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Review Article

From waste to energy: A systematic review of sewage sludge conversion to solid fuels via thermochemical methods

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Abstract. Sewage sludge, a byproduct of wastewater treatment, poses significant risks to human health and ecosystems due to its high levels of harmful pollutants, including heavy metals, viruses, and non-biodegradable materials. To mitigate these hazards, thermochemical conversion has emerged as a sustainable strategy for recovering energy and nutrients while reducing the toxicity of sewage sludge. A comprehensive literature search across Science Direct, Scopus, and Web of Science yielded 46 peer-reviewed papers from an initial 2,715 publications. This paper presents a systematic review of the thermochemical conversion processes used to transform sewage sludge into solid fuels, focusing on pyrolysis, torrefaction, and hydrothermal carbonization. The study highlights the significance of optimizing operational parameters and investigates the physicochemical properties of the biochar produced. The results indicate that reaction temperature, time, and heating rate significantly influence the quality and yield of the resulting biochar. Higher temperatures (300–1000°C) enhance the energy content while reducing solid yield. The environmental impacts associated with thermochemical methods, including emissions and potential pollutants, are discussed along with the challenges in treating and transforming sewage sludge into solid fuels. These findings indicate that hydrothermal carbonization is a promising method for waste management and energy production, supporting global efforts to reduce greenhouse gas emissions and dependence on fossil fuels. However, challenges remain in scaling up these technologies for commercial implementation due to high capital and operational costs This review contributes to the understanding of thermochemical processes and their potential applications in sustainable waste-management practices. Future research should focus on pilot and industrial-scale validation, cost-effective pretreatment strategies, and standardized analytical methods. Supportive policy frameworks and investment in demonstration projects are crucial for promoting thermochemical conversion as a viable waste-to-energy solution, contributing to sustainable development and climate change mitigation.

Keywords: Sewage sludge, Thermochemical, Solid fuels, Biochar, Waste management

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1. Introduction

The worldwide demand for fossil fuels is increasing due to the rapid industrialization and economic development of emerging countries. This places further strain on fossil fuel reserves and leads to greater focus on alternative energy sources (Naqvi *et al.*, 2021). Sewage sludge, a significant byproduct generated from the treatment of municipal wastewater, has emerged as a promising alternative, owing to its capacity to be transformed into valuable energy resources. The composition of sewage sludge is highly variable, influenced by factors such as wastewater treatment processes, the nature of the influent, and regional characteristics. The presence of heavy metals and organic pollutants, particularly from industrial sources, such as printing and dyeing, can limit their use as fertilizers (X. Zhang *et al.*, 2021). However, the nutrient-rich composition of sewage sludge, particularly nitrogen and phosphorus, makes it a valuable resource for agricultural applications (Khalid *et al.*, 2012; Zapałowska, 2023). To ensure environmental protection and human health, a thorough safety assessment is necessary due to the diverse composition of sewage sludge (Zawadzki *et al.*, 2020).

Climate change stands as one of the most critical global issues, with profound effects on ecosystems, public health, and economic systems. The rapid pace of industrialization and urbanization significantly contributes to the rise in greenhouse gas (GHG) emissions, which in turn heighten the frequency and intensity of climate-related events. The COVID-19 pandemic offered a brief insight into the connection between human activities and air quality, as illustrated by studies such as Progiou *et al.*, (2022), which observed marked reductions in air pollution during lockdowns in urban areas like Athens, Greece.

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These findings emphasize the environmental costs of conventional industrial practices and the urgent need for sustainable alternatives. As Martín-ortega *et al*., (2024) point out, transparent and integrated mitigation strategies are essential for meeting climate objectives and managing emissions across various sectors. In semiarid and climate-sensitive regions, the sustainable management of resources—such as water and waste—becomes increasingly crucial, as shown by Nydrioti *et al.,* (2024), who investigated urban water resource challenges under different climate scenarios. In this context, the thermochemical conversion of sewage sludge presents a dual benefit: reducing environmental pollution and aiding climate change mitigation by substituting fossil fuels with renewable energy sources. By transforming waste into energy-rich solid fuels, these processes support circular economy goals and offer scalable climate adaptation solutions, particularly for densely urbanized and industrial regions (Tsimnadis *et al*., 2023; Zafeiriou *et al*., 2022).

The management of sewage sludge is essential in wastewater treatment plant operations. The financial costs associated with the management and disposal of sewage sludge can represent 40-60% of the total expenditure incurred by wastewater treatment facilities, encompassing expenses related to labor, maintenance, energy consumption, and the processing and disposal of sludge (Domini *et al*., 2022). The amount of sludge is becoming a global environmental concern, driven by factors such as population growth and the expansion of industry and agriculture. As urban populations increase, the volume of wastewater generated also increases, resulting in an increased volume of sewage sludge. The global production of sewage sludge has led to diverse treatment strategies across countries, each adapting its own unique infrastructure and environmental policies. Effective management of sewage sludge is essential to mitigate its environmental impact and harness its potential as a resource (Lamastra *et al*., 2018).

The worldwide generation of sewage sludge and various treatment methodologies has significantly increased, as shown in Table 1. Different methods have been employed globally for the treatment of sewage sludge, including incineration, landfilling, agricultural use, composting, and other innovative techniques. India is the leading country for sewage sludge production, generating 75 million tonnes of dry matter annually, followed by China with 39.04 million tonnes (Li *et al*., 2024). Japan and Germany generate more sewage sludge than the European Union, with 20 million tonnes per year whereas the United States, Indonesia, and the European Union generate over 10 million tons each. In contrast, Singapore and Malaysia produce 160,000 tonnes and 7 million tonnes, respectively, with Singapore having only four treatment units while effectively managing its production. Landfilling remains the predominant disposal method in Malaysia, with a total of 161 landfills, consisting of 147 non-sanitary landfills and 14 sanitary landfills (Ministry of Energy, 2017). By 2030, almost 80% of Malaysia's open garbage sites will be closed, as they reach their maximum capacity (Yong *et al*., 2019).

Landfilling is widely used in the management of sewage sludge in developed nations, particularly in areas with abundant available land. The bulk of sludge is immediately disposed of in landfills after undergoing mechanical dewatering, resulting in a moisture content of over 80% and extremely poor compressive strength (Zhen *et al*., 2017). However, these methods are currently discouraged owing to the significant risks of secondary contamination and stringent environmental laws. Moreover, landfills require additional land and contribute to global warming by emitting gases into the atmosphere (Naqvi *et al*., 2021). Alternatively, modern methods, such as agricultural use, soil amendment, incineration, and anaerobic digestion, are widely employed for the treatment and disposal of sewage sludge (Jumasheva, 2023). The utilization of sewage sludge is gaining attention owing to its alignment with the principles of circular economy and ecological sustainability (Duan *et al*., 2022). In the European Union, agricultural use is a significant disposal option (Mancuso *et al*., 2021). However, challenges such as the presence of heavy metals and hazardous substances within the sludge limit its direct agricultural application, making thermochemical conversion methods suitable alternatives for disposal (Kosiński *et al*., 2023).

Thermochemical conversion technologies offer promising solutions for transforming sewage sludge into valuable solid fuels. The potential of sewage sludge as a solid fuel source has been increasingly acknowledged owing to its inherent energy content and capacity for volume reduction (Trinh *et al*., 2013). Various studies have explored different methods for transforming sewage sludge into solid fuel, including pyrolysis (Languer *et al*., 2020), hydrothermal carbonization (Wilk *et al*., 2023), and torrefaction (Poudel *et al*., 2015). These processes aim to increase the energy efficiency of sewage sludge drying and enhance its heating value, thereby rendering it a feasible substitute for fossil fuels (Kim *et al*., 2021). Thermochemical conversion methods can effectively lower the volume of sewage sludge, reclaim energy and materials, and improve pathogen removal (Hu *et al*., 2021). Additionally, these processes can enhance the dewatering capabilities of sewage sludge, facilitating its handling and transportation (X. Zhang *et al*., 2020). Moreover, thermochemical methods offer a sustainable

Table 1
Global generation of sewage sludge and various techniques employed by countries for its management.

