The inclusion of countries with emerging economies such as India and Brazil also indicates a growing recognition of the value of biochar in sustainable development strategies.

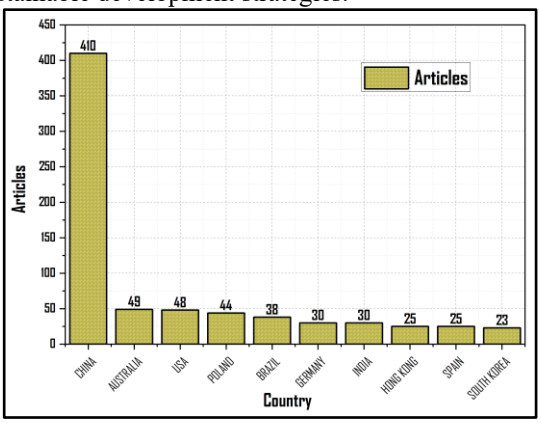

Fig. 2. Highest productive countries

In terms of institutional affiliations, HUAZHONG in China emerges as the leader with 113 papers, underlining the role of universities and research institutes in promoting this technology. Other notable institutions include the INSTITUTE in Australia with 81 articles and TIANJIN in China with 61 articles, illustrating their strong contribution and probably expertise in the field.

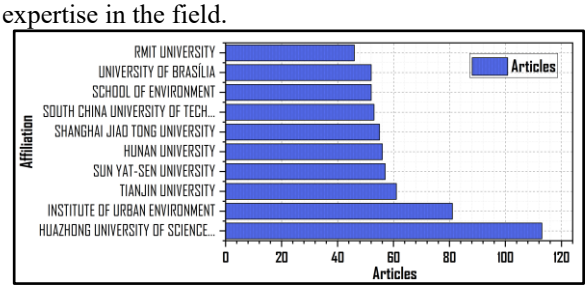

Fig. 3. Highest productive affiliations

The high figures. For these affiliations, suggest a concentration of research resources and expertise, perhaps due to specific funding or programs dedicated to the study of biochar. In addition, the presence of several institutions with significant contributions (over 50 papers) such as SUN YAT-SEN in China, HUNAN in China, and SHANGHAI, demonstrates the diversity and breadth of biochar research within China, corroborating the importance the country attaches to this technology.

2.3 Most relevant authors

Examination of scientific output by author in the field of sewage sludge pyrolysis for biochar production reveals that LI J is the most prolific author with 33 papers, closely followed by WANG Y with 32 papers, which stand out with a high split paper score at 4.89, indicating significant contribution in collaborative publications. ZHANG Y, ZHANG X and LIU Y are also major contributors, with over 20 articles each. Notably, OLESZCZUK P, with a fractionalized article score of 8.28 for his 22 articles, stands out as having considerable influence in the field, suggesting a central role in collaborative research or specialized expertise. This analysis reveals not only the most active authors, but also the depth of their involvement and collaboration in biochar research, which is crucial for understanding the dynamics and trends in this expanding scientific field.

Table 3. Most relevant authors

Authors	Articles	Articles Fractionalized
LI J	33	4.65
WANG Y	32	4.89
ZHANG Y	27	4.21
ZHANG X	24	3.38
LIU Y	23	3.19
OLESZCZUK P	22	8.28
WANG X	22	3.66
ZHANG J	22	3.60
LI H	21	3.29
LIU J	21	3.19

2.4 Highest productive journals

Figure 4 shows the most relevant scientific journals where research into sewage sludge pyrolysis for biochar production has been published. "Chemosphere" leads with 50 articles, indicating that it is a preferred publication platform for work in this field, closely followed by "Science of the Total Environment" and "Bioresource Technology" with 48 and 42 articles respectively.

These journals, being leading publications in the fields of environment and bioresource technology, reflect the growing importance and relevance of biochar research. Other important journals include "Journal of Environmental Management", "Environmental Science and Pollution Research", and "Waste Management", which highlight the diversity of aspects of biochar research, ranging from environmental management and pollution science to waste management. The substantial numbers of articles published in these sources underline the significant impact and continuing interest in studies on biochar from sewage sludge pyrolysis.

