Sci Tech
العلوم والتكنولوجيا
Science Today
ISSN: 3078-994X

A Review of the Gasification of Organic Waste Obtained from Wastewater

Umama Minahil[1], Marcelo Fossa da Paz[2]*

[1]*Department of Chemistry, University of Agriculture Faisalabad, Pakistan*

[2]*Faculty of Biological and Environmental Sciences, Federal University of Grande Dourados, Brazil*

Submitted: 22-01-2026; Accepted: 27-05-2026; Published: 01-07-2026

Abstract

Gasification of sewage sludge provides a renewable solution to the problem of organic waste, transforming it into useful products in the form of syngas and biochar, and other forms of energy carriers. The objective of this review is a detailed study of sewage sludge gasification with an emphasis on the variety of technologies, the mechanisms of the reaction, and the difficulties inherent in the process. The review starts with a discussion of the physicochemical characteristics of sewage sludge and its gasification phenomenon. It subsequently discusses some of the methods of gasification, such as fluidized bed, entrained flow, and supercritical water gasification, the efficiency, merits, and disadvantages of the methods. The paper also explores the chemical reactions that rule the process of gasification and the process of producing syngas and how temperature, pressure as well as the catalyst help improve yields. The main issues of sludge gasification which are discussed in the review include the formation of tar, the behavior of ash, and the prevention of heavy metal emission. Lastly, it comments on the possibilities of incorporating sewage sludge gasification into the framework of a circular economy, which provides future research and technological prospects. The aim of this review is to become a useful source for academics, engineers and policymakers in the development of sustainable management of sewage sludge by use of gasification.

Keywords: sewage sludge, syngas, fluidized bed gasification, thermochemical conversion, gasification techniques.

Review article **Corresponding Author*, e-mail: marcelopaz@ufgd.edu.br; https://doi.org/10.71111/1-26-4-4-st-1

1. Introduction

One of the most significant environmental issues is sewage sludge, which is a by-product of wastewater treatment and has a huge amount of organic waste in it. Urbanization and the increase in intensity of wastewater treatments has overall generated an increased global production of sewage sludge. It is believed that the amount of dry sewage sludge generated around the globe is more than 20 million tons each year with high concentrations of organic carbon [1]. Although it is evident that long-standing sludge disposal techniques including landfilling and incineration are common, they tend to have severe environmental impacts that include discharge of toxic gases, heavy metals, and chronic organic pollutants [2]. Therefore, desire to come up with sustainable and energy-efficient solutions is increasing, and so have thermochemical conversion technologies such as gasification, which have demonstrated substantial prospects [3]. Sewage sludge gasification is a type of partial oxidation performed under controlled conditions on organic material, leading to production of a synthesis gas (a gas commonly referred to as syngas), essentially made up of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and the methane (CH_4) [4].

This process is a good option in recovering power and energy for use in waste because the resulting syngas can be utilized to generate power, synthesize chemicals, or to produce hydrogen. Nevertheless, the process of gasification of sewage sludge is also quite different to use of traditional lignocellulosic biomass since organic waste of wastewater origin is highly moist and contains nitrogen (N), sulfur (S) and inorganic elements [1]. Wet nature of sewage sludge with a moisture content of over 75 percent of the total weight poses problems to the traditional gasification systems that demand pre-drying of feedstock. Presence of this level of moisture requires adoption of alternative methods of gasification, including hydrothermal gasification (HTG) and supercritical water gasification (SCWG), which may utilize wet feedstock without drying [5]. Supercritical water gasification (SCWG) has received much attention since it provides a viable option of converting wet biomass such as sewage sludge. Water at super critical conditions (temperatures over 374ºC and pressures over 22.1 MPa) is a solvent and reactant that facilitates decomposition of organic materials into syngas and other useful products [6]. SCWG has been found to turn 70-90 percent of organic carbon in sewage sludge into hydrogen-rich gas, which promises a viable path to recovering resources and also as a source of renewable energy [7].

