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Review

Biogas and Syngas Production from Sewage Sludge: A Sustainable Source of Energy Generation

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Abstract: Sewage sludge to energy conversion is a sustainable waste management technique and a means of militating against the environmental concerns associated with its disposal. Amongst the various conversion technologies, anaerobic digestion and gasification have been identified as the two most promising. Therefore, this study is focused on a detailed evaluation of the anaerobic digestion and gasification of sewage sludge for energy production. Moreover, the key challenges hindering both technologies are discussed, as well as the practical measures for addressing them. The applicable pretreatment measures for efficient transformation into valuable energy vectors were further evaluated. Specifically, the study evaluated various properties of sewage sludge in relation to gasification and anaerobic digestion. The findings showed that a high ash content in sewage sludge results in sintering and agglomeration, while a high moisture content promotes tar formation, which has been identified as one of the key limitations of sewage sludge gasification. More importantly, the application of pretreatment has been shown to have some beneficial features in promoting organic matter decomposition/degradation, thereby enhancing biogas as well as syngas production. However, this has additional energy requirements and operational costs, particularly for thermal and mechanical methods.

Keywords: sewage sludge; anaerobic digestion; gasification; biogas; syngas; energy

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1. Introduction

Sewage sludge (SS), as observed, is a by-product of wastewater treatment process. Its treatment and management incur about 50% of the total operating costs in wastewater treatment plants (WWTPs) [1]. In terms of generation capacity, approximately 10 million tons of sewage sludge are produced in Europe, 8 million in the United States, and 4 million tons in China annually [2]. The generated sewage sludge poses a threat to the environment and humans alike due to the presence of heavy metal pollutants, a high portion of organic, and toxin contents [3–5]. Despite it being laden with pollutants, the sustainable usage of this growing quantity of produced sewage sludge can make it a valuable resource. Upon processing, sewage sludge can serve as a feedstock or substrate for energy generation [6]. Energy recovery from sewage sludge has received increasing attention in recent years. This could be attributed to the dwindling nature of conventional energy resources (fossil fuel) and the belief that sludge-derived energy, being a renewable source, can assist in achieving a circular green economy [7]. Renewable energy resources such as biomass are considered the most regenerative, renewable, and available raw material for producing different forms of energy and useful products. In addition to providing energy, biomass contains useful biochemical compounds that are used in the production of adhesives, composite materials, paints, alcohols and bioplastics [8,9]. The production of these value-added products relies on energy crops as a raw material, which inadvertently and negatively affects food supply. As such, sewage sludge has been sought out as a viable alternative for the production of energy (biogas, syngas).

Biogas and syngas have been identified as two important renewable energy vectors, capable of partially replacing fossil fuel, that could be produced from sewage sludge. These are achieved through two competitive technologies, namely, anaerobic digestion and gasification. Simply put, anaerobic digestion (AD) involves the degradation of organic matter by microorganisms to produce biogas [10]. Anaerobic digestion could be one of the sustainable means of valorizing sewage sludge to improve its effluent quality and maximize the recovery of nutrients [11]. This stabilization technique serves the dual purpose of producing biogas for heat and power applications and as a fertilizer for agricultural applications. Integrating an anaerobic digester in the wastewater treatment plant (WWTP) process can offset a significant part of the WWTP's energy requirements, making it more energy-efficient [12,13].

Gasification is another viable stabilization technique that offers the benefit of decomposing organic pollutants, neutralizing pathogens and reducing the volume of sewage sludge [14]. Gasification generally involves the thermochemical conversion of biomass into syngas in an oxygen-lean environment. Syngas forms the main product of a gasification process, with tar, char, and/or ash as by-products. Using sewage sludge as a feedstock for energy production through gasification usually necessitates some pretreatment measures [6]. Recently, the gasification of sewage sludge has also emerged as a promising pathway for hydrogen production. The use of gasification and anaerobic digestion technologies for energy generation is not entirely new, as various fuel/biomass types have been investigated [10,15–24]. For instance, a recent review by Atelge et al. [25] has shed light on the current trends in the anaerobic digestion processes and evaluated the operating process parameters needed to increase the conversion of biomass waste into biogas. The authors highlighted that improving the overall processes will ensure reductions in the hydraulic retention time and will equally enhance biogas yield. Hanum et al. [26] studied the current state of sewage sludge treatment in Malaysia along with the challenges that limit the anaerobic digestion of sewage sludge. According to this study, using food waste as a co-substrate will not only increase the efficiency of the process but also help to manage the growing food waste problem in Malaysia. Chow et al. [27] reviewed the anaerobic co-digestion of wastewater sludge with the aim of identifying the best potential co-substrate. Comparing the methane yield of co-digestion to mono-digestions, gains of from 13 to 176% were achieved. Another study analyzed the most recent pretreatment methods for enhancing the anaerobic digestion of sewage sludge. According to this study, standardizing pretreatment processes is absolutely necessary from the perspectives of energy balance and environmental sustainability [28]. The status, effectiveness, and drawbacks of two low-cost techniques for the biological treatment of hazardous sewage sludge using vermicomposting and black soldier fly larvae are explained in the review by [29]. The research by Kamyab et al. [30], offered observations on the technical aspects of the processes for gasifying and combusting sewage sludge. The maximum energy efficiency was demonstrated by the combination of air gasification and external fired gas turbines (EFGT) without carbon capture at 37.1%, exceeding the 35.7% achieved by waste combustion technology. Werle and Sobek's [31] study examined the production of solid adsorbents, gaseous fuel, and phosphorus during sewage sludge gasification. The investigation demonstrated that the solid fraction obtained from the gasification of sewage sludge can be used as a useful source of phosphorus and potential adsorbent material. The resulting phosphorus was similar to that of natural phosphate rocks (28.05%). To the best of our knowledge, however, no study has taken a critical view of energy recovery through anaerobic digestion and the gasification of sewage sludge to date. Therefore, this study summarizes recent advances in gasification and anaerobic digestion and proposes the possibility of combining the energy-bearing gases from both systems derived from sewage sludge for the purpose of increasing the energy value of the gases. A comparison of the pretreatment requirements of sewage sludge to improve its suitability as feedstock for anaerobic digestion and gasification purposes is provided. The challenges and prospects for further research on gasification and anaerobic digestion are also examined, as well as their potential applications.

2. Sewage Sludge: A Product of Wastewater

The growing world population, alongside industrialization and excessive consumerism, has increased wastewater production, particularly in urban regions. The improper disposal of wastewater is a global concern as it is a source of pollution to the ecosystem [32,33]. These organic wastes, if not properly handled, will deteriorate water bodies, air and soil. Currently, the majority of people in developing and less-developed parts of the world usually view waste disposal as a default option, which has contributed to its environmental issues. Nevertheless, this option of indiscriminate waste disposal contradicts the waste management efforts and handling hierarchy in which waste avoidance, recovery, re-use and recycling are preferred to disposal. In light of this, various wastewater treatment approaches exist, and the choice of any of these is mostly guided by a country's environmental policy [34]. In South Africa, for instance, wastewater treatment proceeds through four phases, namely preliminary, primary, secondary and tertiary phases. During the preliminary phase, municipal wastewater first goes through screening for the removal of foreign materials that could interfere with the treatment process. Afterwards, silts, sand, and stones are removed through the grit process to avoid the abrasion of mechanical equipment [35,36]. Based on the efficiency level of the grit process, a third preliminary step called comminution may be applied. This involves a reduction in the size of solid materials via mechanical methods.

However, industrial wastewater follows a different preliminary treatment step that involves the addition of an acid or base for equalization and/or neutralization of the wastewater stream. Next, chemicals are added as a coagulant before sending the waste streams to sedimentation tanks, oxidation ponds, and floating tanks for the primary treatment [37]. Notably, the primary treatment phase is similar for both municipal and industrial wastewater types. The aim of this phase is to maximize the removal of suspended solids through mechanical methods such as centrifugation, coagulation, flotation, filtration, sedimentation and gravity [38,39]. Interestingly, the resultant solids from the primary treatment phase mark the first production of sewage sludge waste, conventionally known as primary sludge. The liquid product from the primary phase is then sent for secondary treatment to remove biodegradable and soluble organic matter through aerobic and anaerobic biological processes [40]. Similarly, the secondary treatment process yields both solid and liquid products, with the liquid being sent for tertiary treatment and disinfection. The produced solid represents the second instance in which sewage sludge is produced, and this is typically referred to as secondary sludge. At the tertiary stage, various technologies, such as distillation, crystallization, precipitation, disinfection, filtration, coagulation, solvent extraction, and electrolysis, are applied [8,38,41]. Principally, the goal at this stage is to remove microorganisms, nutrients, and remaining suspended particles [42]. The extraction of nutrients, which form a crucial part of this stage, results in the production of tertiary sludge. It is worth mentioning that the resultant primary, secondary and tertiary sludges vary in their properties (water content. energy content and pollutants) [4]. Volatile solids are considerably localized in the primary sludge, while nutrients make up a significant portion of the secondary sludge. Figure 1 presents a summary layout of the wastewater treatment steps for the production of sewage sludge and its valorisation for energy production.