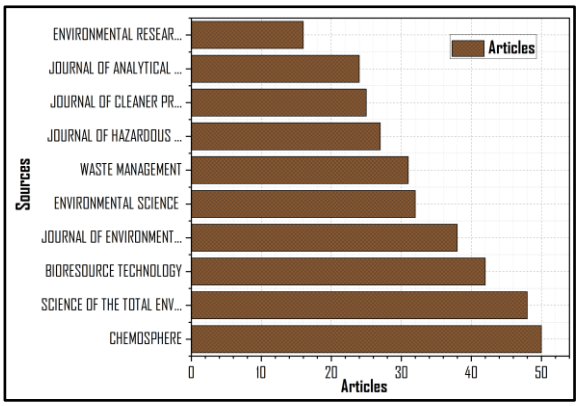

Fig. 4. Most relevant sources

2.5 Co-occurrence of keywords

The Figure 5 illustrates the co-occurrence of keywords in studies on sewage sludge pyrolysis for biochar production, revealing the research themes and connections between them. The keywords "pyrolysis", "sewage", "sludge" and "biochar" are at the heart of the network, indicating that they are the most frequently associated and central terms in research on the subject. Around these central terms, we find clusters of interconnected keywords such as "adsorption", "heavy metals" and "chemistry", which suggest specific lines of research, such as the study of biochar's adsorption capacities, its interaction with heavy metals and the understanding of the chemical processes involved. The connections between these keywords show the multiple facets of biochar research, encompassing environmental issues, engineering applications and chemical considerations, and underline the interdisciplinary nature of this field of study.