Although there has been an improvement in the development of gasification technologies, several challenges still exist. These consist of the formation of tar, nitrogen species (NH_3) and the toxicity of heavy metals in the syngas formed [8]. Such contaminants may lead to problems during the operations of the equipment, including catalyst deactivation and corrosion of gasifiers [9]. Also, alkali and alkaline earth metals can also be found in sewage sludge and serve as both catalysts and inhibitors in the gasification process, which affects yield and quality of syngas obtained [10]. Hence, good catalytic materials, operating conditions, and the optimization of the process play an important role in enhancing the overall effectiveness and the sustainability of sewage sludge gasification (Figure 1). Above are listed some modern and traditional methods of wastewater treatment by the removal of organic waste from it, along with the energy changes in each technique. This review will offer a critical examination of the procedures of gasification of sewage sludge, with concentration to hydrothermal gasification and supercritical water gasification as alternatives that could be offered to traditional gasification processes. By combining the latest research results, we will establish main challenges, gaps in modern knowledge, and possible ways to solve them, to improve the viability of sludge-to-energy technologies.

2. Methodology

2.1. Characteristics of wastewater-derived organic waste relevant to Gasification

Sewage sludge is a waste product obtained as a result of storage and processing of wastewater and is a solid and heterogeneous mixture of organic and inorganic materials, with proteins, lipids, carbohydrates, and inorganic substances being the most common. Sewage sludge is composed of major constituents which differ considerably with conditions like the wastewater treatment process, the source of wastewater as well as geographical location of the treatment plant. The solids of sewage sludge are generally 60-80% heavy water in weight and this poses a major setback to its so as to be used in thermochemical activities such as gasification since excessive moisture produce demands high amount of energy to be dried [5-11]. Besides being rich on moisture content, sewage sludge has been found to contain higher levels of nitrogen (N) & sulfur (S) compounds. Sewage sludge may contain between 2 & 6 percent of nitrogen when it is in dry weight, and sulfur content is usually approximately b/w 0.5 and 2 percent [10]. These components make gasification process complex because they may cause formation of other unwanted nitrogen species like ammonia (NH_3) & hydrogen sulfide (H_2S) during gasification reaction which are capable of inhibiting catalyst activity as well as reducing quality of syngas [6]. Moreover, such contaminants are highly harmful to environment, particularly during syngas cleanup and catalyst deactivation (Table 1) [9].

Sewage sludge producing inorganic fraction is mainly ash-forming minerals, including calcium, magnesium, potassium, sodium, iron, and silica [7]. These minerals may act as catalysts or inhibitors in the process of gasification depending on their chemical representation and concentration. As an illustration, alkali metals (e.g., potassium and sodium) can be used to optimize the gasification process as they can assist in char gasification and syngas yield, as well as silica and aluminum form slag and slag down the gasification process [10-12]. It has been indicated that the gasification rate can be 30-50% higher in presence of alkali metals in sewage sludge [8]. Heterogeneity is another important feature of sewage sludge, resulting from its differences in organic content, moisture and inorganic structure. Such changes may lead to considerable differences in the performance of gasification, such as the composition of the syngas, its yield and quality, among different things, based on the feedstock and conditions under which they operate [7]. Consequently, proper characterization of sludge feedstock such as moisture content, organic carbon content and ash composition of the feedstock plays a central role in mechanism of gasification and constant syngas production.

2.2. Sewage Sludge Gasification Techniques

Sewage sludge gasification technologies may be roughly divided into conventional dry gasification, hydrothermal gasification (HTG) and supercritical water gasification (SCWG). All these approaches have specific pros and cons based on the peculiarities of sewage sludge including moisture level, organic structure, and ash level. In dry gasification, the dry organic matter is often transformed by means of oxygen or high clarity (800-1000°C) to produce a gas, mainly referred to as syngas. Nevertheless, sewage sludge has high levels of moisture, which poses a major challenge to this process. As study [5] reveals, the energy requirement of drying sewage sludge is high thus minimizing the overall energy efficiency of the process. As shown by Zhang et al. (2019), the moisture content of sewage sludge can reach up to 75 percent and causes a high level of energy penalty in traditional gasification, with consequent low syngas production and high operational expenses. Moreover, nitrogen and sulfur in the sludge may cause ammonia (NH_3) and hydrogen sulfide (H_2S) formation that undergo further treatment and clean-up procedures [9]. Better pathways to wet feedstock include hydrothermal gasification (HTG), supercritical water gasification (SCWG), because wet sewage sludge can be fed in process without requirement of its drying. HTG is conducted under temperatures of 300-400ºC and pressures in range of 5- 25 MPa, and SCWG is conducted under supercritical conditions (temporarily over 374°C and pressure of 22.1 Mpa) [6]. The two techniques both use water as a solvent and reactant, which contributes to the process of gasification by decomposing organic matter more efficiently.