Nations	Generation of sewage sludge (million tonnes/year)	Treatment strategies	References
China	39.04	Soil amendment, incineration, sanitary landfill, building materials, recycling and waste to energy	(Li *et al*., 2024)
United State	17.80	Landfill, incineration, construction industry, recycling (fertilizer)	(Han *et al*., 2021; Xiang *et al*., 2024)
Japan	20.00	Incineration without energy recovery, landfill, building material	(Gao *et al*., 2020; Horikoshi *et al*., 2024)
India	75.00	Landfill, recycling, incineration	(Aparna, 2022)
South Korea	1.48	Incineration, landfill, recycling (fuel, composting, construction material)	(An *et al*., 2021)
Mexico	0.64	Landfill, agricultural, recycling and waste to energy	(Garc *et al*., 2024; Luis *et al*., 2022)
Germany	20.00	Landfill, agricultural, thermal treatment	(Gao *et al*., 2020; Schnell *et al*., 2020)
European Union	10.30	Agricultural, composting, landfill, incineration	(Minh *et al*., 2022)
Indonesia	17.04	Landfill	(Koko *et al*., 2022; Pang *et al*., 2023)
Singapore	0.16	Landfill, land disposal and incineration	(Chan *et al*., 2016)
Malaysia	7.00	agricultural use, landfill, and incineration.	(Hanum, F. *et al*., 2019)

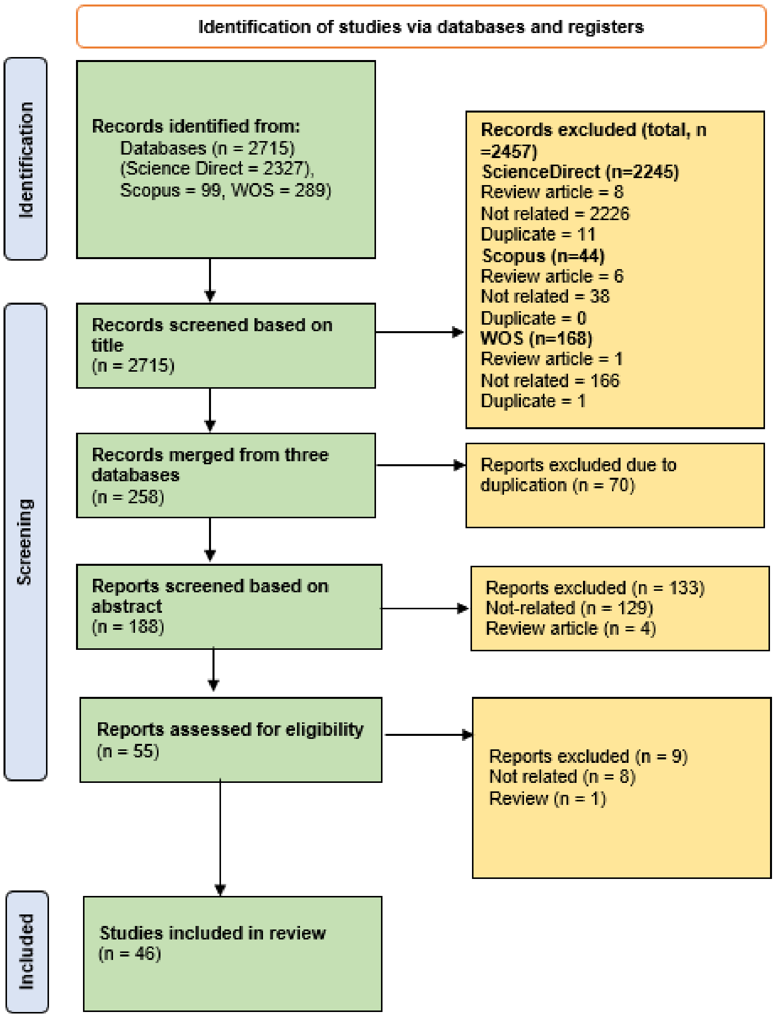

Fig. 1. PRISMA flowchart detailing the study selection methodology and the number of articles identified, reviewed, and included in this systematic literature review.

strategy for the management of sewage sludge by enabling the generation of biofuels (Cebi *et al.*, 2022).

A number of authors have explored the potential of sewage sludge as a source of valuable energy and materials to achieve carbon neutrality (Gururani *et al.*, 2022; Hu *et al.*, 2022; Syed-Hassan *et al.*, 2017). Despite the extensive studies and reviews that have investigated the challenges and opportunities of thermochemical conversion of sewage sludge, such as process complexity and environmental concerns, there remains a significant gap in the systematic synthesis of performance outcomes across different conversion methods. To the best of our knowledge, there has yet to be a thorough review that consolidates and assesses the operational parameters and solid fuel properties of biochar produced from sewage sludge using pyrolysis, torrefaction, and hydrothermal carbonization. This research seeks to address this gap by performing a systematic review of the literature with the following primary objectives: (a) to assess and compare the optimal conditions—such as temperature, reaction time, and heating rate—across major thermochemical conversion methods and (b) to analyze and synthesize the resulting output parameters, including proximate and ultimate composition, higher heating value (HHV), solid yield, and energy yield of biochar, while considering a wide range of geographic and feedstock variations.

This review consolidates these findings to present novel insights into the thermochemical behavior of sewage sludge, offering a valuable resource for future research and industrial applications focused on the sustainable production of solid fuels.

2. Methods

2.1. Searching strategy

A comprehensive review of the existing literature was undertaken utilizing the subsequent electronic databases: Science Direct (SD), Scopus and Web of Science (WoS), employing the search terms: (sewage sludge) AND ((solid-fuel) OR (solid-biofuel)) AND ((carbonization) OR (pyrolysis) OR (torrefaction)) NOT (adsorption). Database searches were conducted from January 1, 2013, to November 30, 2023. For the Science Direct database, the search option was ‘all fields.’ The Scopus search options were ‘title, abstract, and keywords’ and ‘all fields’ for WoS. The article selection process involved two independent authors who evaluated each publication based on the established eligibility criteria. Screening was conducted in three stages: first, by examining titles, then abstracts, and finally full-text articles. When disagreements arose regarding inclusion or classification, the reviewers engaged in discussions to reach mutual agreement.

2.2. Guidelines for inclusion and exclusion

We have added relevant scholarly articles exploring thermochemical methods for producing highly efficient solid fuel products from sewage sludge. Our inclusion criteria focused on full-text articles published in English that examined the transformation of sewage sludge into solid fuels using thermochemical processes. These articles were required to provide well-supported data on proximate and ultimate analyses, high heating values, and energy yields. Studies were excluded if they were literature reviews, book chapters, books, non-English, focused on economic analysis/life-cycle assessment, or only reported heat or activation energy. Any disagreements in the selection process were resolved through collaborative discussion among the authors.

2.3. The process of data extraction and synthesis

Data analysis was conducted using Microsoft Excel and was reviewed by each author. The analysis of the 46 papers yielded results that allowed readers to understand the perspectives and critical elements of each study included in this review. The following ten data items were used: type of sewage sludge, moisture content, carbonization method, reaction conditions, proximate analysis, ultimate analysis, higher heating value (HHV), solid yield, energy yield, and researchers.

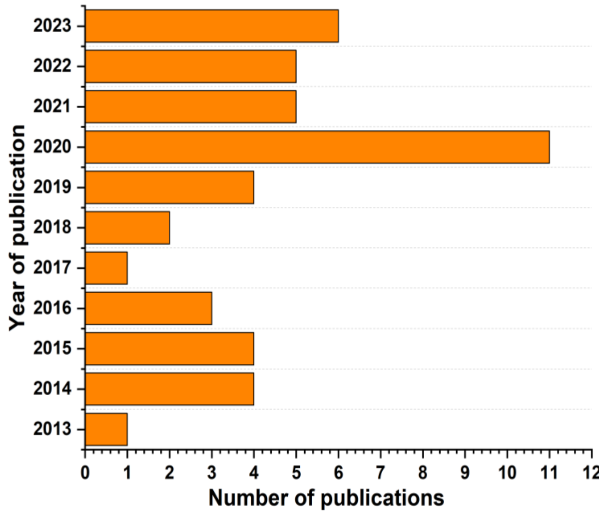

Fig. 2. Number of the selected research published per year

3. Results and Discussion

3.1. Details of the article selection criteria

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Rozehan *et al.*, 2024), as illustrated in Fig. 1. A total of 2715 articles were initially sourced from Science Direct (n= 2327), Scopus (n= 99), and Web of Science (n= 289) using a systematic search approach. Subsequently, 2669 papers were excluded from the screening process for a variety of reasons, categorized by titles (n= 2457), abstracts (n= 133), and full texts (n= 9). This systematic review included 46 important full-text articles that predominantly explored the thermochemical conversion of sewage sludge as a feedstock.

3.2. Trends in yearly literature

Fig. 2 shows the yearly distribution of the analyzed studies. The number of publications fluctuated throughout the review period (2013-2023). In 2020, there was a surge in the number of publications, with a total of eleven studies being published. The observed increase in the first five years (2013-2017) can be attributed to increased global awareness of sewage sludge issues. This has drawn attention to the possibility of using biochar extracted from sewage sludge as a sustainable energy resource, emphasizing its critical role in energy recovery. In contrast to the period from 2018 to 2023, an increase in the number of publications has been recorded. This highlights the significance of elements such as reaction temperature, reaction time, solid-to-liquid ratio, and additional parameters during the thermochemical process that affect the quality, composition, and energy attributes of the resultant biochar as a solid fuel. The keywords or thematic areas relevant to the publication trends from January 2013 to November 2023 were also analyzed using VOS viewer (Fig. 3). An analysis of the data reveals a significant increase in publications that include the terms "sewage sludge," "hydrothermal carbonization," and "hydrochar," which have emerged as the primary keywords.