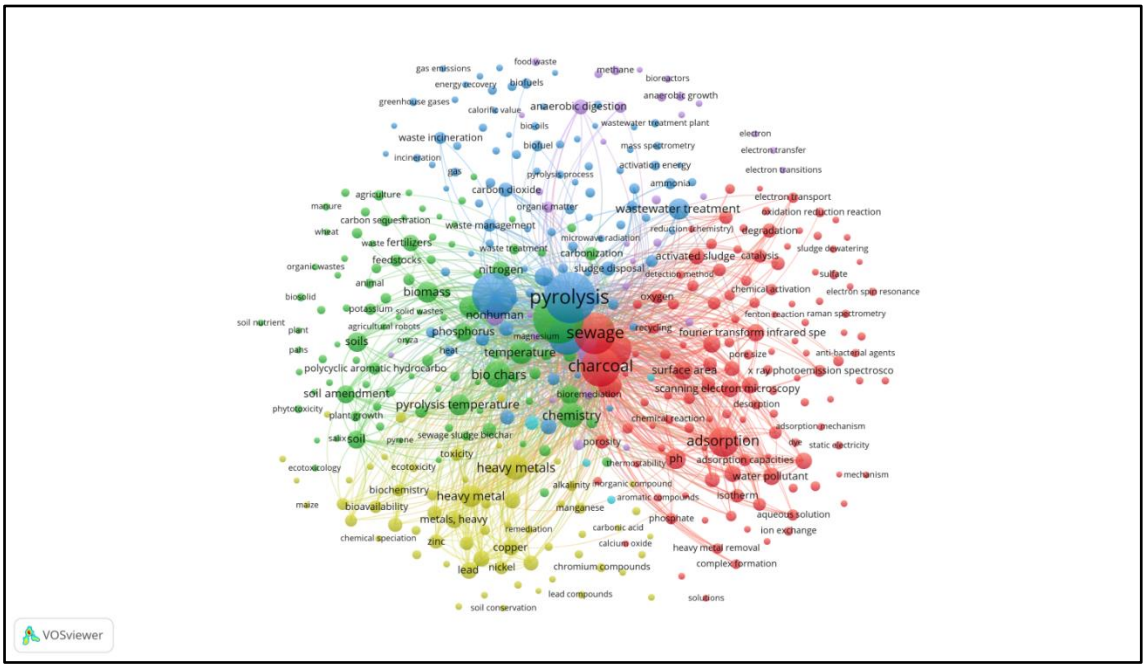

Fig. 5. Co-occurrence of keywords

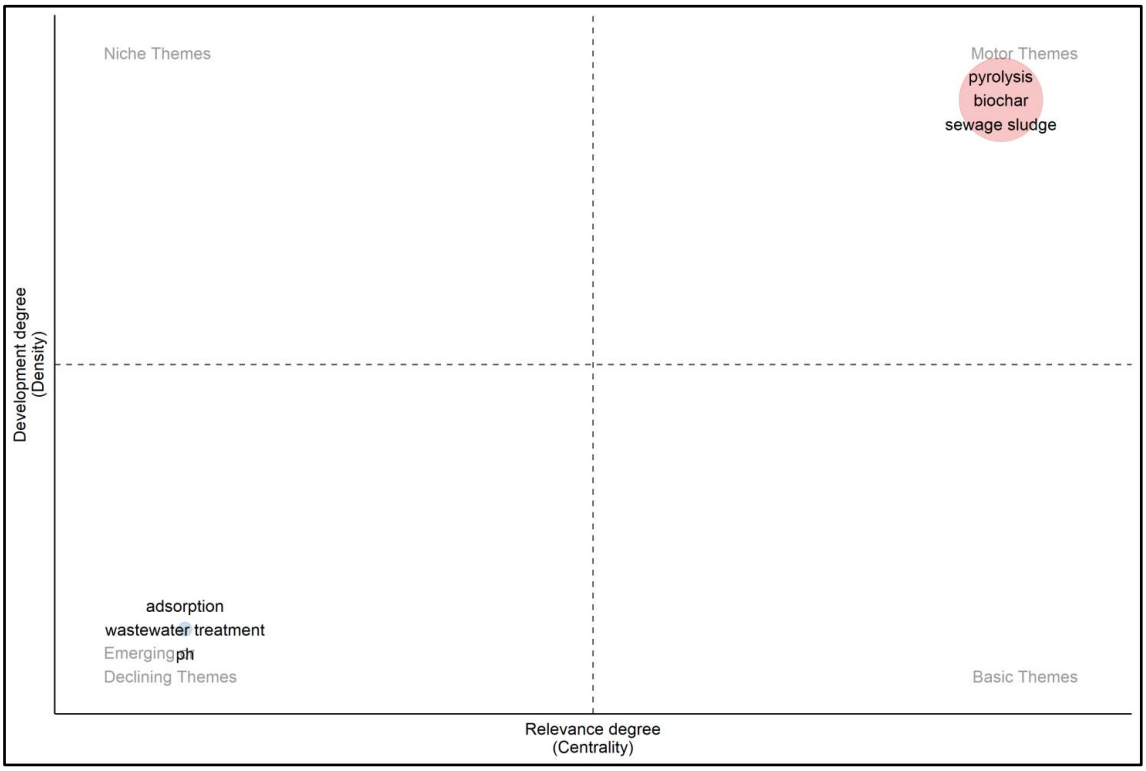

Fig. 6. Thematic map evolution 1

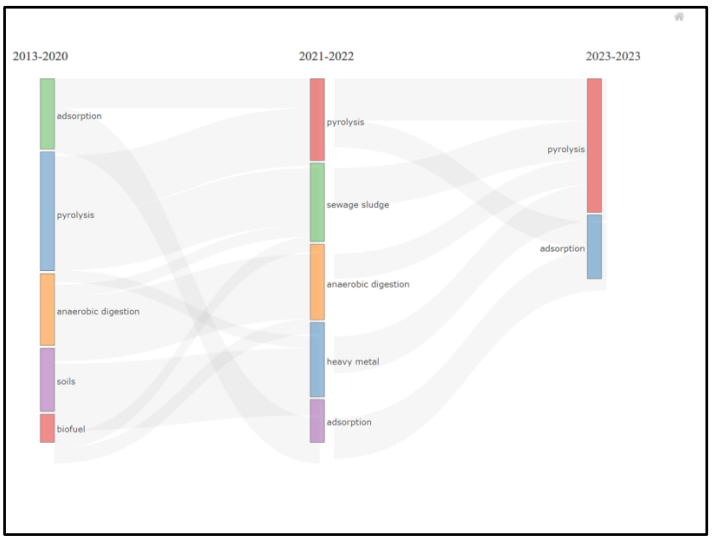

Fig. 7. Thematic map evolution 2

2.6 Thematic Evolution

The thematic maps encapsulated in Figures 6 and 7 provide a compelling visualization of the research terrain in the field of biochar production from sewage sludge pyrolysis. These maps reveal not only the current focus of scientific inquiry but also offer foresight into evolving trends and the maturation of certain themes over time.Central to this scholarly discourse are the themes of "pyrolysis," "biochar," and "sewage sludge," which stand out as the core subjects of study. Their prominence and consistent centrality across timelines suggest that they are the foundational pillars upon which the field is built. These topics have likely reached a point of intellectual saturation, indicating a robust body of knowledge that future research can build upon or pivot from. They serve as the bedrock for further innovation and application in the area of sewage sludge management through pyrolysis. On the other end of the spectrum, "adsorption" and "wastewater treatment" emerge as specialized niches within the broader research scope. Their positioning as niche themes highlights their potential as burgeoning areas of interest that may not have fully unfolded in the research narrative. These areas present fertile ground for pioneering work and signal potential shifts in the focus of future studies. They represent untapped opportunities that could yield significant advancements in the practical applications of biochar, particularly concerning its ability to purify water and enhance wastewater management technologies. The thematic evolution depicted in these maps not only guides current researchers in identifying the saturation and frontiers of the field but also aids in steering the collective scholarly efforts towards areas ripe for discovery and impact. It becomes evident that while the foundational work has been robustly established, the research frontier is advancing into new territories where the understanding of adsorption capabilities and the intricacies of wastewater treatment using biochar are just beginning to unfold. These insights are invaluable in sculpting the research agenda, ensuring a dynamic progression of knowledge that is both rooted in a strong foundation and expansive towards innovative applications.

3 Biochar production

3.1 Pyrolysis process

Sewage sludge pyrolysis is an advanced thermo-chemical process that takes place in the absence of oxygen (Figure 8). The process involves heating the sludge to temperatures generally between 300°C and 700°C [43]. Key process parameters, such as pyrolysis temperature, retention time and inert atmosphere (often nitrogen or water vapor), play a crucial role in determining the quality and characteristics of the biochar produced. At higher temperatures, there is generally an increase in carbonization and a reduction in volatile compounds in the biochar, which directly influences its properties [44].