It was discovered in the study [13] that SCWG was capable of transforming 80-90 percent of organic carbon of sewage sludge into hydrogen-rich syngas, which is also a highly efficient process in comparison to dry gasification. Nevertheless, HTG and SCWG do not lack difficulties. These mechanisms may lead to the formation of tar and other organic substances that can plug the reactors and lower the efficiency of gasification, which is emphasized in the research [8-10]. It is mentioned in study [2] that the alkali and alkaline earth metals of sewage sludge are capable of catalyzing gasification process, increasing yields of syngas & decreasing tar formation, whereas high concentrations of these elements can cause the formation of slagging and blockages in mechanism. Catalysts have been demonstrated to enhance syngas production especially in SCWG process as reported in research [14]. Comparative studies on various forms of gasification through the work in [6] also revealed that SCWG provides highest content of hydrogen in syngas but process is not cheapest since it requires pressures & specific equipment. To conclude, every technology of gasification has both advantages and disadvantages. Traditional dry gasification can work with a dry feedstock, sequestration is less efficient with sewage sludge, as it is very damp. HTG and SCWG, on other hand, have great potential in wet feedstock, but they associated with problems of tar formation, catalyst consumption, and cost of operations. Following is a reaction pathway that includes conversion of organic waste into ash by going through various processes and giving away several byproducts (Figure 2).

2.3. Composition of the Syngas

The gasification process of sewage sludge to produce syngas relies on a variety of factors, such as the gasification process, the feedstock characteristics, and the operating condition, to create quality and composition syngas. Hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) are the key components of syngas and the target proportion of each gas in the syngas will depend on the intended application of the syngas. Syngases with high ratings of hydrogen are especially useful in hydrogen production and fuel cells, whereas high CO and CH_4 ratios are more essential in power generation and synthesizing chemicals [11]. In the case of dry gasification, research indicates that the resulting syngas is high in CO, CO_2 and CH_4 contents and comparatively low in H_2 levels. Study [2] indicates that yield of H_2 in traditional gasification can vary b/w 25 and 45 percent, with rest of gas mainly containing CO and CO_2. According to research [15], existence of sulfur and nitrogen compounds in sewage sludge may result in appearance of undesired gases, including ammonia (NH_3) and hydrogen sulfide (H_2S), which reduces quality of swine gas, and demands further views to purify it. Sewage sludge is low in nitrogen and contains a large amount of sulfur, thereby favoring generation of sulfur compounds that are capable of poisoning catalysts & reducing effectiveness of downstream processes (Table 2) [9]. By contrast, hydrothermal and supercritical water gasification (SCWG) processes yield much more hydrogen-enriched syngas.

According to study [13], SCWG is capable of producing syngas with up to 60-70 percent hydrogen content on a unit basis, which is why it is a promising opportunity in hydrogen production. The reason behind this is the fact that supercritical water is not only a solvent but also a reactant and it can help convert complex organic matter into simple gases which are mostly hydrogen and carbon monoxide. Research [6-10] likewise indicates that tar, which would otherwise be generated in the course of dry gasification, can be minimized with SCWG, resulting in cleaner syngas with less contaminants. Research [6] compared fluidized bed gasification and SCWG of sewage sludge in their study and observed that SCWG was much higher in terms of hydrogen content, but it is also more expensive as it requires a high pressure and specialized reactors. In addition, alkali metallic elements like potassium and sodium commonly present in sewage sludge improves the gasification process, particularly in SCWG, by facilitating the decomposition of organic substances and increasing the production of hydrogen [8]. To sum up, although dry gasification could be a lower cost option in case of non-wet feedstock, the hydrothermal and supercritical water gasification processes can generate better-quality syngas, particularly in terms of hydrogen content. Nevertheless, all these processes are costlier in terms of operations because they require specialized equipment and elevated pressures (Figure 3).