The emerging primary, secondary and tertiary sludge contains organic and inorganic compounds, as well as toxic contaminants, thus necessitating a sustainable treatment approach [43,44].

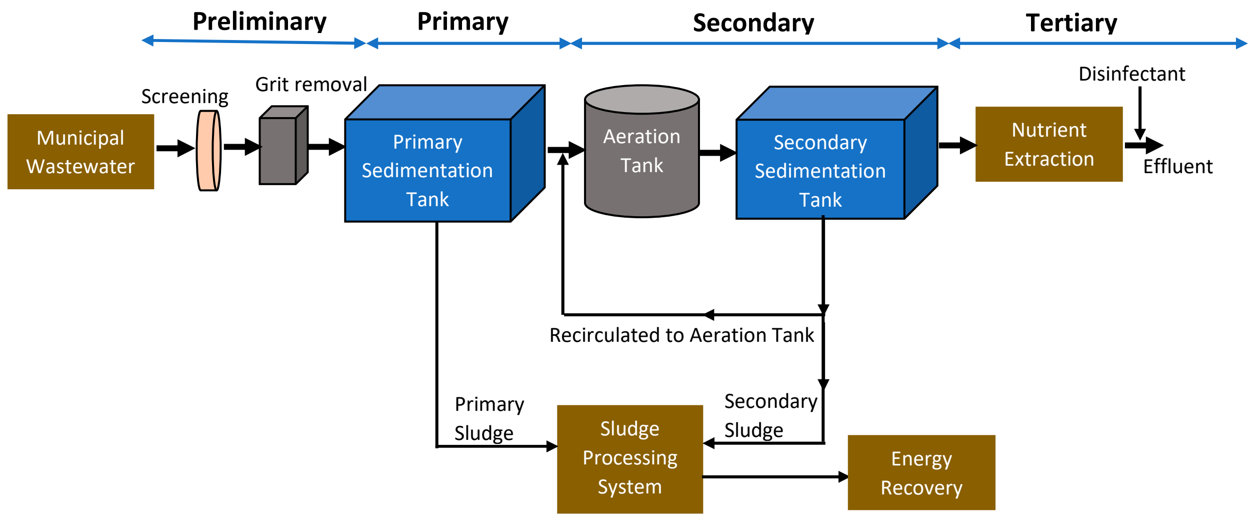

Figure 1. A summary layout of wastewater treatment steps for the production of sewage sludge and its valorisation to energy [5,45].

3. Biogas Production from Sewage Sludge through Anaerobic Digestion

Sewage sludge contains biodegradable materials, making it a viable substrate for anaerobic digestion. In addition to energy recovery, the AD of sewage sludge offers benefits that include solid content reduction, the removal of pathogens, the stabilization of sludge, and enhancements of sludge's dewaterability [46,47]. These beneficial features, when harnessed, can lead to the effective implementation of a circular economy in waste management. On a general note, AD involves the degradation of organic material by microorganisms in the absence of oxygen to produce biogas as the main product and digestate as the by-product (see Figure 2). The AD process uses four metabolic steps, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, to produce biogas [10]. The resultant biogas is a mixture of gases consisting mainly of methane (CH_4) and carbon dioxide (CO_2), with traces of other gases, some of which include carbon monoxide (CO), hydrogen (H_2), hydrogen sulphide, (H_2S), oxygen (O_2), nitrogen (N_2), and ammonia (NH_3) [48].

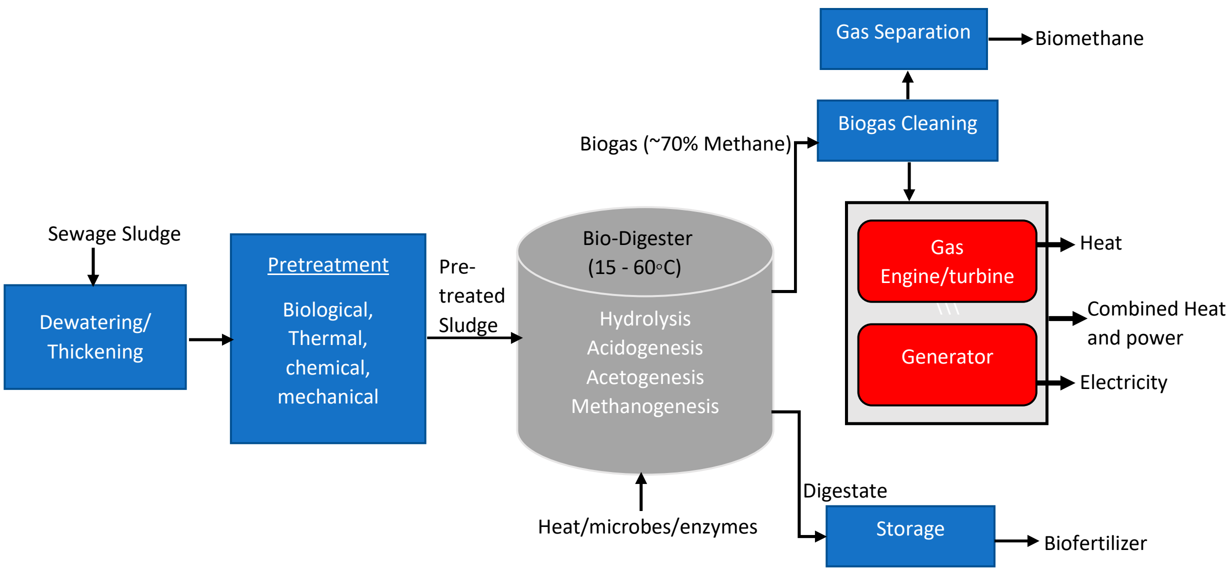

Figure 2. A schematic diagram of the sewage sludge valorisation process for biogas production.

Biogas, as a green energy source, can assist in reducing the greenhouse gas emissions and carbon footprint associated with wastewater treatment plants (WWTPs). Moreover, biogas from sewage sludge can be used for heat and power generation or further processed into biomethane, liquid fuels and chemicals. Further processing involves an upgrading mechanism aiming to enhance the value of the product. For instance, in the conversion of biogas to biomethane, the calorific value and density of the biomethane are enhanced to be equal to that of natural gas [49]. A more detailed analysis of the various upgrading routes for the biogas produced from sewage sludge will be discussed in a subsequent section. Typically, biogas production from sewage sludge follows a three-step process. This includes the AD process, accompanied by biogas production, a post treatment of digested sludge, and the produced biogas, as depicted in Figure 2.

The principal feedstock, comprising a mixture of primary and secondary sludge, is optionally sieved and thickened to a solid content of about 7% before proceeding to pretreatment, and this phase could be referred to as pre-processing. This thickening process is due to the high moisture content of sewage sludge, which varies from 55 to 90% [50,51]. In addition to moisture content, some other inherent properties of sewage sludge are vital and should be considered before digestion. Hence, the characterization of sewage sludge forms an essential path in the determination of its suitability as a feedstock, its biogas potential and its pollutant risk. Depending on the physiochemical properties of sewage sludge, some additional pretreatment mechanisms may be required. Table 1 presents the summarized characteristics of sewage sludge, as reported in the literature.

Table 1. Properties of sewage sludge that are essential to anaerobic digestion.

C/N	COD	VS	TS	pH	SS Type	Reference
-	41.5–44.2 g/L	20.7–21 g/L	29.4–30.5 g/L	6.9–7.3	Primary sludge from municipal sewage treatment plant At 35 °C	[52]
-	38.32 mg/L	57.74 mg/L or 64.7%	89.28 mg/L or 9.1%	6.8	Primary sludge At 28 °C	[53]
-	13.65 g/L	8.25 g/L	11.93 g/L	7.17	Chemically enhanced primary treated sludge At 35 °C	[32]
-	-	-	-	7.1–8.2	Municipal sewage sludge	[54]
6.44	27.5 g/L	13.4 g/L	18.3 g/L	7.5	Secondary sludge At 35 °C for 30 days	[55]
51.7	-	17.10%	32.6%	7.5	Sewage biological sludge at 35 °C for 45–50 days	[56]
7.0	-	12.30%	15.2%	8.0	Sewage chemical sludge	[56]
6.8	-	9.7%	16.9%	-	Primary Sludge	[57]
-	15.7 g/kg or g/L With MC of 74.4%	1.71%	3.77%	7.3	Waste-activated sludge	[58]
14	-	78%	4.8% Or 48 g/L	-	-	[59]
17.1	MC of 93.2%	84.11 vs. (%TS)	6.8% 68 g/L	-	Sewage sludge from sewage treatment plant	[60]
-	30,633.24 mg/L	16.16 g/L	-	5.4	Untreated secondary sewage sludge	[61]
-	-	1.65–3.5%	2.15–4.51% 21.5–45.1 g/L	5.04–7.04	Primary + waste-activated sludge	[62]
	1.2 g/L	27 g/L	34.4 g/L	6.8	Waste-activated sludge	[63]
	275 mg/L	-	603 mg/L	7.3	Primary SS	[64]
	64.6 g/L	38.2 g/L	45.9 g/L	5.74	Primary SS + excess sludge from municipal wastewater treatment plant	[65]

C/N (carbon to nitrogen ratio), COD (chemical oxygen demand), VS (volatile solid), TS (total solid).