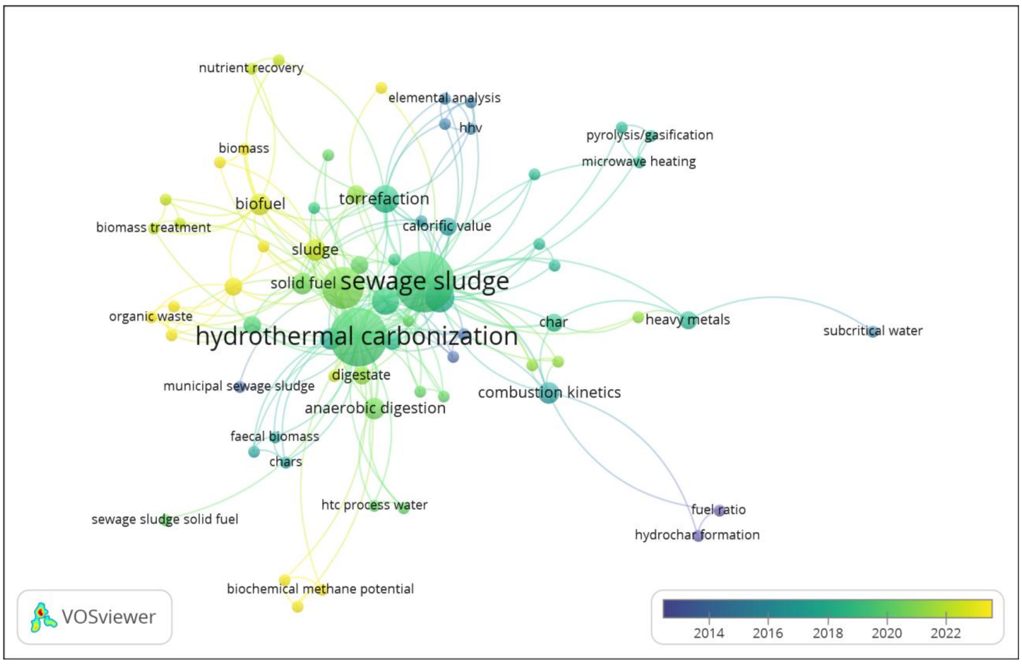

Fig. 3. Visualization of keyword co-occurrence networks by 2013 – 2023 using the VOS viewer.

Table 2
Basic composition of sewage sludge

Type of material	Description
Volatile solids	represents the quantity of organic materials that are available for biodegradation (Luis *et al.*, 2022)
Protein	Protein is a key organic element in sewage sludge, resulting in a significantly higher nitrogen concentration (2.5-9 wt%) (Xu *et al.*, 2018)
Polysaccharides	polymers derived from monosaccharides such as glucose, mannose, and fructose are predominantly found in sewage sludge in the forms of cellulose, hemicellulose, and starch (L. Wang *et al.*, 2019)
Lipids	Typically constituted of triglycerides, which are formed by the esterification of three fatty acid molecules to a glycerol scaffold. These lipids are derived from the direct adsorption processes occurring in wastewater, phospholipids sourced from cellular membranes, as well as metabolic by-products resulting from microbial activity and cellular lysis (L. Wang *et al.*, 2019)
Humic substances	Formed by microbial degradation of organic matter produces a diverse range of compounds, including humic acids, fulvic acids, and humins. These compounds are characterized by aromatic nuclei and contain phenolic and carboxylic groups (L. Wang *et al.*, 2019)

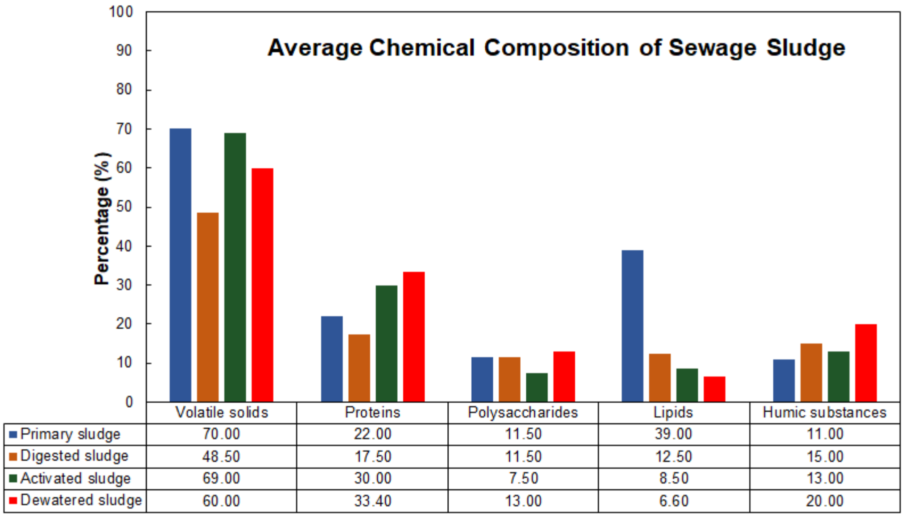

Fig. 4. Average sewage sludge composition. Source: (L. Wang *et al.*, 2019; Yokoyama, 1996)

3.3. The composition of sewage sludge

Sewage sludge represents a category of waste that possesses the potential for energy conversion and encompasses various classifications, such as primary, digested, activated, and dewatered sludge. Primary sludge is derived following mechanical treatment processes (including screening, grit removal, and sedimentation) and contains 93-99.5% water, whereas digested sludge is produced through anaerobic digestion. Activated sludge is produced by biological treatment processes and exhibits a significant concentration of microbial biomass, with a total solid content varying between 0.80 and 1.20%. Dewatered sludge, alternatively referred to as mechanically dewatered sludge, is generated via mechanical and physical methods to reduce its moisture content, resulting in a moisture content range of 73-84% (Syed-Hassan *et al.*, 2017). However, the composition of each sludge type varied according to the nature of sewage and the technical processes utilized in the wastewater treatment facility, as illustrated in Fig. 4. It is commonly recognized that sewage sludge contains a significant amount of organic components, including proteins, polysaccharides, lipids, humic substances, and nucleic acids (L. Wang *et al.*, 2019). The properties of the sludge generated by the same wastewater treatment facility can vary from day to day. A detailed analysis of the constituents of the sewage

Table 3
The physicochemical composition of sewage sludge, biomass and lignite

Sample	Elemental composition (wt.% daf)					Proximate analysis (wt.% db)			HHV (MJ/kg)	References
	C	H	N	O[a]	S	Ash	VM	FC		
Sewage sludge	48.10 – 51.20	6.64 - 7.90	7.90 - 8.85	31.94-36.30	0.80-1.37	13.70-18.51	73.50-78.49	2.01-12.70	17.60-19.22	(Ahn *et al.*, 2020; Villamil *et al.*, 2020; Zhao *et al.*, 2014)
Biomass	47.27-49.22	5.71-8.09	0.40-3.82	39.20-45.32	0.00-0.40	1.30 - 4.43	71.54 - 81.16	16.91-24.03	18.21-20.31	(Abdoli *et al.*, 2024; Babatabar *et al.*, 2024; Wu *et al.*, 2024)
Lignite	60.31-64.03	5.00-5.26	0.88-1.07	21.58-26.76	0.54-0.76	7.57-11.26	40.72-52.23	41.52-51.71	24.39-25.45	(Lu *et al.*, 2022; Zhan *et al.*, 2022)

VM: Volatile matter; FC: fixed carbon; [a] by difference; daf: dry ash free; db: dry basis sludge, including their composition and key substances, is presented in Table 2.

Table 3 presents a comprehensive summary of the physicochemical properties of sewage sludge, biomass, and lignite, emphasizing their potential for energy production and environmental effects. Sewage sludge exhibits a significant carbon content (60.31-64.03%), which favors energy generation; however, its high ash content (13.70-18.51%) poses challenges in combustion systems due to slagging and fouling (Ahn *et al.*, 2020; Villamil *et al.*, 2020; Zhao *et al.*, 2014). Biomass, with a carbon content of 47.27-49.22% and a very low ash content of 1.30-4.43%, is advantageous for clean energy applications, offering high volatile matter (71.54-81.16%), which suggests an excellent energy release potential (Abdoli *et al.*, 2024; Babatabar *et al.*, 2024; Wu *et al.*, 2024). Conversely, lignite possesses the highest carbon content at 60.31- 64.03%, indicating strong energy production capability, but its high sulfur content (0.54-0.76%) could lead to significant SOx emissions, necessitating emission control measures (Lu *et al.*, 2022; Zhan *et al.*, 2022).

The HHV of these materials further support their potential as energy sources. Lignite exhibits a higher HHV of 24.39-25.45 MJ/kg, indicating its significant energy content. Biomass demonstrates moderate HHV of (18.21-20.31 MJ/kg), making it a renewable energy option with moderate energy density. Sewage sludge, although slightly lower with an HHV of 17.60-19.22 MJ/kg, remains a competitive energy source, particularly in comparison to other low-rank fuels such as lignite and the majority of biomass varieties. Each analyzed sample offers distinct advantages and challenges. Biomass is the most environmentally favorable option owing to its minimal ash composition and elevated volatile matter content, which facilitates clean combustion and effective energy release (Zaini *et al.*, 2023). In contrast, Lignite, which offers a high energy potential, requires careful handling to mitigate its environmental impact, particularly with regard to sulfur emissions. Although sewage sludge is less efficient than biomass in terms of energy release, it still provides considerable energy potential and can be a viable alternative, especially when properly managed to address its high ash content and other combustion challenges.