2.4. Gasification Mechanism and Reaction Chemistry

Thermochemical reactions occurring during the gasification of organic wastes obtained in wastewater are rather complex; they are sensitive to the chemical structure of wastewater sludge, the medium of reaction and the conditions of operation. Sewage sludge has a greater proportion of proteins and lipids compared to lignocellulosic biomass, which have a strong impact on devolatilization behavior and gas-phase reactions during the gasification process [1-10]. As indicated by the study [16], in a thermal decomposition process, first stage of process is decomposing sludge within the temperature range of 200-500 degC and in the process proteins are decomposed to give out nitrogen-containing volatiles and lipids are also decomposed to form long-chain hydrocarbons which can be tar precursors. There are two most common reactions in traditional dry gasification: char gasification ($C + H_2O = CO + H$ 2), Boudouard reaction ($C + CO_2 = 2CO$), and water-gas shift ($CO + H_2O = CO_2 + H_2$) [17]. It was reported in research [6] which evidenced that, by fluidized-bed gasifying municipal sewage sludge an increase in temperature between 750 and 850ºC resulted in a higher conversion rate of char but also led to discharge of more nitrogen to gaseous phase. Conversely, research [18] established that steam gasification enhances increased hydrogen production but concomitantly elevates production of ammonia, given that protein cracking in the latter research is heightened. Unlike dry gasification, hydrothermal and supercritical water gasification is a process that brings in different reaction mechanisms. Organic matter is hydrolyzed, reformed, and subjected to reactions of water-gas shift in one-phase environment in subcritical and supercritical water [13].

Research [13] also asserted that hydrothermal conditions prefer the quick de-polymerization of proteins and carbohydrates into small oxygenated substances, which are further reformed into H_2 and CO_2. The initial experiments by Modell [19] demonstrated that supercritical water inhibits altogether the formation of char; the reaction route of the reaction is switched to products in gas phase. Comparative analysis shows that SCWG has achieved high carbon conversion efficiency when compared to dry gasification. Studies done in [14] had reported carbon conversion rates of more than 85 percent, whereas the traditional fluidized-bed systems usually show 60-75 percent conversion of sewage sludge [6]. In addition, Matsumura in study [20] emphasized that in the vicinity of distribution of critical point, ionic product of water is accelerating reforming reactions, which increase amount of hydrogen produced (Table 3). Nevertheless, impact of catalytic effects differs greatly in accordance with inorganic content of sludge. In their study [21], Jiang observed that natural alkali and alkaline Earth metals facilitate gasification reaction with char, and excess calcium and silica may hinder conversion process by developing refractory phases.