Optimizing the pyrolysis process requires a thorough understanding of the chemical reactions involved, including the decomposition of organic matter and the restructuring of carbon compounds. This process leads to the formation of three main products: solid biochar, a condensable liquid (pyrolysis oil) and non-condensable gases [45]. The proportion of these products is highly dependent on operating conditions.

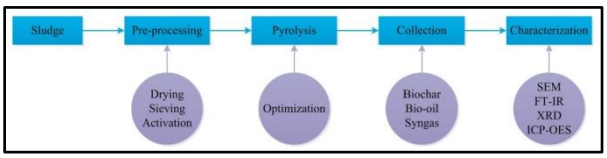

Fig. 8. Pyrolysis process of sludge

3.2 Biochar characteristics

Biochar produced from the pyrolysis of sewage sludge exhibits a set of unique physicochemical properties [46]. These include a high specific surface area, high porosity and a rich, stable carbon composition. Specific surface area and porosity are key factors in biochar's

effectiveness as an adsorbent, influencing its ability to trap pollutants or retain water in soils [47].

Chemically, biochar is mainly composed of carbon, with variable quantities of hydrogen, oxygen, sulfur and ash, depending on pyrolysis conditions. Elemental and spectroscopic analyses (such as Fourier transform infrared spectroscopy or nuclear magnetic resonance spectroscopy) are used to characterize the chemical structure of biochar. These studies reveal the presence of various functional groups on the biochar surface, which may play a key role in its interactions with metals, nutrients and organic contaminants.

The stability of carbon in biochar is another important aspect, as it determines its potential for carbon sequestration and the reduction of greenhouse gas emissions. Finally, understanding the properties of biochar is essential for optimizing its application in various fields, including soil quality improvement, water treatment and waste management.

4 Discussions

4.1 Summary of results

A thorough review of the scientific literature reveals significant and promising results with regard to biochar production and applications. According to a study by Lehmann and Joseph (2015) in "Biochar for Environmental Management", sewage sludge pyrolysis is an effective process for transforming waste into a useful product with multiple applications. Biochar, with its distinct characteristics such as high specific surface area, porosity and stable carbon content, is particularly suitable for a variety of applications. These include soil fertility improvement, carbon sequestration, water treatment and even some uses in energy production and construction.

In agriculture, the positive impact of biochar on soil structure, water and nutrient retention, and plant growth has been widely documented. Glaser et al (2002), in their publication in "Science", showed that biochar can significantly improve soil quality, thereby increasing agricultural productivity [48]. This improvement is attributed to biochar's ability to increase water and nutrient retention in the soil, which is essential for plant health. With regard to water treatment, biochar has proven to be an effective adsorbent for various contaminants. In a study conducted by Inyang and al. (2016) and published in "Critical Reviews in Environmental Science and Technology", it was shown that biochar can effectively remove heavy metals and organic compounds from water. These results suggest that biochar could play a crucial role in reducing environmental pollution and promoting sustainable practices in agriculture and industry.