3.4. Thermochemical process of sewage sludge

Our comprehensive review encompassed scholarly articles published within the last decade that examined the utilization of sewage sludge as a solid fuel as well as the various factors influencing the characteristics of solid fuel derived from distinct carbonization techniques and operational conditions. Conventional thermochemical conversion methods such as torrefaction, pyrolysis, and HTC are frequently used to extract energy and materials from sewage sludge (Table 4). Fig. 5 shows the proportion of articles found for different carbonization methods. HTC (33 articles), torrefaction (8 articles), and pyrolysis (5 articles) were the most popular processes used in solid fuel research, accounting for 71.7%, 17.4%, and 10.9%, respectively. The effectiveness of thermochemical processes and the characteristics of their outputs are influenced by various internal and external factors, including physical and chemical properties as well as operational conditions. This thermal decomposition method yields a range of products in solid, liquid, and gas forms, depending on the specific operational parameters employed.

Sewage sludge undergoes a series of treatments, such as drying, grinding and densification to enhance its suitability for thermochemical processes. Initially, sewage sludge is collected from wastewater treatment facilities and typically undergoes thickening, anaerobic digestion, and dewatering to reduce its moisture content to as high as 79.5% (Kolosionis *et al.*, 2021). The sludge was then stored at low temperatures (e.g., 4 °C or -20°C) to preserve its characteristics (Huezo *et al.*, 2021; Volpe *et al.*, 2020). Prior to undergoing the thermochemical process, sewage sludge must undergo drying at 105°C and be ground to achieve a particle size smaller than 0.5 mm (Kolosionis *et al.*, 2021; X. Zheng *et al.*, 2020). Additionally, adjusting the pH of the sludge can optimize the thermochemical process, as a lower pH is preferred to avoid unfavorable reactions (Huezo *et al.*, 2021). These preparatory steps are essential to improve the effectiveness of energy recovery and nutrient management from sewage sludge (Shan *et al.*, 2023).

3.4.1. Torrefaction

To mitigate the drawbacks of the poor HHV of sewage sludge, it can be improved via a thermochemical conversion process known as torrefaction. During this process, sewage sludge is thermally destroyed in an inert or nitrogen atmosphere at atmospheric pressure and temperatures between 200 and 300°C, employing gradual heating rates for several minutes to hours (Atienza-Martínez *et al.*, 2015). Torrefaction is often characterized as a gentler version of pyrolysis, occurring at temperatures much lower than those typical of traditional pyrolysis. This process may also be referred to as roasting or high temperature drying. Sewage sludge undergoes transformation into charred-like substances through torrefaction. This process is typically conducted inside a torrefaction reactor, which can be a rotary, fixed-bed, or fluidized bed (Atienza-Martínez *et al.*, 2015; Karki *et al.*, 2018). It enhances several characteristics, including hydrophobicity and water resistance, energy density, grindability and reactivity, sludge brittleness, reduced atomic O/C and H/C ratios, and uniformity, rendering it appropriate for direct application as a fuel (Lee *et al.*, 2019). This transformation is attributable to the emissions of water, CO_2, CO, and lightweight organic compounds (Karki *et al.*, 2018). Additionally, torrefaction can reduce the expenses associated with the transportation, management, processing, and storage of sewage sludge (Lee *et al.*, 2019).

3.4.2. Hydrothermal carbonization

HTC, also referred to as wet torrefaction, is an emerging thermochemical process that has become increasingly popular as an alternative approach for managing sewage sludge. The exothermic reaction involves the transformation of sewage sludge into hydrochar, a carbon-rich byproduct, through a process that takes place in a closed vessel. This conversion occurs at temperatures ranging from 150 to 300°C under high-pressure conditions for multiple hours (Silva *et al.*, 2020). Additionally, the process yields a liquid phase, commonly termed liquor, along with a gaseous phase predominantly comprising carbon dioxide and methane (Huezo *et al.*, 2021). Within the framework of the HTC process, water functions as both a pivotal solvent and reactant. This treatment is particularly beneficial for wet sewage sludge with a moisture level of 70–80%, thereby promoting hydrochar formation (Zaharah *et al.*, 2024). The HTC process is primarily governed by dehydration, decarboxylation, and aromatization (Jjagwe *et al.*, 2021). The efficacy of this process is influenced by various parameters, including the reaction duration, temperature, and ratio of sewage sludge to the aqueous phase, making it a spontaneous and exothermic reaction that involves mixing sewage sludge with water and introducing it into a sealed reactor. In conclusion, HTC offers a promising approach for converting waste biomass into valuable energy resources, thereby promoting the principles of a circular economy and

Table 4
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Dewatered sewage sludge	90.32 – 95.51	HTC	Temperature: 160 - 240°C Time: 30 - 120 min Solid load ratio: 5 - 10% Heating rate: 3°C/min	55.46 - 62.24	25.52 - 37.30	7.13 - 12.24	24.05 - 27.87	2.50 - 3.21	5.48 - 14.38	1.91 - 2.90	0.73 - 1.08	9.56 - 11.57	61.8 - 94.2	-	(Gao *et al.*, 2019)
Sewage sludge	82.20	Torrefaction	Temperature: 150 - 600°C Time: 0 - 50 min Heating rate: 10°C/min Flowrate: 2 L/min (N_2)	15.00 - 44.00	54.00 - 85.00	-	47.00 - 52.00	3.00 - 7.00	11.00 - 23.00	7.60 - 8.50	0.10 - 0.40	15 - 22.5	25 - 98	23 - 98	(Poudel *et al.*, 2015)
Dewatered activated sludge	87.00 – 92.00	HTC	Temperature: 170 - 230°C Time: 60 min	16.40 - 28.8	54.00 - 75.20	8.40 - 17.20	46.30 - 50.50	5.60 - 6.20	8.40 - 24.00	6.30 - 6.60	0.40 - 0.50	20.60 - 22.40	29.70 - 48.50	-	(Kolosionis *et al.*, 2021)
Dewatered activated sludge	85.00	HTC	Temperature: 208°C Time: 60 min Solid load ratio: 15% Stirring rate: 100 rpm Heating rate: 3°C/min	19.70	65.40	14.90	53.70	7.20	33.00	5.70	0.20	21.6	40.3	50.1	(Villamil *et al.*, 2020)
Dewatered sewage sludge	82.50	HTC	Temperature: 220 - 380°C Time: 20 min Stirring rate: 500 rpm	35.82 - 43.20	12.86 - 51.82	12.36 - 47.03	41.43 - 44.48	4.46 - 5.09	2.42 - 9.14	3.22 - 4.48	3.56 - 4.04	18.52 - 20.35	-	-	(He *et al.*, 2014)
Primary Sewage Sludge	95.00 – 96.00	Microwave HTC	Temperature: 180 - 200°C Time: 30 min	-	93.10	6.90	38.80 - 39.50	5.00 - 5.10	53.10 - 53.40	2.40 - 2.70	-	16.0 - 16.40	51.40 - 54.80	55.00 - 57.50	(Afolabi *et al.*, 2017)
Sewage sludge	81.98 - 86.23	HTC	Temperature: 200°C Time: 120 min Stirring rate: 250 rpm	27.6	59.81	12.48	45.34	6.09	16.91	4.73	0.6	21.46	65.76	-	(Song *et al.*, 2019)

alleviating the environmental impacts associated with waste management (Hejna, Małgorzata *et al.*, 2023).

3.4.3. Pyrolysis

Pyrolysis refers to the thermochemical breakdown of biomass at elevated temperatures (generally 300–800°C) in the absence of oxygen. The experiment utilized a pyrolysis reactor or kilns, including rotary kilns, fixed-bed reactors, and fluidized-bed reactors, in a controlled environment. As a conversion method, pyrolysis shows significant promise for the production of gas, liquid bio-oil, and biochar. This process operates as a crucial element within the larger frameworks of gasification, combustion, or HTC (Sobek *et al.*, 2020). The essential product is char, which is characterized by a heterogeneous constitution of thermally decomposed (carbonized) organic and inorganic elements, revealing a notable ash content (ranging–50-80%) (Kolosionis *et al.*, 2021). Nevertheless, pyrolysis leads to a higher concentration of heavy metals in biochar, especially non-volatile

Table 4 ..(continued)

The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Sewage sludge	82.00 - 85.00	HTC	Temperature: 200°C Time: 30 min	20.80	65.90	13.30	50.30	7.50	26.80	7.80	0.90	19.72	-	-	(Silva *et al.*, 2020)
Activated sewage sludge		HTC	Temperature: 220°C Time: 300 min Solid to liquid ratio: (1:0.25) - (1:3)	53.53 - 59.83	25.06 - 34.52	10.63 - 20.74	27.37 - 29.03	3.90 - 4.25	0.55 - 7.67	5.22 - 5.81	0.52 - 0.60	12.26 - 12.89	55.12 - 63.96	65.11 - 73.61	(Paiboonudomkarn *et al.*, 2023)
Dewatered sewage sludge	85.70	HTC	Temperature: 200°C Time: 4 - 12h	43.89 - 46.69	45.00 - 50.64	5.35 - 8.31	32.50 - 33.33	4.10 - 4.44	16.90 - 18.50	2.10 - 2.20	3.80 - 3.90	14.37 - 15.09	53.80 - 60.40	-	(He *et al.*, 2013)
Sewage sludge	78.00	Microwave pyrolysis	Temperature: 450 - 600°C	64.12 - 70.02	-	-	20.73 - 23.47	1.09 - 2.19	4.95 - 7.32	3.21 - 3.78	-	6.48 - 8.70	32.98 - 62.26	-	(Zhou *et al.*, 2018)
Digested sewage sludge	-	Torrefaction	Temperature: 200 - 300°C Time: 20 - 60 min Heating rate: 50°C/min	38.13 - 50.57	46.84 - 59.90	-	-	-	-	-	-	11.51 - 14.98	72.63 - 96.20	59.15 - 97.94	(Świechowski *et al.*, 2020)
Activated sludge	-	HTC	Temperature: 180 - 300°C Time: 30 min Heating rate: 4°C/min Stirring rate: 150 rpm	38.02 - 42.91	54.75 - 59.71	0.43 - 4.41	44.35 - 47.69	4.98 - 6.52	3.14 - 8.14	0.70 - 1.03	2.47 - 3.54	17.98 - 22.88	69.26 - 85.11	-	(Z. Wang *et al.*, 2020)
Digested sewage sludge	81.40	HTC	Temperature: 180 - 240°C Time: 60 min	28.60 - 36.80	-	-	37.00 - 38.50		-	-	-	16.10 - 16.90	50.70 - 63.50	52.80 - 60.50	(Ebrahimi *et al.*, 2023)