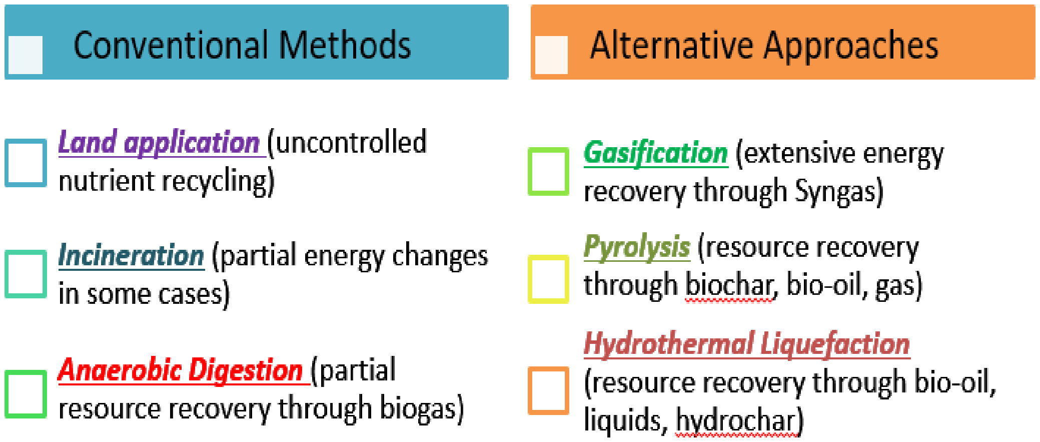

Figure 4. Wastewater Sludge Treatment Methods and energy changes in them

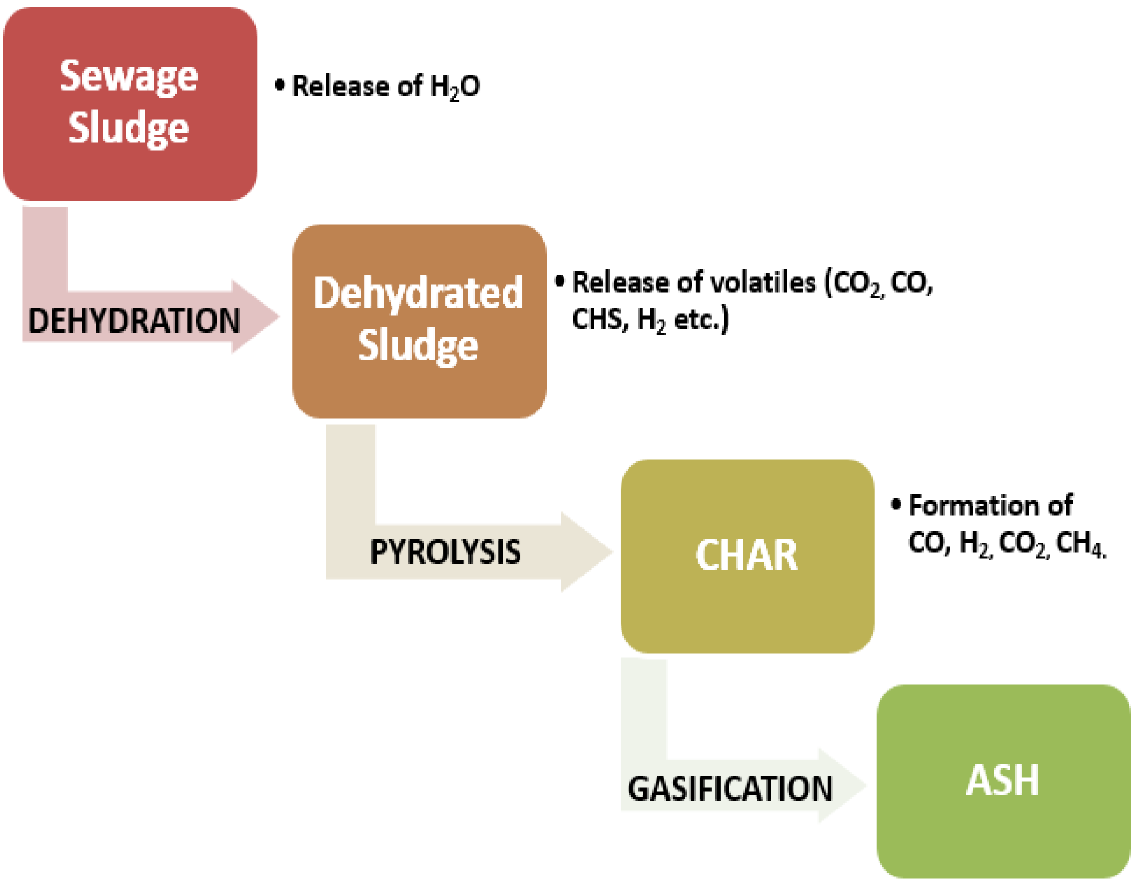

Figure 5. Reaction pathway for organic waste gasification

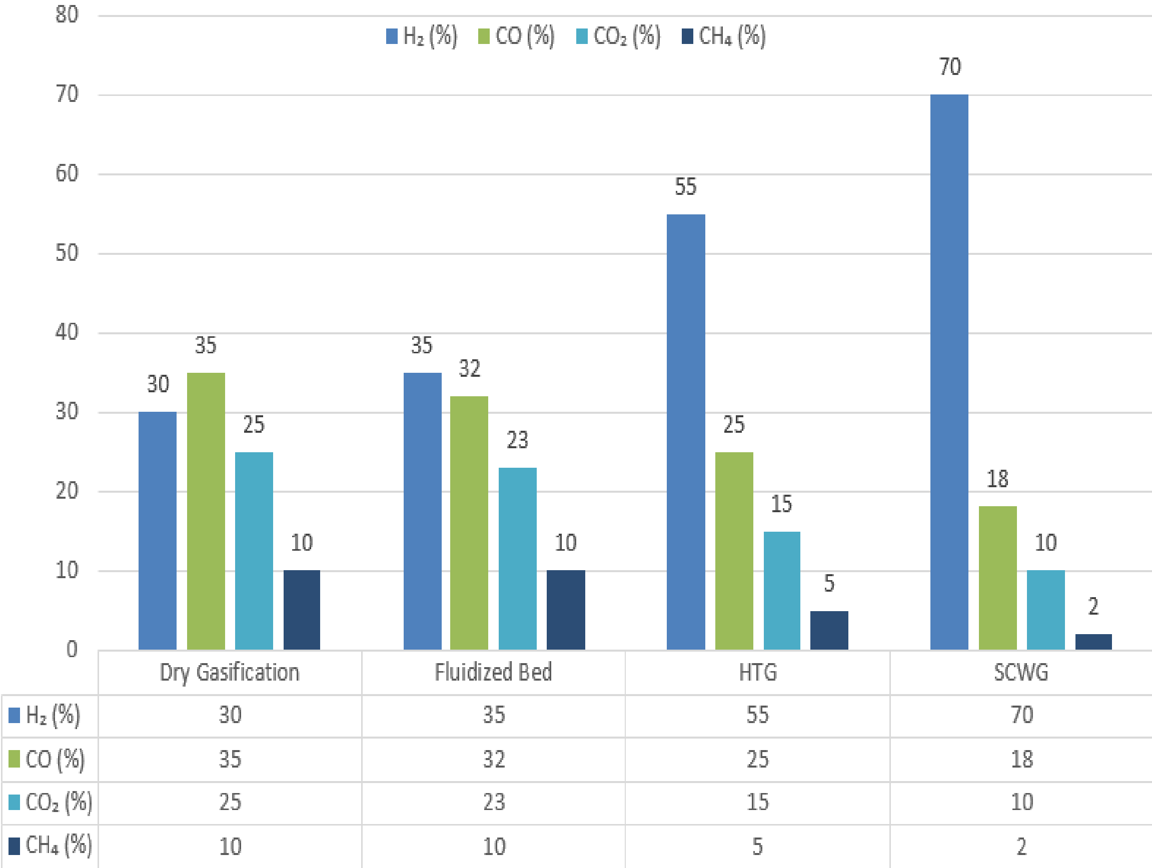

Figure 6. Syngas Composition Across Gasification Technologies

Table 4. Physicochemical Composition of Sewage Sludge

Parameter	Typical Range in Sewage Sludge	Supported References
Moisture (%)	70–85	(3, 9)
Volatile Matter (%)	45–65	(3, 9)
Fixed Carbon (%)	5–15	(3)
Ash (%)	20–45	(9, 28)
Nitrogen (%)	2–6	(9)
Sulfur (%)	0.5–2	(14)

Table 5. Comparison of Gasification Technologies

Technology	Temperature (°C)	Pressure	Carbon Conversion (%)	Key Advantage	Limitation
Dry Gasification	800–1000	Atmospheric	60–75	Mature tech	Drying needed
Fluidized Bed Gasification	750–900	Atmospheric	55–70	Stable syngas	Ash agglomeration
Hydrothermal Gasification	300–400	5–25 MPa	70–85	Wet feedstock	Tar formation
SCWG	>374	>22.1 MPa	80–95	High H_2 yield	High cost

Table 6. Operational Challenges and Mitigation

Challenge	Cause	Impact	Mitigation Strategy	References
Tar formation	Protein cracking	Reactor fouling	Catalysts	(9,16)
Slagging	Ash melting	Bed blockage	Temp control	(12,19)
NH_3 formation	High N content	Gas cleanup load	Gas scrubbing	(8,16)
Heavy metals	Zn, Pb volatilization	Emission risk	Phase separation	(14,28)
Catalyst poisoning	Sulfur	Yield loss	Sulfur-resistant catalysts	(21,22)

In general, reaction behavior of sewage sludge gasification is very system-specific & inconsistencies between studies highlight necessity of feedstock-specific mechanistic knowledge as opposed to direct extrapolation of bio-mass gasification models.