All organic wastes are degradable; however, their characteristics determine their biodegradability index. As observed from Table 1, the TS content of sewage sludge varies across the literature. Some of the reported values fall within the optimum range of 4–10% [66], while others [32,56] are outside the range, thus necessitating some pretreatment or augmentation measures to enhance biogas production. For instance, the concentration of sludge TS and VS alongside other parameters such as total nitrogen and phosphorus were enhanced in the study following the addition of fishery by-product broth as a co-substrate. Notably, the anaerobic co-digestion of sewage sludge and fishery by-product broth at a mixing ratio of 5:5 translated to higher TS and VS removal efficiencies of 48.67% and 53.57%, respectively. Comparatively, the TS and VS removal efficiencies of the co-digested samples (5:5 mixing ratio) were found to be 2.53 and 1.85 times higher than those of the mono-digested sample of sewage sludge [55]. A previous study has shown that higher TS and VS removal efficiency increases biogas and methane production [67]. This is true, as TS and VS removal efficiency indicates a reduction in organic matter content, which is the aim of anaerobic co-digestion [68].

Co-digestion has also been identified as a mechanism for solving the problem of the inhibition and inappropriate C/N ratio associated with mono-digestion. Sewage sludge is characterized by a low C/N ratio (as shown in Table 1), which can result in a high ammonium concentration during AD. This will lead to microbial growth inhibition, particularly for the methanogens responsible for methane production. However, these limitations can be resolved by co-digesting sewage sludge with a carbon-rich substrate (such as plants residues) to attain the optimum recommended C/N ratio of 20–30 [69]. pH is another vital parameter of consideration during AD, as its variation influences the activities of a specialized group of microorganisms called archaea [60]. Moreover, pH also impacts the chemical equilibria of volatile fatty acids (VFA's), ammonia and hydrogen sulphide. In the case of sewage sludge, a neutral pH has been found to be beneficial in terms of methane yield. A study on the anaerobic digestion of waste-activated sludge showed that a decrease in pH from 7.0 to 5.0 decreased VS destruction and COD removal. As such, a reduction in methane content from 65% to 41% was observed [70]. This could be attributed to the dominancy of acidogens and a decrease in the percentage of methanogens at a pH lower than neutral. These acidogens and methanogens, alongside the hydrolytic bacteria and acetogens, are the groups of microorganisms that assist in the degradation of organic material into biogas. They achieved this through a series of biochemical reactions described in [10].

First, the hydrolytic bacteria will break down the insoluble organic material and high molecular compounds in the sewage sludge into soluble organic substances. These soluble organic compounds form the substrates for the acidogenic bacteria that further degrade them into volatile fatty acids. At the acetogenesis stage, the acetogens convert the volatile fatty acids into acetic acid, H_2 and CO_2 [71]. Finally, the methanogens, which could be acetophilic methanogenic bacteria or hydrogenophilic methanogenic bacteria groups, will further digest the acetate into CH_4 and CO_2 [72]. This forms the final gaseous product called biogas. The produced biogas is beneficial due to its versatile applications (for production of heat and electricity) and high calorific value. Recently, more attention has been paid to improving the AD of sewage sludge to enhance biogas production and methane yield. Some of the adopted measures include pretreatment, co-digestion, and process optimization.

4. Sewage Sludge Pretreatment for Enhanced Biogas Quality

Notably, many pretreatment technologies have been applied, with the aim of improving the biodegradability of sewage sludge. The rate-limiting step of hydrolysis is usually accelerated through pretreatment. Pretreatment methods can be categorized into biological, thermal, chemical, and mechanical methods [73]. The goal of each pretreatment method is to enhance the solubilization rate by reducing the size of the organic compound in the substrate, thus making it more biodegradable. In mechanical methods, for instance, techniques such as microwave irradiation, ultrasonication, milling/grinding and high-pressure homogenization are used for the disintegration of sludge into smaller particles. This disintegration process increases the surface area, thus making more sludge mass available for microbial digestion. The key considerations during mechanical pretreatment are the power supply and the treatment time. These two parameters, when optimally applied, are beneficial; however, excessive application impacts the activities of the microbes [74,75]. Li et al.'s [76] study showed an improvement in sludge COD removal between 30 and 50% with an increase in pretreatment time. In this study, waste-activated sludge was pre-treated in an ultrasonic system with an energy density of 0.5 W/mL for 0–100 min. The observed improvement could be traced to an increase in the sludge's compositional soluble fraction.

A direct proportional relationship exists between solubilization and the applied pretreatment energy. Xu et al.'s [77] study further confirms this, as an increase in energy density (0.12–1.5 W/mL) caused a corresponding increase in the soluble COD (from 10.78% to 15.11%) of waste-activated sludge. Mechanical pretreatment, in some cases, is used in conjunction with other pretreatment methods, particularly thermal methods. Thermal and mechanical pretreatment are usually referred to as physical methods due to their use of external energy sources. Thermal pretreatment, from its initial application, aimed to improve sludge's dewaterability [78]. At present, this has more beneficial features, including sludge solubilization, a reduction in solid content, enhanced biogas production, pathogen sterilization, and odour removal [79]. The effectiveness of thermal pretreatment in achieving these benefits depends on the temperature and pretreatment time. However, pretreatment time is observed to have a lesser effect compared with temperature in terms of sludge solubilization. Although various temperature ranges are employed in the thermal pretreatment processes, an optimal temperature range between 160 and 200 °C within a pre-treatment time of 30–60 min is recommended for sewage sludge [80,81]. Pretreatment temperature can be classified into low-temperature (<100 °C) and high-temperature (>100 °C) ranges, with high temperatures requiring less time for solubilization and VS reduction compared to low temperatures. The accelerated solubilization at high temperatures could be attributed to the increase in ion diffusivity that fuels heavy metal transportation from sludge flocs into aqueous forms during degradation [82]. Despite the benefits associated with a high pretreatment temperature, a temperature above 250 °C should be avoided, as this could initiate unwanted pyrolysis reactions.

Biological pretreatment, on the other hand, is still at the pilot scale, unlike the thermal methods that has already been commercialized. The low solubilization yield, elongated treatment time, and difficulty in modelling its outcome are some challenges that limit its full-scale application [83]. Notwithstanding, the biological pretreatment method still offers the benefits of minimized inhibitory substances and low capital costs compared to other methods. Biological pretreatment enhances the hydrolysis process, as it serves as an additional stage to the four AD stages [84]. This biological enhancement is achieved using aerobic, anaerobic processes and enzymatic methods. For the anaerobic process, temperature-phased anaerobic digestion (TPAD) was found to be effective. TPAD involves the use of dual temperatures (thermophilic and mesophilic) in improving the floc and solid structure disintegration, as well as biogas yield [28]. The thermophilic conditions enhance sewage sludge hydrolysis and the acidogenesis process, and the mesophilic conditions assist in acetogenesis and methanogenesis improvements. Akgul et al.'s [85] study reported a 37–43% improvement in methane production with the use of TPAD in municipal sewage sludge.

Chemical pretreatment is very promising, particularly for complex organic waste, but is unsuitable for easily biodegradable substances. Its effectiveness depends on the characteristics of the organic compound, the type of chemical used and the applied method. Acids, alkalis and oxidants (such as ozone, hydrogen peroxide, peroxymonosulfate and dimethyldioxirane) are the most-used chemical reagents for sludge disintegration, leading to improved biogas production [28]. For sewage sludge, alkali pretreatment received more attention compared with acid pretreatment, which is more effective for lignocellulosic substances. Both reagents assist in the solubilisation of macromolecules such as carbohydrates and protein. As an example, the subjection of sewage sludge to alkaline pretreatment using sodium hydroxide (NaOH) caused an increase of 179.4% and 201.1% in soluble carbohydrates and protein, respectively. Consequently, an increase in biogas production of about 41.4% was observed [86]. In another study, a 58% reduction in total COD and 52% in volatile suspended solid (VSS) was achieved by the application of acid pretreatment [87]. More importantly, the enhanced solubilization process also increased the biogas production. Despite the advantages that acid and alkaline pretreatment offer, strong concentrations of acid could result in the production of inhibitory by-products such as furfural [88]. While alkaline pretreatment could produce residual chemicals that can alter the buffering capacity of the AD system, thus leading to the inhibition of microbes and alterations in the lignin structure for lignocellulose [89,90]. In light of these, a combination of alkaline and acid pretreatments, as an integrated method, could assist in maintaining a neutral influent sludge pH that prevents microbes' inhibition. Moreover, the goal of integration is to complement the limitation of any single method by the combined efficient interactions of the pretreatment methods.