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Sewage sludge	86.40	HTC	Temperature: 220°C Time: 30 min Heating rate: 5°C/min Stirring rate: 100 rpm Solid load ratio: 11.11%	71.50	23.43	5.07	18.28	1.76	6.41	1.64	0.41	6.3	59.41	50.24	(Shan *et al.*, 2023)
Digestate sewage sludge	83.50	HTC	Temperature: 180 - 240°C Time: 60 min Heating rate: 3°C/min	42.90 - 48.10	44.00 - 50.90	6.20 - 7.90	30.80 - 32.60	4.10 - 4.30	10.00 - 16.80	41.0 - 4.20	1.00 - 1.10	14.70 - 15.10	51.80 - 74.20	-	(Marin-Batista *et al.*, 2020)
Dewatered sewage sludge	69.26	HTC	Temperature: 170 - 350°C Time: 60 min Heating rate: 3°C/min Solid load ratio: 10%	57.62 - 68.87	22.66 - 39.10	3.28 - 9.99	38.72 - 44.04	4.39 - 4.83	46.00 - 51.03	1.73 - 3.06	2.37 - 3.26	4.34 - 5.49	73.43 - 88.42	50.43 - 75.70	(R. Wang *et al.*, 2019)
Dewatered activated sludge	85.94	HTC	Temperature: 180 - 240°C Time: 15 – 45 min Solid to liquid ratio: (2:1)	22.02 - 34.68	57.42 - 74.47	2.06 - 7.42	52.19 - 67.96	5.71 - 6.72	16.25 - 30.81	7.98 - 9.29	1.18 - 1.56	18.30 - 20.17	-	-	(Zhao *et al.*, 2014)
Sewage sludge	84.50	Torrefaction	Temperature: 200 - 450°C Heating rate: 10°C/min Flowrate: 2 L/min (N_2)	5.07 - 19.04	46.55 - 68.05	26.55 - 34.41	36.94 - 43.81	3.91 - 6.38	15.22 - 21.20	4.56 - 5.24	-	18.95 - 19.58	66.91 - 99.90	68.02 - 99.66	(Lee *et al.*, 2019)
Sewage sludge	-	HTC	Temperature: 220°C Time: 1 h Solid to liquid ratio: (1:9)	52.58	31.74	15.68	43.58	4.79	42.63	9.52	1.03	16.21	-	-	(Gai *et al.*, 2016)

elements. The elevated levels of heavy metals in biochar derived from sewage sludge pose a considerable obstacle to their potential application in the future.

3.5. *Effect of operating conditions*

Thermochemical methods such as torrefaction, HTC, and pyrolysis promote the production of biochar from sewage

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Dewatered sludge	74.90	HTC	Temperature: 190 - 250°C Time: 30 - 60 min Solid to liquid ratio: (0.03:1)	28.43 - 43.36	49.07 - 65.67	4.04 - 9.94	35.07 - 36.61	4.05 - 5.42	14.07 - 23.52	3.12 - 5.81	-	15.33 - 16.30	66.80 - 88.20	-	(Merzari *et al.*, 2020)
Sewage sludge	80.12	Torrefaction	Temperature: 200 - 350°C Time: 0 - 50 min Heating rate: 10°C/min Flowrate: 300 Nm^3/min (N_2)	27.50 - 34.50	57.60 - 64.50	7.60 - 9.80	-	-	-	-	-	15.91 - 16.90	-	-	(Karki *et al.*, 2018)
Centrifuged digested sewage sludge	-	HTC	Temperature: 190 - 210°C Time: 60 - 180 min Solid load ratio: 15%	38.50 - 44.60	-	-	-	-	-	-	-	16.12 - 16.50	68.5 - 90.5	-	(Volpe *et al.*, 2020)
Anaerobic digested sewage sludge	-	HTC	Temperature: 180 - 260°C Time: 30 - 70 min Stirring rate: 120 rpm	52.30 - 67.80	-	-	21.20 - 29.00	2.00 - 3.50	1.00 - 20.00	1.00 - 2.00	1.00	12.26	62 - 78	-	(Huezo *et al.*, 2021)
Anaerobic digested sewage sludge	96.20	HTC	Temperature: 180 - 280°C Time: 30 min Stirring rate: 200 rpm	29.35 - 40.02	47.28 - 62.28	8.37 - 12.70	39.98 - 48.45	4.13 - 5.92	42.47 - 46.68	4.94 - 7.18	0.01 - 0.24	17.30 - 22.40	80.40 - 93.90	89.60 - 93.10	(Kim *et al.*, 2014)

sludge. This section elucidates the influence of diverse operational parameters on the characteristics of the solid fuels obtained from sewage sludge. As shown in Table 4, several key variables affect the yield of solid fuel and quality of products during thermochemical conversion processes. These factors include temperature, pressure, reaction duration, atmospheric

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Dewatered sewage sludge	73.07 - 83.70	HTC	Temperature: 150 - 300°C Time: 30 - 150 min Heating rate: 4°C/min Stirring rate: 150 rpm Solid load ratio: 10 - 30%	40.39 - 57.00	23.29 - 42.96	16.30 - 19.71	33.95 - 39.78	3.85 - 4.71	1.69 - 9.38	2.13 - 3.93	1.38 - 1.81	16.63 - 18.49	48.46 - 80.56	48.96 - 90.32	(Roslan *et al.*, 2023)
Dewatered sewage sludge	83.00	HTC	Temperature: 200 - 220°C Time: 120 min	36.58 - 38.98	48.09 - 51.21	12.21 - 12.93	40.90 - 41.2	4.95 - 5.16	10.45 - 12.16	3.72 - 3.9	1	18.85 - 19.04	-	-	(Wilk *et al.*, 2023)
Centrifuged sewage sludge	-	HTC	Temperature: 160 - 240°C Time: 60 – 180 min	39.10 - 53.70	42.80 - 59.80	1.10 - 3.52	32.40 - 36.10	3.70 - 5.90	7.70 - 13.70	2.20 - 5.70	-	12.60 - 14.00	35.00 - 68.00	-	(Malhotra *et al.*, 2023)
Dewatered sewage sludge	80.00	HTC	Temperature: 200°C Time: 120 – 240 min Solid to water ratio: (1:8)	49.12 - 49.36	39.46 - 39.59	9.24 - 9.42	30.40 - 30.80	3.83 - 3.84	11.93 - 12.67	2.52 - 2.55	1.43 - 1.55	13.76 - 15.12	58.00 - 61.00	54.00 - 63.00	(Wilk *et al.*, 2022)
Dewatered activated sludge	85.00	HTC	Temperature: 140 - 260°C Time: 120 - 600 min Solid to water ratio: 10 - 30%	37 - 46	40.00 - 70.50	6.00 - 7.50	-	-	-	-	-	17.09 - 18.21	65.73 - 86.12	60.00 - 85.00	(L. Wang *et al.*, 2020)
Dewatered sewage sludge	81.00	HTC	Temperature: 100 - 200°C Time: 0- 60 min Solid to liquid ratio: (1:2)	23.92 - 38.31	48.77 - 59.77	8.00 - 15.06	32.36 - 37.22	4.09 - 4.99	18.42 - 31.65	3.22 - 4.48	1.57 - 1.76	13.10 - 16.17	73.73 - 89.01	66.00 - 92.00	(Silva *et al.*, 2020)

conditions, flow rate, solid-to-water ratio, heating speed, and stirring intensity. Optimizing these parameters is crucial for achieving the desired outcomes.

3.5.1. Temperature

The characteristics of the solid fuel produced from sewage sludge are greatly influenced by the temperature of the thermochemical process, primarily through its impact on the chemical reactions and physical properties of the resulting hydrochar or biochar (Q. Zheng *et al.*, 2022). In HTC,

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies were used in 46 included articles.