2.5. Contaminants, Ash Behavior, and Operational Challenges

Contaminants formation and intricate behavior of inorganic ash fraction represent one of the most urgent constraints of sewage sludge gasification. Sewage sludge is usually rich with higher levels of heavy metals, phosphorus, sulfur and nitrogen which directly affect the quality of gas and performance of the reactor [15-22]. The study [15] reports that sewage sludge ash can have a considerable content of Zn, Cu, Pb, and Ni that can either volatilize or condense depending on the temperature and nature of gasification. During sludge gasification, nitrogen-based compounds are of great concern. A number of literature sources indicate that up to 20-50 percent of bound nitrogen is converted to ammonia (NH_3) during the gasification process [16-23]. In their study, Thomsen [6] noted that the level of ammonia in gas formed during circulating fluidized-bed gasification of sewage sludge was high (more than 3000 ppm), and that further gas purification was seriously problematic. Likewise, Rauch in [15] observed that sludge, containing sulfur, contributes to the formation of H_2S that promotes corrosion and catalyst poisoning. Another decisive factor that determines operability of gasifier is Ash behavior. Sewage sludge ash has also substantial proportions of phosphates, iron oxides & silica in comparison with biomass ash, which may favor slagging and agglomeration [9]. Study [9] also found that the formation of slag was a noteworthy operational problem in high-temperature sludge gasification plants, especially when calcium and iron-rich ash reacts with silica to create low-melting eutectics. Contrastingly, it was found in study [7] that lower temperatures of gasification minimized slagging but led to the un conversion of carbon. Hydrothermal and supercritical water gasification have varied pathways of contaminants. According to research [24], during SCWG, heavy metals remain mostly in the solid or aqueous state, minimizing their uptake into the gas phase. Nevertheless, it is noted in studies [14-25] that under supercritical conditions salt precipitation, and reactor clogging become predominant issues, particularly when using actual sewage sludge as feed, as opposed to model compounds. Kruse [25] pointed out that in SCWG systems, the deposition of alkali salts can drastically reduce long term reactor performance. On the systems side, study [26] put forward a stance that most sludge-to-energy systems need integrated systems that combine the feedstock pretreatment, choice of catalyst and gas cleaning technology. This discrepancy in the reported contaminant behavior of studies indicates that operational problems are very site- and feed stock-specific. In its turn, this implies that ash chemistry and contaminants management must be considered to convert laboratory-scale sludge gasification to full-scale use.

2.6. Catalysts and Process Enhancement Strategies

Catalysts are important in enhancing the process of sewage sludge gasification by increasing the efficiency of carbon conversion, the yield of hydrogen and tar cracking, especially in steam and hydrothermal conditions. Through sewage sludge is unique to the lignocellulosic biomass, the large quantities of alkali and alkaline earth metals (AAEMs) including potassium, sodium, calcium, and magnesium are present and can serve as in situ catalysts during gasification [21]. This study also found that the presence of potassium and calcium facilitates the char-steam reaction, which enhances the gasification of kinetics and enhances the production of hydrogen. Not all catalytic effects reported in literature are positive though. Study [21] also demonstrated that moderate levels of AAEM increase process of steam gasification, whereas higher levels of calcium suppress reactivity by creating stable mineral phases. In the same way, research [6] has found that the catalytic activity of ash-rich sewage sludge was lower than expected because active metal species were encircled in phosphate matrices. These results emphasize that catalytic behavior is closely influenced by sludge ash chemistry and not inherent metal content by itself. Sewage sludge gasification has also been analyzed using external catalysts. It was found that Ni-based catalysts used by study [3] improved greatly in hydrogen yield when used in catalytic hydrothermal gasification of sludge-derived liquids and that they reached hydrogen concentrations of over 60% vol.

However, study [5] obtained opposite conclusion, where alkali-promoted catalysts displayed greater stability in supercritical water conditions compared to traditional transition-metal catalysts which experienced sintering and sulfur poisoning. These results indicate that the selection of catalysts should consider the severity of the chemical conditions, such as rich content of sulfur and nitrogen, in sludge gasification. Catalysis has also been studied as process enhancement strategies. As study [16] state, sewage sludge co-gasification with biomass or refuse-derived fuel (RDF) can dilute the unwanted ash content and enhance the quality of the syngas. Research [6] had noted enhanced stability of gasification with co-gasification of sludge with woody biomass in circulating fluidized beds. Moreover, it has been established that microwave-assisted pretreatment increases reactivity of sludge by destabilizing organic structures and increasing devolatilization behavior [4]. In general, the literature has shown repeatedly that catalysis and process optimization may considerably increase the effectiveness of sludge gasification, but they are strongly affected by feedstock variation. This was achieved by the results that were in contrast to those reported in research and highlights the importance of sludge catalyst specific design and not a direct transfer of biomass gasification strategies.