Other integrated pre-treatment methods (thermochemical and physiochemical method) exist, which have shown positive results. For instance, the pretreatment of a mixture of primary sludge and waste-activated sludge (WAS) (at a 1:1 mass ratio) via a thermo-chemical method showed a 75% VSS-removal efficiency. In comparison to a standalone thermal pretreatment at 90 °C, the integrated values were 26% higher [91]. Notably, the choice of any pretreatment method or its combination should be guided by the overall energy requirements, pretreatment cost, capital investment, required process equipment and influent sludge properties, such as pH, COD, organic loading rate (OLR) and working temperature [79]. Table 2 presents a summary of the sewage sludge pretreatment methods and the associated outcomes found in the literature.

Table 2. Sewage sludge -retreatment measures for enhanced biogas production.

Pretreatment Techniques	Substrate Type	Impact of Pretreatment	Reference
Mechanical—high-pressure homogenization (HPH) at 20, 40 and 60 MPa	Domestic Sewage	Cumulative biogas production increased by 27%, 73% and 82% for HPH of 20, 40 and 60 Mpa, respectively.	[92]
Chemical—with addition of 0.3 g/g-SS of sodium citrate and stirred for 1 h at 150 rpm	Waste-activated sludge	Improved biohydrogen yield with increase ratio of 157.8%.	[93]
Thermal—heated at 121 °C for 30 min	Waste-activated sludge	Increase in biohydrogen productivity by 79.7%.	[93]
Chemical + Thermal—with addition of sodium citrate and heated at 121 °C for 30 min	Waste-activated sludge	Improved biohydrogen yield with increase ratio of 346.9%.	[93]
Chemical—ozonation using two doses of 0.05 g and 0.1 g of O_3 per total solid	Waste-thickened activated sludge	Cumulative biogas production increased by 169% for 0.05 g dose and 140% for 0.1 g dose.	[94]
Thermal hydrolysis at 180 °C for 76 min	Sewage sludge	340% increase in methane production was obtained.	[95]
Mechanical—high-pressure homogenization at 40 Mpa	Sewage sludge	Biogas production increased by 12%, methane content in biogas by 5%, total chemical oxygen demand (TCOD) by 12% and volatile solid removal by 8%.	[92]
Mechanical—cutting at a speed of 35,000 rpm for 6, 8 and 10 min using a high-speed blender	Waste-activated sludge	The cumulative biogas production for pre-treated waste-activated sludge was 2.86, 3.06 and 2.91 (for 6, 8 and 10 min respectively) times more than untreated sludge.	[96]
Biological—enzymatic pretreatment using Fungal mash	Waste-activated sludge	Yielded a 52% increase in net methane production.	[97]
Biological—temperature-phased biological hydrolysis at 55 °C	Municipal wastewater sludge	Led to a 20% increase in methane production and 324% increase in sCOD.	[98]
Chemical + Thermal—5 M of NaOH was added and stirred for 1 h at 200 rpm before heating at 75 °C	Waste-activated sludge	Led to TS solubilization of 9.6% and VS solubilization of 17.2%.	[99]

Table 2. *Cont.*

Pretreatment Techniques	Substrate Type	Impact of Pretreatment	Reference
Triple—heated at 90 °C for 5 h, followed by the addition of NaOH to obtain pH of 12 (alkaline) and, lastly, hydrogen peroxide (30 mg H_2O_2/g TS) was added	Waste-activated sludge	It gave rise to 96% higher methane production and increase in COD solubilization of 30.37%	[100]
Chemical—with the addition of 60 mg of H_2O_2/g TS and stirred for 24 h at 150 rpm	Waste-activated sludge	14.01% increase in methane production with 9.05% solubilization of COD was recorded	[100]
Mechanical—ultrasonic irradiation of sludge at a frequency of 37 kHz and 250 W power	Sludge	Biogas yield increased by 32.3% with organic compound biodegradability index of 50.9%.	[101]
Biological—lysozyme, protease, and α-amylase pretreatment	Waste-activated sludge	When compared to protease and -amylase, lysozymes increased sCOD concentration in the sludge by 2.23 and 2.15 times, respectively, and improved sludge flocculation disintegration.	[41]
Thermal—low-temperature heating between 65 °C and 85 °C	Municipal and industrial sludge	Enhancement in sludge solubilization and methane yield up to 110%.	[102]
Biological + Chemical—addition of enzyme cocktail at 400 U/g dosage followed by trace element enhancer at a concentration of 1.24%	Sewage sludge	Cumulative methane production increased by 45.29% and daily methane yield by 84.7%, respectively.	[103]

Pretreatment of sewage sludge, notwithstanding the type, was observed to be beneficial across the literature, as shown in Table 2. The most outstanding of these benefits is the improvement in biogas and methane yield. Specifically, the improved yield can be traced to the disruption of microbial aggregates (flocs) through pretreatment, thus making more soluble organic matter accessible to the microbes. However, the improvement mechanism usually varies among the different pretreatment methods. In the Yang and Wang [93] study, for instance, the application of sodium citrate as a chemical pretreatment method had less impact on sewage sludge solubilization compared to thermal pretreatment. The recorded increase in biohydrogen yield following the addition of sodium citrate was attributed to the favourable hydrolysis condition of organic compounds in the sludge. The sodium citrate pretreatment may have released active hydrolases such as amylase and protease trapped in the sludge flocs, allowing them to participate in the fermentation process [104]. Floc disintegration can also be accomplished mechanically, as demonstrated by the use of high-pressure homogenization. Nabi et al. [92] reported that a part of the organic matter in the sludge was transformed from solid to liquid after undergoing high-pressure homogenization. Consequently, the VS removal efficiency increased alongside the homogenization pressure, with a pressure of 40 Mpa yielding a 23% removal efficiency. Notably, VS removal represents the rate of organic matter degradation, thus explaining the increase in biogas production recorded in the study. Moreover, the use of four homogenization cycles at a pressure of 80 Mpa resulted in 43.94% COD disintegration degree [105]. In another study, high-pressure homogenization increased sugar and protein solubilization from 2% to 15% [106].

Furthermore, in a semi-continuous mode, the application of microwave pretreatment as another mechanical approach enhanced the methane yield and biodegradability by 20% and 70%, respectively [107]. For thermal pretreatment, particularly at high temperatures, the solubilization of organic particles is noted as the key contributor to the increase in biogas production. De los Cobos-Vasconcelos et al. [108] established that the treatment of waste-activated sludge within a temperature range of 125–175% made it more biodegradable. Liao et al. [109] obtained a disintegration rate of 9.1, 13.0, and 16.6% when sewage sludge was treated at temperatures of 60, 70, and 80 °C. Consequently, the production of biogas increased by 7.3, 15.6, and 24.4%, respectively. Biological pretreatment, designated as an eco-friendly approach, accelerates the rate-limiting hydrolysis phase by enhancing the hydrolytic activities of the endogenous microbial population. Montalvo et al. [110] documented 0.3 vvm, 48 h, and 35 °C as the optimum conditions to achieve higher hydrolytic activities using micro-aeration. This yielded a 211% increase in methane production, similar to that reported in [97]. In summary, all the pretreatment mechanisms can improve anaerobic digestion and, consequently, biogas production. However, the economic, energy, and environmental implications associated with each mechanism need to be further considered for full-scale application and sustainability. Additionally, the downstream process required for the recovery of chemical inputs during the pretreatment process needs detailed research to prevent residual negative effects in the environment. Ultimately, a shift from testing existing pretreatment techniques to designing specific pretreatment methods based on energy-recovery purposes, waste-management needs and environmental concerns will facilitate the use of sewage sludge in the realization of a sustainable green economy.

5. Syngas Production from Sewage Sludge via Gasification

The thermal decomposition of sewage sludge into fuels and valuable products is the basis for thermochemical processes. Gasification, pyrolysis and liquefaction are the most common of these processes, and each has its own set of benefits and drawbacks. In comparison to the regularly used incineration technology, sewage sludge gasification is a more sustainable option that can produce a clean and combustible gaseous fuel called syngas, as depicted in Figure 3.