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Sewage sludge	-	HTC	Temperature: 190°C	26.50 - 54.50	38.70 - 57.10	6.80 - 16.40	28.20 - 44.10	3.60 - 5.60	3.00 - 6.00	10.00 - 17.80	0.7	15.69 - 20.64	-	-	(Park *et al.*, 2020)
Anaerobic centrifuged digested sewage sludge	82.60	Torrefaction	Temperature: 200 - 300°C Time: 60 min	32.00 - 45.70	35.00 - 55.00	-	-	-	-	-	1.58 - 1.65	14.90 - 15.50	26.00 - 40.00	32.00 - 40.00	(Pulka *et al.*, 2016)
Sewage sludge	85.00	Microwave pyrolysis	Microwave power: 200 - 300 W Time: 20 min	28.00 - 66.00	11.00 - 62.00	10.00 - 23.00	-	-	-	-	-	8.90 - 17.46	40.89 - 76.46	22.49 - 83.90	(Y. F. Huang *et al.*, 2015)
Dewatered sewage sludge	80.00	HTC	Temperature: 160 - 260°C Time: 30 - 150min Solid to liquid ratio: (1:10)	-	-	-	14.06 - 20.24	1.90 - 3.03	-	1.10 - 2.14	-	5.59 - 7.72	63.90 - 82.69	-	(Guo *et al.*, 2022)
Dewatered sewage sludge	89.32	HTC	Temperature: 180 -260°C Time: 30-480 min Heating rate: 4°C/min Solid to liquid ratio: (1:9)	59.53 - 72.02	16.79 - 34.33	6.14 - 13.24	19.62 - 24.49	3.22 - 3.92	2.13 - 10.54	1.12 - 1.64	0.49 - 0.67	9.80 - 12.06	53.00 - 66.19	-	(Peng *et al.*, 2016)
Digested sewage sludge	82.50 - 95.00	HTC	Temperature: 200-380°C Time: 20 min, Mass: 182g DSS and 150g water, Stirring rate: 500 rpm	32.76 - 43.20	12.86 - 55.55	11.52 - 47.03	41.43 - 44.56	4.46 - 5.49	1.57 - 10.58	3.22 - 5.15	3.55 - 4.19	18.52 - 20.35	-	46.96 - 70.37	(He *et al.*, 2015)

temperatures typically range from 150 to 300°C (Roslan *et al.*, 2023). Higher temperatures generally promote dehydration, decarboxylation, and carbonization reactions. This leads to an enhancement in the fixed carbon content and a reduction in the volatile matter within the char, ultimately improving its carbon content and increasing its HHV (Ibitoye *et al.*, 2023; Silva *et al.*, 2020). For instance, chars produced at 300°C exhibit lower O/C and H/C atomic ratios, suggesting considerable dehydration and decarboxylation, which are imperative for enhancing fuel quality (Peng *et al.*, 2016). Another study conducted by Karki et al., (2018) examined the effects of torrefaction temperature on the physical and chemical attributes of torrefied products, focusing on a temperature range of 200-350 °C. The findings indicated that as the temperature increased, the weight percentage of carbon increased, whereas the H/C and O/C molar ratios decreased, indicating an enhancement in the solid fuel properties.

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies used in 46 included articles

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Sewage sludge	-	Pyrolysis	Temperature: 500°C Heating rate: 10°C/min	59.64	8.95	-	27.36	0.94	69.86	1.29	0.55	10.04	58.7	-	(Ghodke et al., 2021)
Anaerobic digested sewage sludge		Microwave Torrefaction	Temperature: 220- 320°C Time: 3.60-10.20 min	-	-	-	-	-	-	-	-	12.23 - 13.79	-	66.40 - 97.80	(Atienza-Martínez et al., 2015)
Dewatered sewage sludge	77.50	Torrefaction	Power: 480 - 800W Time: 5-25min Flowrate: 50 mL/min (N_2)	59.67 - 77.61	-	-	-	-	-	-	-	5.53 - 8.31	86.72 - 100.00	-	(C. Zhang et al., 2021)
Activated sludge	99.70	Torrefaction	Temperature: 200 – 300°C Time: 30 - 60 min	25.00 - 33.10	63.90 - 78.10	2.80 - 5.20	26.60 - 40.00	3.90 - 6.10	47.70 - 64.20	4.40 - 8.10	0.70 - 1.10	18.20 - 18.90	66.70 - 84.50	80.00 - 90.00	(Lin et al., 2022)
Dewatered sewage sludge	82.11	HTC	Temperature: 180-280°C, Time: 30-120 min Solid to liquid ratio: (1:9)	54.00 - 60.00	30.00 - 40.00	6.00 - 8.00	26.41 - 28.91	2.67 - 3.77	4.41 - 9.02	2.25 - 2.69	0.58 - 0.73	11.38 - 12.49	50.00 - 55.00	38.00 - 44.00	(X. Zheng et al., 2020)
Anaerobic stabilized sewage sludge	82.10	HTC	Temperature: 180 - 300°C Time: 30 - 180 min Stirring rate: 120 rpm	32.23 - 39.76	56.42 - 65.53	1.64 - 4.20	44.69 - 48.80	5.70 - 6.36	0.51 - 10.40	2.50 - 3.73	2.61 - 2.99	22.00 - 24.02	21.00 - 63.00	25.00 - 67.00	(Hejna et al., 2023)

Table 4 ..(continued)
The proximate, ultimate, and solid fuel characteristics of biochar generated from various sewage sludge types and biochar production technologies used in 46 included article**s**

Type of Sewage sludge	Moisture content (%)	Carbonization method	Reaction conditions	Proximate Analysis (wt%)			Ultimate Analysis (wt%)					HHV (MJ/kg)	Solid Yield (%)	Energy Yield (%)	References
				Ash	VM	FC	C	H	O	N	S				
Sewage sludge	96.21	Pyrolysis	Temperature: 300 - 500°C Time: 30 min Heating rate: 10°C/min Flowrate: 100 mL/min (N_2)	50.71 - 62.52	24.36 - 38.99	9.86 - 13.12	21.34 - 28.43	1.36 - 2.99	11.17 - 13.61	2.77 - 4.53	0.59 - 0.91	8.21 - 11.50	51.50 - 65.00	34.00 - 60.00	(R. Wang *et al.*, 2019)
Dewatered sewage sludge	79.50	Pyrolysis	Temperature: 400 - 700°C Time: 240 min Heating rate: 10°C/min	56.48 - 70.06	13.95 - 27.08	15.99 - 16.44	27.80 - 30.43	1.90 - 3.62	0.84 - 3.36	0.64 - 2.94	1.73 - 3.17	10.79 - 13.57	44.40 - 54.60	-	(Kolosionis *et al.*, 2021)
Dewatered sewage sludge	-	HTC	Temperature: 190 - 260°C Time: 1-24 h	46.65 - 51.85	-	-	35.92 - 38.60	4.93 - 5.31	3.11 - 7.96	1.73 - 1.92	-	16.74 - 18.33	-	-	(J. hong Zhang *et al.*, 2014)

Roslan et al., (2023) found that the producing sewage sludge biochar at 150°C resulted in a higher solid yield (73.93%) compared to production at 300°C (48.46%). The lower yield observed at higher temperatures can be attributed to decarboxylation, which is supported by the reduced O/C ratio and formation of water-soluble organic materials (Hejna, Małgorzata *et al.*, 2023). Moreover, higher temperatures may contribute to lower solid yields as sewage sludge transforms into gaseous and liquid components. Research by Chen et al., (2021) revealed that pyrolysis at temperatures under 400 °C converted 50-60% of raw sludge energy into biochar, emphasizing the crucial role of temperature in energy recovery efficiency. X. Zheng et al., (2020) explored the influence of HTC temperature on hydrochar ash content. Their results showed a substantial increase from 55.12% at 180 °C to 62.14% at 280 °C, suggesting that elevated temperatures contributed to the higher ash content of the produced hydrochars. Thermochemical processes performed at higher temperatures can enhance the dewaterability of sewage sludge, which is beneficial for the subsequent handling and transportation of solid fuel (R. Wang *et al.*, 2019).

3.5.2. Reaction time

Reaction time is recognized as a significant variable in thermochemical processes; however, it is not as critical as the temperature. The reaction time refers to the exposure of the raw materials to a specific temperature. The reaction time critically influences the hydrochar yield, with prolonged exposure typically resulting in a reduction in both the yield and HHV (Guo *et al.*, 2022; Huezo *et al.*, 2021). According to Gao et al. (2019), the solid yield decreased from 71.24 to 66.04% when the reaction time increased from 30 to 120 min, demonstrating a negative relationship between the reaction time and yield. An increase in the reaction time leads to more extensive devolatilization and breakdown of organic compounds, leading to a lower solid yield (Roslan *et al.*, 2023). However, beyond 90 min, the improvement in dewaterability was marginal, indicating that hydrothermal temperature exerted a more pronounced influence than reaction time on the moisture content of the sewage sludge (Gao *et al.*, 2019). If the reaction time is excessively prolonged, it may not considerably impact the carbon enrichment of the hydrochar, as the carbonization process may have reached completion. Research by Huezo, Vasco-Correa, & Shah, (2021) observed that HTC yielded the highest carbon content (28%) in 22 min. Extended HTC durations decreased the carbon and hydrogen levels in the hydrochar, thereby diminishing its quality as a solid fuel. Similarly, Merzari et al., (2020) reported that hydrochar produced from concentrated sludge under comparable HTC conditions (220°C, 30 min) exhibited the highest HHV and a moderate ash content, indicating better fuel properties. In a separate study, Silva et al., (2020) determined that HTC performed at 150°C for 30 minutes generates hydrochar with the maximum HHV of 16.17 MJ/kg, suggesting superior fuel quality compared to other durations. In contrast, Karki et al., (2018) reported that the ideal reaction time for achieving desirable solid fuel characteristics during torrefaction was approximately 50 min at 250°C. For microwave pyrolysis, Y. F. Huang et al., (2015) found that a 20-minute processing time is sufficient to achieves the desired thermal treatment effects.