In conclusion, the scientific literature clearly indicates that biochar, derived from the pyrolysis of sewage sludge, offers considerable potential in a variety of environmental and industrial applications. These studies, conducted by leading researchers in the field, underline the importance of biochar as a versatile tool for a sustainable future.

4.2 Challenges and limitations

Although biochar has many potential benefits, its production and use raise a number of challenges and limitations that require particular attention.

One of the major challenges in the use of biochar is the significant variability of its properties, which are highly dependent on the nature of the raw materials used and the specific pyrolysis conditions. This variability can significantly affect the quality and efficiency of biochar for specific applications. For example, studies such as that by Spokas and al. (2011) have shown that biochar produced at lower temperatures can be less effective in carbon sequestration than that produced at higher temperatures, due to its less stable carbon content. Similarly, the adsorption capacity of biochar can vary, influencing its effectiveness in water treatment or soil improvement.

Producing biochar on a sufficient scale to meet agricultural and industrial needs is another major challenge. Scaling up biochar production involves significant logistical and economic challenges. Costs associated with the collection and transportation of raw materials, as well as the installation and operation of pyrolysis equipment, need to be considered. As Roberts and al. (2010) point out, the economic viability of biochar production is crucial to its widespread adoption.

The environmental aspect of biochar production is also of concern. Although pyrolysis is generally regarded as a relatively clean process, it is not exempt from the production of gases and other by-products that require proper management to minimize pollution. Furthermore, as Woolf and al. (2010) point out, the large-scale use of biochar needs to be assessed in terms of potential impacts on the global carbon and water cycles, to avoid undesirable effects on the environment.

5 Biochar applications

5.1 Soil amendment

The application of biochar as a soil improver represents a major advance in sustainable agricultural practices, offering substantial benefits in terms of improved soil fertility and carbon sequestration. By integrating biochar into the soil, its physical and chemical characteristics can be significantly modified, leading to an overall improvement in soil quality [49].

From a physical point of view, biochar, characterized by its porous structure and high specific surface area, helps to improve soil structure. It increases porosity, facilitating better aeration and more efficient drainage. This is particularly beneficial in clay soils, where biochar can help reduce compaction, and in sandy soils, where it improves water retention capacity. These physical improvements are crucial to healthy plant growth, enabling better rooting and optimal absorption of nutrients and water.

Chemically, biochar acts as a reservoir for essential nutrients such as nitrogen, phosphorus and potassium. It acts by retaining these nutrients and gradually releasing them, thus minimizing leaching and improving fertilizer

efficiency. This property of biochar is particularly useful in nutrient-poor soils, where it has been shown to significantly boost crop productivity [50]. Biochar also promotes microbial activity in the soil. Its structure provides a suitable habitat for beneficial microorganisms, which can play a crucial role in the biological transformation and availability of nutrients [50]. One of biochar's most significant assets is its ability to sequester carbon. Rich in stable carbon, biochar added to soil resists degradation, enabling carbon to be stored over long periods. This characteristic makes biochar a potentially powerful tool in the fight against climate change. Sequestering carbon in the soil via biochar can help reduce greenhouse gas levels in the atmosphere, a crucial step in mitigating the effects of climate change. In short, incorporating biochar into agricultural soils offers multiple advantages, combining improved soil health and fertility with considerable environmental benefits, particularly in terms of carbon sequestration. These aspects make biochar a key component of sustainable agricultural strategies and an important ally in the fight against climate change.

5.2 Water treatment

The application of biochar in water treatment is another promising facet of its use, exploiting its unique properties for the filtration and adsorption of contaminants [51]. Due to its large specific surface area and high porosity, biochar has proven to be an effective adsorbent for various types of pollutants present in water, ranging from heavy metals to drug residues and organic chemicals.

A notable example of this application is the use of biochar to remove heavy metals such as lead, mercury and cadmium from water. Studies have shown that biochar produced from certain biomasses, such as coconut husks or agricultural residues, can effectively adsorb these metals, reducing their concentration in water to levels that meet safety standards [52]. This is particularly relevant for the treatment of industrial run-off or contaminated groundwater.