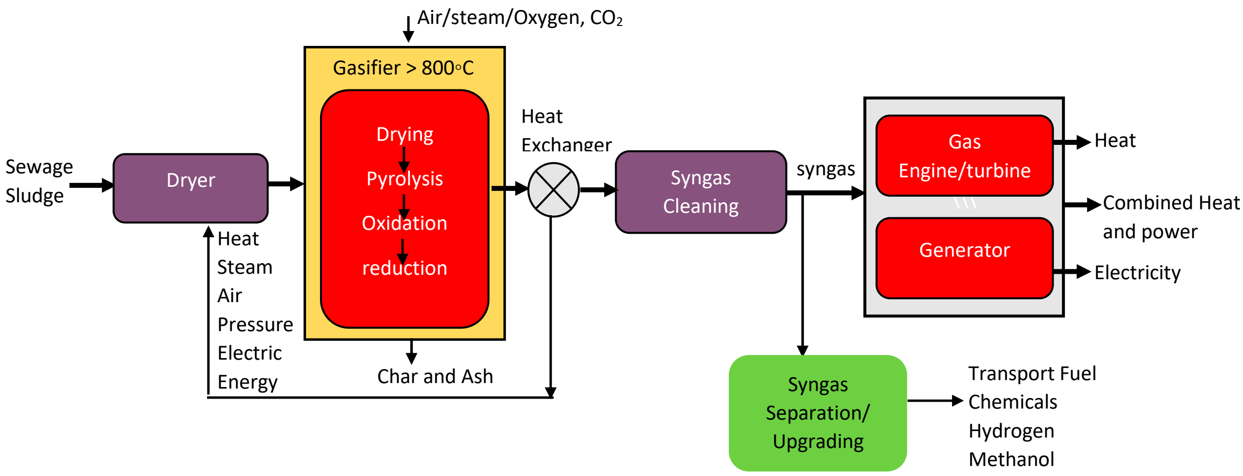

Figure 3. A schematic diagram of the sewage sludge valorisation process for syngas production.

The produced syngas is a mixture of gases consisting of H_2, CO, CO_2, and CH_4. Depending on the gasifying agent used, the composition and quality of the syngas may vary [111–114]. Gasifying agents such as oxygen, steam, air, CO_2, or a mixture of these, are mostly used. The air gasification of sewage sludge (see Equation (1)) [115] is cheap; however, it produces syngas with a high concentration of nitrogen, which dilutes the energy content of the gas.

$$\text{Sewage sludge} + \text{Air} \rightarrow N_2 + H_2 + CO_2 + CO + CH_4 + \text{other CHs} + \text{tar} + H_2O + \text{char} \quad (1)$$

As an example, Calvo et al. [116] reported a nitrogen concentration of 34–36%, which exceeded the composition of other gases. Experimentally, the study evaluated the gasification of sewage sludge in a fluidized bed reactor using air. The produced gas had a heating value of 8.4 MJ/Nm, resulting in hot gas and cold gas efficiencies of 70% and 57%, respectively. A more recent study by [117] used a mix of nitrogen and air as a gasification agent to gasify sewage sludge at a temperature of 850 °C in a fluidized bed reactor, although at bench-scale. The heating value of the produced gas was influenced by the higher gasification agent flow, as evidenced by the decrease in H_2/CO ratio and increase in CO_2/CO ratio. However, this favoured the decomposition of tar, as evidenced in the recorded 21.6% decrease in tar generation. On another note, the steam gasification of sewage sludge (see

Equation (2)) [118] seems promising, probably due to its contribution to enhancing the quality of syngas.

$$\text{Sewage sludge} + \text{Steam} \rightarrow H_2 + CO_2 + \text{other CHs} + \text{tar} + \text{char} \quad (2)$$

Although steam generation consumes a lot of energy, this is compensated by the elimination of the need for expensive gas-separation techniques. The thermochemical conversion of sewage sludge via steam gasification was explored by Nipattummakul et al. [119]. The study found that steam gasification produced a 40% higher mole percentage of hydrogen than air gasification. Lee et al. [68] experimentally evaluated the steam gasification of sewage sludge to determine the feedstock decomposition characteristics and the chemical kinetics of the produced syngas. The study showed accelerations in carbon conversion with the increase in the flow rate of steam and reached saturation point at 15 g/min flow rate. Moreover, Gai et al. [120] observed a slight decline in H_2 and CO_2 concentrations after an increase, as the steam to sewage sludge (S/B) ratio increased from 0.5 to 2.0. A high S/B ratio is thought to have shifted the water–gas shift reaction's equilibrium toward H_2 generation, encouraging hydrocarbon steam reformation. Regardless of the type of gasifying agent used, an optimal equivalence ratio (ER) is needed because a lower ER (<0.2) promotes incomplete gasification, while a higher ER (>0.5) promotes the complete combustion of chars and tars, thus leading to more CO_2, H_2O and heat energy. Nevertheless, this is achieved at the expense of the syngas' calorific value and yield [121,122]. An optimal equivalence ratio in the range of 0.2–0.4 was found to support the production of CO, H_2, CH_4 at a maximal level and increase efficiency [123,124].

Although it has been established that a gasifying agent plays a substantial role in the final composition of syngas produced from sewage sludge gasification, it does not do this in isolation. Other variables, such as reactor configuration, operational parameters (such as temperature) and sewage sludge properties, all play a part [6]. With regard to temperature, Lee et al.'s [68] study showed that the production of CH_4 and CO_2 was more controlled by reactor temperature than other factors. Furthermore, Hantoko et al.'s [125] study evaluated the gasification of sewage sludge in supercritical water for the production of H_2 and made the following observations. The reaction temperature had a significant impact on syngas and hydrogen yields, as it increased from 147.79 kg/100 kgfeed to 178.08 kg/100 kgfeed and 1.99 kg/100 kgfeed to 9.06 kg/100 kgfeed, respectively. The effect of temperature on the product distribution of sewage sludge gasification in supercritical water was observed by Chen et al. [126]. Observations revealed that when the temperature rose, the mass fraction of the gaseous products increased, the mass fraction of the liquid products decreased, and the mass fraction of the solid products remained constant. The temperature increase also caused an increase in gasification efficiency, carbon efficiency and hydrogen yield potential to maximum values of 63.96%, 60.7%, and 35.38 mol/kg, respectively. Moreover, a study examined the effect of temperature on the composition of syngas produced from the steam gasification of char derived from sewage sludge. The findings showed that the concentration of H_2 and CO increased as the temperature increased from 750 to 950 °C [120]. Notably, the observed impact could be explained by the fact that the chemical reaction's equilibrium is governed by the gasification temperature within the reactor [127]. The reactor temperature is usually enhanced by either preheating the gasifying agent or increasing its ratio. Werle [128] observed that using preheated air resulted in a syngas of higher calorific value compared to non-preheated air. The observed increase in combustible gases with an increase in temperature found in the literature would eventually improve the calorific value of the syngas. However, because sewage sludge has a high ash content, a very high temperature may result in clinker formation. Hence, an optimum temperature that will not only promote the quantity and quality of the produced syngas but will also support the reduction of tars and avoid clinker formation is then required. Sludge properties are another parameter of concern upon which the end product of sewage sludge gasification is dependent. Tables 3 and 4 present the proximate and ultimate analysis of sewage sludge found in the literature.

Table 3. A summary of sewage sludge proximate analysis parameters for gasification.

VM	FC	MC	Ash	Type of SS Feedstock	Ref.
44.30	21.8	1.74	33.91	SS	[119]
36.87	4.89	nr	58.18	SS	[129]
54.96	-	-	35.39	Raw SS	[111]
39.3	19.40	11.20	30.10	Industrial SS	[130]
55.10	7.10	7.9	37.9	SS from Oakland California	[116]
54.3	5.1	10.0	30.60	Municipal SS from Italy collected in January	[117]
60.9	4.8	10.0	24.30	Same but collected in April	[117]
55.5	9.0	6.0	35.5	Dried sludge	[131]
52.10	5.96	-	41.94	Raw sludge from Wuhan, China	[132]
62.3	6.5	71.0	31.2	Aerobically digested sludge	[133]
54.7	7.2	81.0	38.1	Anaerobically digested	[133]
59.7	6.5	80	31.2	Dewatered SS from Shanghai, China	[134]
54.7	4.4	83.5	40.9	Dewatered SS from Centra, Spain	[135]
52.9	17.3	82.4	29.8	Municipal SS from Alabama, USA	[136]
71.57	9.27	4.60	19.16	Dried SS from Dalian, China	[137]
49.77	5.42	2.54	42.27	Municipal SS	[138]
59.72	7.70	6.33	26.17	Dried SS from Ocala, Florida	[68]
15.60	15.90	78.00	68.50	Wet SS from Wuhan, China	[139]
57.78	11.46	-	30.76	Municipal raw sewage from Beijing	[120]
9.78	1.84	80.07	8.31	Municipal sewage sludge from Taiwan	[140]
31.52	5.25	79.00	63.23	Wet SS from Nanjing, China	[141]
61.63	9.41	84.0	28.96	Shaanxi, China	[126]
56.59	4.17	5.63	33.61	SS from Qingdao, China	[142]
46.24	4.59	0.05	49.12	SS from Guangdong, China	[143]
35.14	2.29	-	62.57	Hangzhou, China	[144]
55.00	3.20	-	41.80	SS from	[145]
51.51	1.20	86.21	47.29	Dewatered sewage sludge from Hefei Anhui, China	[146]
46.24	4.59	0.05	49.12	SS from Foshan	[147]
53.90	3.10	8.70	43.0	Anaerobic sewage sludge from Brazil	[148]
64.9	7.60	18.40	27.50	Aerobic sewage sludge from Brazil	[148]
57.65	13.49	-	28.86	SS from Singapore	[139]
52.31	18.51	8.98	29.18		
49.01	10.71	6.94	40.28	SS from Taiwan	[149]
55.1	7.10	7.9	37.9	SS from California	[116]
48.22	7.07	-	44.71	SS from China	[76]

Volatile matter (VM), fixed carbon (FC) and moisture content (MC).