The reaction time during torrefaction plays a significant role in determining the energy yield of sewage sludge (Atienza-Martínez *et al.*, 2015). Extended reaction periods can result in more thorough decomposition of sludge, subsequently diminishing the energy yield. Nevertheless, at temperatures of 220 and 270°C, the energy yield remained above 90%, irrespective of the reaction duration (Atienza-Martínez *et al.*, 2015). To effectively promote hydrolysis and polymerization processes, it is crucial to regulate the extent of sewage sludge breakdown within a given timeframe (Djandja *et al.*, 2021). Research has shown that the HTC process for sewage sludge can range from 30 min (Roslan *et al.*, 2024) to 24 h (He *et al.*, 2014), which is substantially shorter than the natural coalification process (Kolosionis *et al.*, 2021). Consequently, the likelihood of achieving comparable outcomes is minimal and can only be achieved at high temperatures by adjusting the reaction time.

3.5.3. Other parameters

Other factors influencing the thermochemical process and product yield and their properties include heating rate, stirring rate, solid-to-water ratio, pressure, and moisture content. A lower heating rate is generally preferred for torrefaction processes because it leads to superior char output and energy yield, although the energy density might be lower than that at higher heating rates (Lee *et al.*, 2019). A modest heating rate of 3°C/min facilitated the generation of hydrochar exhibiting a higher HHV along with lower oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C) ratios, in contrast to the rapid heating rate of 50°C/min (Villamil *et al.*, 2020). This is because a slower heating rate allows for more complete reactions, consequently improving the quality of solid fuel. The stirring rate affected the mixing of sewage sludge in the reactor, and ranged from 60 to 500 rpm (H. J. Huang *et al.*, 2014; Prajitno *et al.*, 2017). The heating and stirring rate characteristics significantly affected the heat and mass transfer (L. Wang *et al.*, 2019). During the HTC process, the temperature mainly varied under autogenous pressure, reaching 89 bar (Hejna, Małgorzata *et al.*, 2023). The solid-to-water ratio is particularly relevant in HTC, where a fixed solid loading, such as 10% or 30%, can significantly affect the solid yield and HHV of the resultant hydrochar (Roslan *et al.*, 2023). Moreover, the moisture content of the sewage sludge before pyrolysis can affect the efficiency of the thermochemical process (Y. F. Huang *et al.*, 2015). For instance, during pyrolysis, a lower moisture content improves heat transfer and reduces the energy required for drying, which can enhance the overall energy efficiency of the process (Ghodke *et al.*, 2021). In contrast, in HTC, the process can utilize the inherent moisture as a reaction medium, eliminating the need for drying pretreatment and making it particularly suitable for biomass with a high water content (Gai *et al.*, 2016; Z. Wang *et al.*, 2020). In summary, the management of moisture content is vital for optimizing both the efficiency and quality of products in thermochemical processes, as it affects both the chemical reactions and energy dynamics of the system.

3.6. Effect of carbonization conditions on solid fuels characteristics

3.6.1. Proximate and ultimate analysis

The results of the proximate and ultimate analyses of various types of sewage sludge are presented in Table 4. Understanding hydrochar properties is crucial for its effectiveness as a fuel. The proximate analysis of the synthesized hydrochar incorporated the analysis of moisture levels, ash content, and volatile matter. The moisture content was evaluated by placing the char sample in a drying apparatus set at 105°C for one hour, followed by ash content determination using a muffle furnace according to the ASTM D3174-02 standards. The volatile matter content was assessed by burning a sieved solid fuel sample at 950 °C in a closed crucible, according to ASTM D3175-07 standards (Silva *et al.*, 2020). The fixed carbon content was determined using the difference method (He *et al.*, 2015). The ash composition within the hydrochar increased from 33.14% to 46.65% as a result of HTC, indicating the considerable presence of inorganic materials (J. hong Zhang *et al.*, 2014). Research has revealed a positive relationship between the thermal conditions of the HTC procedure and ash composition of the fuel. These findings suggest that higher temperatures lead to increased ash content, with the ash content rising from 26.06% to 29.57% when the

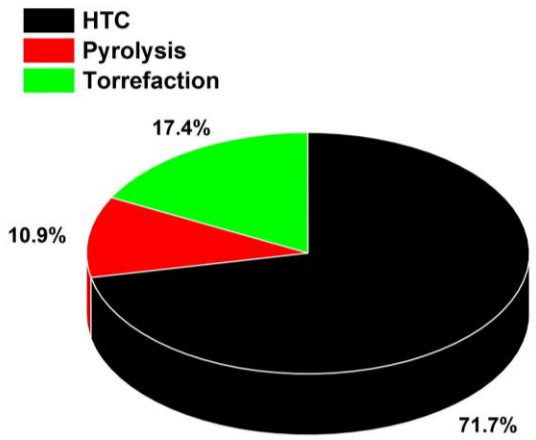

Fig. 5. Percentage of relevant literature related to different types of carbonization techniques

temperature reached 220°C, which is potentially attributable to excessive depletion of volatile matter through hydrothermal processes (Kim *et al.*, 2014). Similarly, proximate analysis of biochar produced from pyrolysis indicated a reduction in volatile matter and an increase in fixed carbon with increasing pyrolysis temperature. For instance, at 500°C, the volatile matter content was 24.36%, while the fixed carbon content was 13.12%. The decrease in volatile matter results from chemical processes, including dehydration and decarboxylation (Shan *et al.*, 2023). Thermochemical processes can produce biochar with improved fuel characteristics such as increased fixed carbon levels and reduced volatile matter, which are advantageous for applications involving solid fuels (He *et al.*, 2015).

In addition to these findings on composition, further analysis can determine the ultimate analysis of solid fuels, which refers to the elemental contents of carbon, hydrogen, nitrogen, oxygen and sulfur within a sample using an elemental analyzer (Lin *et al.*, 2022). The level of oxygen was determined by subtracting the amounts of the other four elements from 100% of the sample (Lin *et al.*, 2022). Understanding these elements, such as the combustion efficiency and emission profiles, is essential for various aspects of fuel utilization. Studies have shown that biochar derived from sewage sludge samples contains promising amounts of carbon (18.28 to 67.96%) and hydrogen (1.76 to 12.2%) (Shan *et al.*, 2023; Zhao *et al.*, 2014). This enhancement of carbon levels, along with the decline in oxygen levels, is a key parameter that enhances the combustion properties of the hydrochar. These findings indicate that the HTC process effectively enhances the carbon content and heating value of biofuel, thereby making it comparable to lignite or sub-bituminous coal, subject to specific reaction conditions (Zhao *et al.*, 2014). However, oxygen, nitrogen and sulfur can be disadvantageous when sewage sludge is used as solid fuel. These constituents can diminish the HHV of the fuel and emit harmful pollutants, such as SOx and NOx during combustion (Pulka *et al.*, 2016).

3.6.2. Higher heating value and energy yield

The HHV and energy yield of sewage sludge are critical parameters for evaluating its potential as biofuel. HHV is a crucial characteristic of fuels that quantifies the energy density of charred materials such as hydrochars. It represents the total amount of energy released upon the complete combustion of a fuel, with the resultant products being cooled to a standard temperature, encompassing the latent heat associated with the vaporization of water. The HHV of the hydrochar can be determined using a bomb calorimeter in accordance with standard methods (Roslan *et al.*, 2023). The HHV can also be calculated based on the elemental composition of the fuel, typically expressed in terms of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), as given by the formula developed by Perry and Chilton, which is derived from the Dulong formula (Peng *et al.*, 2016; Z. Wang *et al.*, 2020):

$$HHV = 0.339C + 1.443(H - 0.125O) + 0.0224(9H) + 0.0093S + 0.001464N \quad (1)$$

The HHV of the sewage showed notable variability depending on the treatment process applied. For instance, untreated sewage sludge has an initial HHV of approximately 9.82 MJ/kg on a dry basis (Gao *et al.*, 2019). However, the HHV can be enhanced through processes such as HTC. HTC-treated hydrochar from sewage sludge can achieve HHV ranging from 10.4 to 11.57 MJ/kg. This enhancement is associated with an elevation in carbon concentration and a decrease in oxygen levels, which is a consequence of deoxygenation occurring throughout the process (Gao *et al.*, 2019). In a comparative study, the HHV of hydrochar produced from sewage sludge was comparable to that of sub-bituminous coal, with values of approximately 13 MJ/kg under optimized HTC conditions (Malhotra *et al.*, 2023). This enhancement is attributed to the decarboxylation and dehydration reactions that occur during HTC, resulting in a higher concentration of fixed carbon and lower moisture content (Malhotra *et al.*, 2023). Additionally, the energy content of sewage sludge was significantly affected by the pyrolysis process conducted at varying microwave power intensities. For example, the HHV of pyrolyzed sewage sludge, subjected to a microwave power level of 200 W in the absence of any additives, is quantified at 17.46 MJ/kg, accompanied by an energy yield of 83.90% (Y. F. Huang *et al.*, 2015).