In addition, biochar has been tested for the removal of organic pollutants such as pesticides and herbicides, as well as pharmaceutical compounds and endocrine disruptors. Its carbon structure traps these molecules, effectively reducing their presence in treated water. For example, research has shown that biochar derived from the pyrolysis of wood waste was particularly effective in adsorbing atrazine, a commonly used herbicide, from contaminated water [53].

Biochar has also been used in more complex water filtration systems. For example, some systems combine biochar with other materials such as sand and gravel to create multi-layer filters capable of removing both solid particles and dissolved contaminants from water [54]. These filtration systems, often used in rural or developing contexts, offer an inexpensive and effective solution for improving drinking water quality.

In conclusion, biochar is a versatile and effective water treatment tool, capable of removing a wide range of contaminants. Its ease of production from a variety of biomass sources, as well as its ability to be regenerated and reused, makes it an ecologically and economically viable option for water treatment systems, contributing to environmental protection and public health.

5.3 Other Biochar applications

Beyond its use as a soil improver and water treatment agent, biochar has applications in a variety of other fields, notably in energy production and as a building material, highlighting its versatility and potential as a sustainable resource [55].

Biochar can play a significant role in the production of renewable energy. As a source of carbonized biomass, it can be used as a fuel for thermal power generation. Its high carbon content and low moisture content give it a higher calorific value than untreated biomass. For example, biochar derived from the pyrolysis of agricultural waste can be burned in biomass boilers to produce heat or electricity, offering an alternative to fossil fuels [55].

Biochar is also being studied in the context of biogas production. The addition of biochar to anaerobic digesters, used for biogas production from organic waste, can improve the digestion process and increase biogas yield. This is due to biochar's ability to promote the growth of the micro-organisms involved in anaerobic digestion.

Biochar is also useful as a building material. Because of its thermal insulation properties and fire resistance, biochar is incorporated into building materials such as bricks, concrete and insulating panels. For example, adding biochar to concrete can not only improve its insulating properties but also reduce its overall carbon footprint, as the carbon sequestered in the biochar is efficiently stored in the building structure [55].

Incorporating biochar into building materials offers several advantages. It can improve the moisture resistance and durability of materials, while offering a solution for carbon sequestration. Studies have shown that building materials enriched with biochar can have a longer lifespan and better insulating properties, thus reducing the energy costs associated with heating and cooling buildings [56].

In short, biochar is proving to be a multifunctional resource, with innovative applications in energy production and the construction industry. These diversified uses not only add value to an otherwise problematic waste product, but also contribute to sustainable development initiatives, offering environmentally-friendly alternatives in key sectors of the economy.

6 Conclusion

The journey through the landscape of biochar production from sewage sludge pyrolysis as detailed in this review illuminates the vast potential and the challenges that lie ahead in this field. As we have seen, the transformation of sewage sludge into biochar through pyrolysis represents a promising avenue for sustainable waste management, with applications that span soil amendment, water treatment, carbon

sequestration, and even energy production and construction materials. The versatility of biochar, coupled with its environmental benefits, underscores its importance as a tool for a sustainable future.

However, the path forward is not without its obstacles. The variability in biochar properties, the scale-up of production processes, economic considerations, and the environmental impacts of biochar production and use all represent significant challenges that must be addressed. To this end, future research must focus on optimizing pyrolysis conditions to produce biochars with tailored properties for specific applications, developing cost-effective and scalable production technologies, and rigorously assessing the environmental impacts of biochar throughout its lifecycle. Moreover, the integration of biochar into existing waste management, agricultural, and industrial systems requires a multidisciplinary approach that involves engineers, scientists, policymakers, and stakeholders. Collaboration across these domains will be crucial to overcoming the technical, economic, and regulatory hurdles that currently limit the wider adoption of biochar technology.

As we look to the future, it is clear that biochar from sewage sludge pyrolysis holds the potential not only to mitigate the environmental and economic challenges associated with sludge management but also to contribute significantly to the global efforts against climate change and environmental degradation. In this light, the continued exploration and innovation in biochar research and applications are not only warranted but imperative. The journey is far from over, and the road ahead promises to be both challenging and rewarding, offering opportunities for significant contributions to environmental sustainability and the well-being of future generations.

Author contribution

A.T. (Ph.D. student), Y.E. (Ph.D) and I.A. (Ph.D. student) conducted the analysis and wrote the manuscript. M.M. (Ph.D. student) collected data. M.E. (Professor) and H.F. edited the original draft. F.D. (Professor) and K.H supervised and guided the review.

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