Table 4. A summary of sewage sludge's ultimate analysis parameters for gasification.

Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen	HHV (MJ/kg)	Ref.
45.79	2.99	1.49	1.11	14.70	16.34	[119]
56.20	8.99	9.19	1.38	24.23	-	[129]
34.52	4.98	8.80	1.2	15.16	14,230 kJ/kg	[111]
40.93	5.01	3.85	0.88	49.33	-	[51]
69.20	4.60	2.20	1.70	22.30	-	[130]
36.20	4.50	5.60	1.10	14.70	15.40	[116]
49.16	8.50	6.06	1.18	35.02	10.60	[117]
51.75	7.91	6.70	1.37	26.64	14.8	[117]
34.08	4.33	5.34	0.98	19.69	14.435	[131]
28.27	4.43	5.36	1.14	-	11,337 kJ/kg	[132]
52.3	8.0	6.7	0.7	32.3	16.70	[133]
49.1	7.3	8.1	1.5	34.0	14.0	[133]
35.7	5.5	4.5	1.0	19.5	-	[134]
32.7	4.9	5.1	1.0	15.4	-	[135]
33.1	5.5	5.0	0.7	25.9	14.1	[136]
41.28	6.55	7.60	Nr	25.41	18.25	[137]
28.71	4.66	5.01	0.5	18.82	12.82	[138]
35.76	6.10	6.34	0.52	25.12	16.01	[68]
12.90	2.54	2.37	0.05	16.30	14.89	[139]
33.98	6.02	6.24	0.92	52.84	13.17	[120]
6.27	1.09	0.77	0.28	3.20	678 kcal/kg	[140]

Table 4. *Cont.*

Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen	HHV (MJ/kg)	Ref.
20.95	8.66	3.47	0.9	2.79	-	[141]
38.18	3.40	4.67	1.05	23.74	14.63	[126]
45.74	5.62	1.03	1.23	42.8	11,000 kJ/kg	[142]
26.05	4.29	4.12	0.67	15.70	11.05	[143]
18.94	2.21	2.89	0.60	12.79	5.89	[144]
21.86	3.37	3.83	0.64	28.50	10.98	[145]
25.93	4.13	4.58	0.75	17.33	11.77	[146]
26.05	4.29	4.12	0.67	15.70	-	[147]
16.11	1.88	2.46	0.51	16.47	6.34 kJ/g	[150]
23.70	4.95	3.15	3.44	21.42	14.00	[148]
33.90	6.30	5.88	0.67	25.5	16.60	[148]
36.17	5.28	5.58	0.81	23.30	-	[139]
51.58	8.23	8.79	Nr	31.40	15.04	[129]
28.40	5.29	4.65	2.66	25.58	11.38	[149]
36.2	4.5	5.60	1.1	14.7	15.4	[116]
24.67	4.65	4.51	0.95	20.52	11.61	[76]

From the proximate analysis results presented in Table 3, the volatile matter content of sewage sludge varied from 31.52 to 71.57%, fixed carbon from 1.84 to 21.80% and ash content from 19.16 to 63.23%. The amount of volatile content and fixed carbon in the sewage sludge generally affect how quickly char is converted into syngas. Ash content impacts the high heating value (HHV) of sewage sludge. In actuality, VM also defines the HHV of sewage sludge (SS) and constitutes a significant factor of consideration in sewage sludge's suitability for energy use. The HHV of SS typically ranges from 10.60 to 18.25 MJ/kg due to its relatively high VM content [35], demonstrating a close comparison to biomass and its suitability for energy recovery. Moreover, high levels of ash in sewage sludge can result in ash agglomeration and frequent solid discharge during gasification, thus making the process exceedingly unstable. However, such an operating problem could be solved through co-gasification with biomass. According to data from most research presented in Table 3, the sewage sludge moisture content is often >80% when reported as received. Nevertheless, a sewage sludge moisture content in the range of 1.74–10.0%, as observed in [116,131,137,142], could be attained through drying, either via an oven at 105 °C for 24 to 72 h or air-drying for several weeks. The high moisture content in the sewage sludge promotes tar generation and incurs additional energy requirement costs. This impacts the reactor's operation, product distribution, and product gas quality. In an attempt to address these challenges, previous studies have applied measures including torrefaction, low-temperature pyrolysis to produce pyro-char, and hydrothermal carbonization to produce hydrochar [120,151,152]. Following these measures, improved dewaterability can be achieved and energy for water removal can be saved during the gasification process. As a typical example, Nwokolo et al.'s [50] study evaluated the torrefaction performance of sewage sludge at four temperature levels (200, 250, 300, 350 °C) to ascertain its influence on gasification. The findings showed that the application of torrefaction lowered the equilibrium moisture content of sewage sludge and consequently increased the hydrophobicity properties of the sample. With the above improvements, the volatile matter content also decreased as the torrefaction temperature rose. It seems plausible to attribute this to the partial devolatilization of protein, lipids, carbohydrates, and other organic matter in the sewage sludge during torrefaction. However, it is worth noting that further research is needed to determine how torrefaction affects the reactivity of sewage sludge during gasification. In terms of ultimate analysis, sewage sludge has a high nitrogen content (Table 4) compared with other types of biomasses. This is attributed to its protein component, which is supplied by the microbes involved in wastewater purification. In most lignocellulose biomass, the nitrogen content is usually <1 [127] but that of sewage sludge varied from 1.49 to 7.60% (Table 3). The significant sulphur content of sewage sludge may lead to a high concentration of hydrogen sulphide (H_2S) in the produced syngas. Therefore, depending on the end-use application of the syngas, the use of sorbents or more effective treatment methods may be required to ensure very low concentrations of H_2S. Thus, reviewing the various sewage sludge pre-treatment techniques is a necessity to ascertain its impact and advancement state.

6. Improvement Measures for the Gasification of Sewage Sludge

Sewage sludge is a high-moisture precipitant with abundant organic and inorganic components. However, its high ash content and moisture content make its valorization difficult, particularly through gasification. Thus, the application of some special measures are required for its conversion into value added fuel. Pretreatment before gasification and co-gasification is gaining attention as a better way of using this feedstock (sewage sludge). Table 5 presents a summary of some of the pretreatment measures adopted for sewage sludge prior to gasification.

Table 5. A summary of sewage sludge pretreatment techniques for enhanced syngas production.