The energy yield denotes the quantity of energy generated from a specific amount of feedstock during a thermochemical process, such as pyrolysis (Kolosionis *et al.*, 2021). It is often expressed as a percentage or ratio (Hejna, Małgorzata *et al.*, 2023). The energy yield varied according to the treatment method and conditions. For example, the energy output derived from pyrolyzed sewage sludge can range between 22.49% and 83.90% depending on the microwave power level and the presence of rice straw (Y. F. Huang *et al.*, 2015). Furthermore, the energy content of sewage sludge can be compared to lignite due to its higher HHV, although its utilization is often hindered by high moisture levels and the presence of contaminants such as heavy metals and pathogenic microbes (He *et al.*, 2014). Despite these challenges, sewage sludge is considered a viable alternative fuel, especially when pretreated through processes such as HTC, which not only enhances its HHV, but also addresses issues related to moisture and contaminants (Park *et al.*, 2020). Overall, the treatment of sewage sludge through various thermochemical processes significantly improved its HHV and energy yield, confirming its potential as a sustainable approach for energy recovery and waste management.

4. Environmental impacts associated with thermochemical methods for converting sewage sludge into solid fuel

The application of sewage sludge for the production of solid fuel via thermochemical conversion has both positive and negative implications for environmental sustainability and resource recovery. It is crucial to comprehend these impacts to optimize conversion processes, reduce environmental pollution, and improve resource efficiency.

One of the primary environmental concerns associated with thermochemical conversion is the emission of pollutants during the conversion processes. For instance, pyrolysis and torrefaction can release volatile organic compounds (VOCs), particulate matter, and other harmful air pollutants if not controlled adequately (Świechowski *et al.*, 2020). Thermochemical processes can also produce harmful emissions, such as NOx and SOx, owing to the presence of elements such as nitrogen and sulfur (Ahn *et al.*, 2020). Moreover, the presence of heavy metals in sewage sludge presents a potential hazard during thermal treatment because they can be released into the environment (Merzari *et al.*, 2020). The HTC procedure has the potential to promote heavy metal immobilization and reduce environmental risks (He *et al.*, 2015). Torrefaction also results in lower levels of hazardous heavy metals, including Cd, Cr, Hg, Pb, and Ni, making the resulting biochar suitable for combustion without significant environmental contamination risks (Lin *et al.*, 2022). Therefore, it is essential to implement stringent emission control measures, such as acid washing, to minimize the release of these pollutants and produce cleaner fuels (Kolosionis *et al.*, 2021).

Another significant environmental impact is that the ash generated from thermochemical conversion processes such as HTC and pyrolysis has significant environmental implications because of its composition and behavior during combustion. The ash content tends to increase with higher reaction temperatures, resulting from the preservation of inorganic minerals and the transformation of organic substances into gaseous and liquid phases (Kolosionis *et al.*, 2021). This increase in ash content can lead to operational challenges, including the buildup of sticky ash deposits on reactor surfaces, which are exacerbated by the presence of alkaline earth metals, such as potassium and sodium, which form low-temperature melting compounds during combustion. An elevated presence of alkaline earth metals, including calcium and magnesium, can also lead to the formation of precipitates that can affect soil and water quality if not properly managed (R. Wang *et al.*, 2019). Thus, understanding and mitigating the environmental impacts of ash are crucial for the sustainable application of thermochemical conversion technologies.

Furthermore, thermochemical conversion processes, such as HTC, can significantly alter the combustion behavior of sewage sludge, thereby enhancing its viability in energy recovery applications. These processes involve stages such as drying, decomposition, and burning, which facilitate the efficient conversion of organic materials into energy, consequently diminishing dependence on fossil fuels and alleviating greenhouse gas emissions (Kolosionis *et al.*, 2021). By converting waste materials into energy-rich products, thermochemical conversion represents a promising strategy for mitigating methane emissions from landfills and reducing the carbon footprints associated with waste disposal. This process serves not only as a sustainable energy solution but also enhances waste management, thereby playing a dual role in environmental conservation and energy production. The application of thermochemical conversion technologies in waste management frameworks can be a pivotal step towards achieving climate-change mitigation goals through the reduction of greenhouse gas emissions and promotion of renewable energy alternatives.

The thermochemical transformation of sewage sludge into solid fuel presents both opportunities and challenges in terms of its environmental impact. Although the potential for energy recovery and resource valorization is significant, careful consideration of emissions, by-products, and process efficiency is crucial for minimizing the negative environmental effects. Ongoing research and technological advancements are essential for optimizing these processes and enhancing their sustainability.

5. Challenge in treating and transforming sewage sludge into a solid fuel

Despite significant attempts to transform sewage sludge into solid fuel through thermochemical methods, numerous obstacles persist along with opportunities for further research and advancement in the domain of sewage sludge. These obstacles are principally attributable to the physicochemical qualities of sewage sludge, complexity of thermochemical conversion processes, and presence of pollutants. Recent research on the transformation of sewage sludge utilizing thermochemical approaches has discovered several critical overarching obstacles and restrictions, including the following:

i. Feedstock Heterogeneity: The composition of sewage sludge is inherently heterogeneous and governed by a range of factors, including the origin of the wastewater, the treatment methods implemented, and seasonal variations. Generally, sewage sludge is composed of a heterogeneous blend of organic and inorganic elements, including microbial biomass, nutrients (notably, nitrogen and phosphorus), heavy metals, and pathogens. This variability poses challenges in achieving consistent and uniform thermochemical processes.
ii. High moisture content: The moisture content of sewage sludge exceeds 80%, which can complicate its handling and reduce its calorific value when used as fuel source. This high moisture content is primarily due to the water retention capacity of sludge, which is influenced by its flocculation structure and the existence of various forms of water, including free, interstitial, surface, and bound water.
iii. High ash content: The ash content of sewage sludge is a significant factor that influences its management, utilization, and environmental impact. The variability in ash content, combined with the detection of heavy metals and diverse pollutants, necessitates careful consideration of the methods used for ash management and their potential applications.
iv. Process optimization: The performance of the thermochemical process may be improved through the calibration of operational parameters, including pod dimensions, processing duration, and thermal conditions. Moreover, the synthesis of multiple thermochemical technologies can improve the sustainability and efficiency of the procedure. By addressing these challenges, it is possible to enhance the efficiency and sustainability of sewage sludge as an important energy source.
v. Economic viability: The generation and application of sewage sludge as a solid fuel necessitate considerable financial resources for apparatus and infrastructural development, which may pose a substantial obstacle to the implementation of large-scale systems.

6. Conclusion

This review has shown that despite the inherent challenges posed by the high moisture content, ash, and heavy metal levels in sewage sludge, thermochemical conversion methods—particularly hydrothermal carbonization(HTC) present a highly promising, energy-efficient, and environmentally friendly approach for sustainable sludge management and energy recovery. A key finding of this study is the significant impact of operational parameters such as temperature, reaction time, and heating rate on the quality and yield of the resulting biochar or hydrochar. Elevated temperatures (300–1000 °C) tend to enhance the energy content of the final product while reducing solid yield due to the formation of gaseous byproducts, highlighting the strong fuel potential of treated sludge as a substitute for fossil fuels.

However, most available data come from laboratory-scale experiments, and a major challenge lies in scaling up these technologies for commercial implementation. The high capital and operational costs, influenced by factors such as infrastructure requirements, energy demands, and labor, remain a barrier to broader adoption. Moreover, the analysis in this review is limited by the heterogeneity in reported studies—differences in experimental conditions, sludge characteristics, and measurement methodologies can reduce the comparability and generalizability of findings.

To address these challenges, future research should prioritize experimental validation of optimal process parameters under pilot and industrial-scale conditions. This includes developing cost-effective pretreatment and dewatering strategies, exploring integrated systems that merge sludge pretreatment and thermochemical conversion in a single facility, and standardizing analytical methods and reporting practices. Additionally, interdisciplinary research combining engineering, environmental science, and economics is essential to produce holistic evaluations through techno-economic assessments and life cycle analyses, which are critical to understanding the full potential and limitations of thermochemical technologies.

The findings of this review also hold important implications for policy and sustainable waste management strategies. Given the increasing volume of sewage sludge generated globally, there is a pressing need for supportive regulatory frameworks that promote thermochemical conversion as a viable waste-to-energy solution. Governments can play a pivotal role by providing incentives such as subsidies, tax relief, and carbon credits for facilities that utilize pyrolysis, torrefaction, or HTC for sludge treatment and energy recovery.

Furthermore, establishing clear and consistent guidelines for the classification, handling, and safe application of biochar and hydrochar—particularly in agriculture and industry—will be essential for market adoption. Investment in research and pilot-scale demonstration projects will help validate the commercial and environmental feasibility of these technologies in real-world settings. By aligning policy efforts with circular economy principles and climate goals, sewage sludge can be effectively transformed from an environmental burden into a valuable resource, contributing to national energy security, emissions reduction, and sustainable development.

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