Pretreatment Technique	Substrate Type	Impact of Pretreatment	Reference
Chemical—Fenton peroxidation (Fe^{2+}/H_2O_2) and CaO conditioning.	Raw sewage sludge	Hydrogen yield almost doubled and s slight increase in CO and CO_2 was observed. In addition, carbon-conversion efficiency was enhanced by 43.7%, 42.2% and 30.4%.	[132]
Chemical—Raw sludge was mixed with CaO under magnetic stirring at room temperature, dried at 105 °C for 16 h and used to form pellets.	Raw sludge	Improved the carbon utilization efficiency of sewage sludge to as much as 20.4%, resulting in higher yields of CO. Secondly, syngas with separated H_2- and CO-rich streams was produced.	[153]
Chemical—Hydrothermal carbonization at a temperature of 220 °C and retention time of 1 h	Municipal sewage sludge	It improved gasification reactivity as well as interactions between the carbon surface and hydrogen bonding, hence leading to higher yield of hydrogen.	[120]
Chemical—Addition of activated carbon with coconut shell base at 2–8 wt.%,	Sewage sludge	At 8 wt.% activated carbon and 400 °C, syngas production and cold gas efficiency significantly increased from 2.98% to 6.44% and 11.15% to 27.93%, respectively.	[125]
Thermal—Torrefaction of SS sample at varying temperature (240–320 °C) and constant residence time of 40 min under an inert atmosphere.	Sewage sludge	Enhanced the removal of about 33.3% of N and 52.8% of S from sewage sludge, which reduces precursor emissions of NO_x and SO_x.	[154]
Thermal—Co-hydrothermal carbonization of sewage sludge and saw dust at 220 °C for 60 min	Sewage Sludge	The produced syngas had a higher carbon monoxide content compared to raw sludge due to increased gasification reactivity and aromatization degree.	[145]
Mechanical—Ultrasonication of SS at a frequency of 24 kHz, power of 300 W and input energy of 4500 kJ/kg of solid sludge	Fermented sludge (anaerobically stabilized sludge)	The gas by product yield increased from 26.7 wt% to 55.0 wt% at a process temperature of 360 C.	[111]
Thermal—Torrefaction of SS at temperature levels of 200, 250, 300 and 350 °C and residence time of 0–50 min.	Raw sewage sludge	The overall value of chemical exergy increased as the torrefaction temperature increased. In addition, the volatile fraction of the SS decreased as torrefaction temperature increased, which caused an increase in fixed carbon and ash content.	[155]
Thermal/Chemical—Gasification of varying mass ratios of Cao-SS pellets in a two-stage sorption-enhanced steam gasification system (SESG)	Municipal sewage sludge	The Cao/SS mass ratio of 3:7 yielded a H_2-rich gas stream of 72 vol% at first stage and CO-rich gas stream of 60.5 vol% at the second stage.	[156]
Thermal—Torrefaction of SS at 391.9 °C	Sewage sludge	The torrefied sewage sludge resulted in producer gas with higher energy value (LHV) of 17.51 MJ/m^3 compared to LHV of 13.51 MJ/m^3 reported for raw SS. A 7.4% decrease in the concentration of the condensable compounds.	[152]
Chemical—Hydrothermal Carbonization conversion of sewage sludge with CO_2 co-gasification of hydrochar	Sewage sludge	The hydrothermal carbonization of the SS resulted in the removal of about 50% of nitrogen contained in the sludge	[157]
Hydrothermal treatment of SS	Sewage sludge	Increased the lignin content of the SS, which translated to more methane concentration in the product gas after steam gasification.	[158]

As observed in Table 5, the use of thermal, chemical, and mechanical pretreatment measures is common for sewage sludge gasification and is successful. Hydrothermal carbonization, a chemical treatment method, has been found to enhance sewage sludge's fuel properties through the evolution of aromatic structures, reduction in heavy metal content and changes in carbon functionalities [5,154,159]. The observed changes in sewage-sludge-derived hydrochars translate in a more stabilized gasification process, as evidenced in the studies of Zhuang et al. [160], and Moon et al. [158]. Of the utmost importance in hydrothermal carbonization is temperature and time, as both impact the char reactivity, although temperature plays a more significant role than time [151]. A new, promising approach involving the integration of a two-stage, sorption-enhanced steam gasification (SESG) with the application of syngas has been introduced [156]. This approach aims to promote the decomposition of tar during gasification, resulting in enhanced syngas production. In terms of syngas production, Pawlak-Kruczek [152] showed that the torrefaction of sewage sludge prior to gasification can positively influence the quality of the syngas. Evidently, the syngas from the torrefied sewage sludge had a higher LHV of 17.51 MJ/m^3 compared to raw sewage sludge, which yielded syngas with an LHV of 13.51 MJ/m^3. However, the opposite result was obtained for the properties of sewage sludge prior to gasification. Both the high heating value (HHV) and low heating value (LHV) of the SS decreased after torrefaction. This is counterintuitive compared to the other literature reports [161–163] in which torrefaction enhanced the heating (energy) value of feedstocks. Thus, the study opined that the contrast with the results of other studies could be linked to the autocatalytic effect of the inorganic fraction of the sewage sludge as well as the sewage sludge's origin. This suggests the need for a more detailed experimental study to ascertain the reason for this disparity.

To further investigate the impact of sewage sludge pretreatment on its use as a feedstock for gasification, Abdelrahim et al. [164] carried out a numerical investigation on biosolid (treated sewage sludge) gasification. The main objectives of this study were to assess the impact of some sludge pretreatments (i.e., torrefaction, hydrothermal treatment, anaerobic digestion, carbonization, and copelletization of sewage sludge with beech sawdust and lignite) on the gas composition, syngas yield, heating value, cold gas efficiency and carbon conversion efficiency. The research concluded that, among the examined pretreatment methods, torrefaction is the most suitable for biosolid valorization. This is a consequence of their results showing that torrefied feedstocks produced more H_2 and CO, and less CO_2, which led to a higher LHV. However, the anaerobic digested sludge slightly reduced the syngas quality, as indicated by the decrease in the H_2/CO ratio and the increase in the CO_2/CO ratio. The results from the sludge treatment using the carbonization, hydrothermal, and copelletization processes were similar to the digested sludge. It is worth mentioning that these findings are numerically base; therefore, an experimental investigation is required to this effect. Nevertheless, the established truth is that pretreatments improve the fuel properties of sewage sludge as well as the gasification performance, as summarized in Table 5.

In addition to pretreating sewage sludge to improve its gasification, other approaches have been tested. For instance, supercritical water gasification (SCWG) and supercritical partial oxidation (SCWPO) were employed in Qian et al.'s [165] study as the preferred means of converting wet sewage sludge to gaseous products. This study evaluated the influence of moisture content, oxidation coefficient, and pressure on the gaseous and energy recovery using a thermodynamic approach. Pressure, unlike the moisture content, had a negligible impact on both the equilibrium and experimental gas yield. Whereas the change in moisture content from 87 wt% to 95 wt% caused a decrease (from 11,064 kJ/kg to 6969 kJ/kg) in the LHV of the gaseous product as well as a 0.5% decline in the energy-recovery rate. Hence, the optimum conditions for sludge gasification via SCWG and SCWPO were 87 wt% moisture content, zero oxidation coefficient and 25 MPa pressure. In another example, Weijin et al. [166] investigated the supercritical water gasification of sewage sludge using a batch reactor. The study observed that the addition of hydrogen peroxide during gasification promoted the degradation of sludge organic compounds. Correspondingly, the gasification efficiency (GE), carbon gasification efficiency (CE), carbon-removal efficiency (X_{TOC}) and phosphorus release rate (Xp) were enhanced. We highlight that, at an optimum temperature of 420 °C, pressure of 27 Mps and 6 min retention time, the hydrogen yield was 55.72% and the hydrogen molar fraction was 19.86 mol/kg.

A different study on supercritical water gasification further explored the transformation pattern of the sulfur element during the SCWG of sewage sludge. The study found that organic sulfur was part of the sulfur compounds in sewage sludge, while the inorganic sulfur content of the sewage sludge, such as SiS_2, was converted into H_2S and SO_2 during SCWG. Moreover, an increase in temperature promoted the yield of H_2S and SO_2, However, the study opined that the use of additives, KOH, to be precise, could reduce both the yield and concentration of these sulfur compounds [49]. Interestingly, the syngas desulfurization ability of KOH was tested alongside four other additives (K_2CO_3, NaOH, Na_2CO_3, AL_2CO_3) during the supercritical water gasification of sewage sludge. Although K_2CO_3 was observed to provide the best desulfurization effect, KOH best promoted the yield of syngas. In comparison to the use of no additives, a 12% increase in KOH and K_2CO_3 loading might reduce sulfur in syngas by almost 90% [167].

Further reviewing these additives, a recent study applied limestone as a bed additive during the steam-oxygen gasification of sewage sludge with the aim of reducing H_2S, COS, and tar, thereby mitigating the downstream cleaning problems. The addition of 0.06 kg kg^{-1} limestone to the fuel ratio was found to be sufficient to lower the heavy tar concentration by 75%. Additionally, the concentration of H_2S and COS decreased by 40–65% alongside an increase in the limestone additive ratio. With these improvements, the use of limestone as an additive can be an effective and low-cost means of producing a cleaner syngas [168]. Moreover, the combination of steam and oxygen as a gasification agent in the above study resulted in syngas with high concentrations of H_2 and CO of up to 0.37 m^3 m^{-3} and 0.18 m^3 m^{-3}, respectively. The addition of catalyst has been established as contributing to the reduction in pollutants. For instance, high levels of tar reduction and lower NOx production have been associated with the use of nickel-based catalysts [95,113]. However, the deactivation of such catalysts still poses a challenge, particularly at high temperatures. The co-gasification of sewage sludge and other biomass materials is another approach that can positively impact the quality of the produced syngas and the conversion efficiency. It offers the benefit of abating harmful matter containing sulphur and nitrogen, as the alkali and alkaline earth metals can form sulphates and capture these species.

To illustrate this, Urych and Smolinski, [169] presented a kinetics and reaction mechanism study for the gasification of sewage sludge and phytomass (Salix viminalis) char blends. This involved a two-stage gasification process using a thermogravimetric analyser and a fixed-bed reactor. It was shown that, with an increase in the phytomass fraction in the mixture, the investigated char's maximal reactivity and reactivity values at the 0.5 conversion rose to 1.2×10^{-1} and 1.1×10^{-1} min^{-1}, respectively. Another study explored the co-gasification of sewage sludge and palm kernel shells using a thermogravimetric analysis integrated with the Fourier transform infrared spectroscopy method (TG-FTIR) and a bubbling fluidized bed gasifier. A synergy was found to exist between the two fuels, and an increase in sewage sludge fraction above 30% caused a corresponding increase in C=O band, C=C bond, C–O, and C–C bond yields. In terms of the syngas yield, the maximum H_2/CO ratio of 0.563 was obtained at the optimum conditions of 900 °C gasification temperature, 30% blending ratio, 15% added catalyst (Olivine) and 70% $CO_2/(CO_2 + H_2O)$ ratio. However, the $CO_2/(CO_2 + H_2O)$ ratio was identified as the most dominant parameter, followed by catalyst addition [149]. The addition of a catalyst promotes the water–gas shift reaction, thereby increasing the H_2 yield [170]. This further strengthens the added value of a catalyst in sewage sludge gasification. In summary, sludge gasification has proven successful to date; however, the high concentrations of inorganic elements (ash-related problems), tar minimization, and sludge properties (heavy metals, moisture, sulphur and nitrogen) pose the biggest hurdles to its gasification efficiency, and specific research should focus on designing an efficient protocol to overcome these impediments. Notwithstanding, gasification also aids in the fixing of heavy metals such as lead, chromium, and nickel, as well as reducing such compounds' volatility in residual ash.

7. Application and Economic Feasibility of Anaerobic Digestion and Gasification

Economically, anaerobic digestion has significant potential for practical applications, as it allows for the conversion of biomass waste into biogas, which is a renewable form of energy. Owing to the benefits of methane gas, it is proposed that biomethane and biogas will account for 32% of the energy share in the EU and will dominate, or at least have about 14% of the total share, and can be used in the transport sector to reduce the dependence on fossil fuel or natural gas. This has led to an increase in the installation capacity of biogas production plants for electricity generation at a capacity of 9985 GW [171]. The need to expand the frontier of environmental sustainability while deriving energy from waste has led to an increase in the establishment of biogas production plants, such as the green gas project capable of producing about 48–50 billion Nm^3 of biomethane per year. The gasification of wood biomass led to the production of about 66 billion Nm^3 of Syngas. Herbaceous plant biomass gasification yielded 11 billion Nm^3, while those from energy crop are within the range of 48–143 billion Nm^3 [172,173]. The evidence presented here has shown that the energy extraction from biomass wastes is highly feasible and economical, although the production systems are not yet perfect, as there is need to improve the pretreatment process or technology to increase organic matter hydrolysis and the digestion of recalcitrant biomass. Additionally, improvements in the production technologies for biogas and syngas will reduce the need for gas-cleaning and upgrading, lowing the cost of the process [174]. In a study analysing the economic feasibility of installing a biogas production plant near a Chinese university, Huiru et al. [175] observed that the project will have a power capacity of 168 kWe with a net production of 142 kW. Interestingly, they recorded that an average of 7.8 years will be the most likely period to return on the investment for the project. This makes the project a profitable one and worth investing in.

In another study analysing the economic feasibility of biogas production from the biomass wastes generated in Bangladesh revealed that it could meet about 10.88% of the country's households' electricity needs, cut down on greenhouse gas production, and increase the return on investment [30]. In Saudi Arabia, the proposed financial model shows that the development of a waste-to-energy system involving anaerobic digestion and gasification could meet the country's energy needs, reduce the carbon footprint, and promote the return on investment. Another study showed that the coupling of anaerobic digestion and gasification could increase the total electricity generation from the waste by 11% and 14% for income derived from the process [176]. Therefore, energy production from biomass waste and its use in heat generation, electricity and transportation is economically feasible and favorable, and should be adopted in areas where it is not yet in use and advanced in areas where it is already in use to maximize its full potential.

8. Limitation of Anaerobic Digestion and Gasification of Sewage Sludge

The application of pretreatment, as observed in previous sections, enhanced the anaerobic digestion and gasification of sewage sludge. Although anaerobic digestion and gasification technologies have advanced in recent decades, some technological, environmental, and economic issues remain, providing limitations to their successful operation. Table 6 provides a summary of the key limitations/challenges associated with the anaerobic digestion and gasification of sewage sludge.

Table 6. Technological, socio-environmental and economic limitations of the anaerobic digestion and gasification of sewage sludge technology [35,43,177,178].

S/N	Anaerobic Digestion	Gasification
Technology		
1	Long retention time	Dewatering/drying to >50 wt% solids content required
2	Low conversion efficiency	Complex reaction
3	High organic pollutants from process	Technology use still in its infancy
4	Ammonia toxicity leading to anaerobic digester failure	Extensive syngas cleaning required
Social and Environment		
5	Appropriate treatment required after digestion to avoid health hazards to the public	Emission of heavy organic pollutants
6	Polluting odour in the vicinity	Formation of tars
7		Formation of NOx and SOx precursors
Economics		
8	High capital and maintenance costs	High investment and operational costs
9		High energy requirements

A long retention time (≥20 days), as indicated in Table 6, has been associated with the anaerobic digestion of sewage sludge. This can be traced to the presence of extracellular polymeric substances with a low volatile solid degradation of about 30–50% [179,180]. To accelerate the degradation of these substances, measures such as pretreatment, as discussed earlier, have been adopted. However, these pretreatment measures lead to high energy demands and high capital costs, as well as a complex maintenance process, as summarized in Table 6. Under mesophilic conditions, the digestion of sludge with a total solid concentration between 10% and 20% resulted in total ammonium nitrogen (TAN) and free ammonia nitrogen (FAN) levels between 2000 and 4000 mgL^{-1} and 200 to 800 $mg\ L^{-1}$, respectively [181]. This accumulation of FAN and TAN can inhibit methanogenic activities and subsequently lead to digester failure. Some remedial approaches, such as gas stripping, adsorption, dilution, mixing, and chemical precipitation, all categorized under the physiochemical pretreatment method, have been adopted as a means of reducing ammonia toxicity [182,183]. Moreover, bioaugmentation using the consortia of syntrophic acetate oxidation (SAO) bacteria and hydrogenotrophic methanogens has been explored in the alleviation of ammonia toxicity [184]. The presence of teratogenic and carcinogenic compounds in tars formed during sewage sludge gasification poses a threat to human health. Technically, tar formation also causes some operational problems due to the clogging of filters and lines, thus incurring some additional costs in the maintenance of the downstream equipment. In addition, tar formation lowers the energy-efficiency of the process due to the significant amount of energy trapped in the tar [177]. Currently, the scientific community has developed some practical strategies for tar minimization/removal, including thermal cracking, scrubbing, electrostatic precipitation, catalytic cracking/reformation, and non-thermal plasma [185,186]. Although plasma technology has been found to be too complex and expensive to implement, particularly at a large scale, more research is needed in this regard. Furthermore, the high moisture content of sewage sludge makes drying an inevitable part of the gasification process, leading to additional energy requirements and operational costs. Another concern is the release of NO_x and SO_x precursors under oxidation conditions, which could result in the secondary pollution of acid rain and photochemical smog. As such, it is essential to develop measures that could minimize these emissions. This would require an understanding of the sewage sludge–nitrogen nexus during gasification, as well as the organic sulfur transformation [187]. To minimize these limitations, more research is needed to verify the proper design, suitable conditions, and practical approach for the utilization of sewage sludge using anaerobic digestion and gasification technology.

9. Conclusions and Future Prospects

A proper sewage sludge management approach in the context of the circular economy is of great interest at present. Due to sewage sludge's high content of organic, toxic, and heavy metal pollutants, the disposal of this sludge is difficult and poses serious environmental risks. However, converting sludge to energy recovery via anaerobic digestion and gasification processes has proved to be an effective approach to waste valorisation. Although studies have looked at the various pretreatment methods that can be used to improve the quality of sewage sludge as feedstock, little attention has been paid to increasing the fuel quality of the gas produced through anaerobic digestion and gasification. We therefore propose that further research should examine the energy value of the combined biogas and syngas, as well as seeking suitable, economical ways of separating the biogas and syngas. For maximum energy recovery, digestate from the anaerobic digestion process should be subjected to the gasification process for syngas production, while paying attention to the cost–benefit analysis of the individual process.

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