2.7. Future Implications and Research Suggestions

Although great improvements have been made in the sewage sludge gasification, there are still several research and technical gaps. One limitation that is found repeatedly in the literature is the unavailability of long-term pilot- and full-scale data of operations especially in the conditions of real wastewater sludge. The majority of experimental studies make use of model compounds or dried sludge, which probably do not reflect on actual feedstock complexity. Stability of catalysts is a crucial issue. Although catalytic enhancement has also been enhanced with higher yields of hydrogen, several studies have recorded the rapid catalyst deactivation that could have been caused by sulfur poisoning, ash deposition, and sintering of metals. Moreover, discrepancies within reported syngas composition, tar development pace and carbon-converting efficiencies in several gasification platforms clearly show that experimental procedures should be standard. Integration of gasification and nutrient and phosphorus recovery is another frontier that has not fully been explored despite the fact that sludge ash yields removable useful minerals. Lastly, techno-economic and life-cycle assessments are still limited, and systemic-wide sustainability measurements are necessary to make sustainability commercial. The only way to ensure that sludge gasification passes out of the laboratory phase is to handle these gaps.

3. Conclusions

Gasification proves to be an encouraging avenue of wastewater-derived organic waste valorization, which has the potential to generate renewable energy and reduce the waste volume and to reclaim the resources. In summary of the reviewed papers, supercritical and hydrothermal gasification yields a high carbon conversion efficiency and hydrogen-enriched syngas relative to traditional dry gasification, especially using wet sewage sludge. However, operational issues, such as the formation of tar, slagging caused by ash, emissions of contaminants, and the degradation of catalysts, are still some of the obstacles impeding the large-scale implementation. Comparative studies also point out that the performance of the gasification process is extremely sensitive to the feedstock makeup, the reactor design, and integration strategies of the processes, which explains the differences in efficiencies and syngas output observed. Although the co-gasification and catalytic refinements provide performance benefits, it is still economically limited due to costs of capital and complexity of the system. In general, the evidence examined indicates that sewage sludge gasification is technically feasible, but it needs further improvements in reactor design, catalyst life, control of contaminants and combined recovery of resources. Sludge gasification can be a long-lasting, sustainable component of a wholesome practice of wastewater reuse with specific research and with supporting policy frameworks.

References

[1] L. Zhang, C. Xu, P. Champagne, W. Mabee. (2014). Overview of current biological and thermo-chemical treatment technologies for sustainable sludge management. Waste management & research. 32(7): 586-600.

[2] Q. Zhang, J. Hu, D.-J. Lee, Y. Chang, Y.-J. Lee. (2017). Sludge treatment: Current research trends. Bioresource Technology. 243: 1159-1172.

[3] X.-P. Zhang, C. Zhang, X. Li, S.-H. Yu, P. Tan, Q.-Y. Fang, G. Chen. (2018). A two-step process for sewage sludge treatment: Hydrothermal treatment of sludge and catalytic hydrothermal gasification of its derived liquid. Fuel Processing Technology. 180: 67-74.

[4] A. Zaker, Z. Chen, X. Wang, Q. Zhang. (2019). Microwave-assisted pyrolysis of sewage sludge: A review. Fuel Processing Technology. 187: 84-104.

[5] T.L.-K. Yong, Y. Matsumura. (2012). Catalytic gasification of poultry manure and eucalyptus wood mixture in supercritical water. Industrial & engineering chemistry research. 51(16): 5685-5690.

[6] T.P. Thomsen, Z. Sárossy, B. Gøbel, P. Stoholm, J. Ahrenfeldt, F.J. Frandsen, U.B. Henriksen. (2017). Low temperature circulating fluidized bed gasification and co-gasification of municipal sewage sludge. Part 1: Process performance and gas product characterization. Waste Management. 66: 123-133.

[7] S. Werle, M. Dudziak, Gasification of sewage sludge. In *Industrial and municipal sludge*, Elsevier: 2019; pp 575-593.

[8] K. Śpiewak, G. Czerski, K. Bijak. (2021). The effect of temperature-pressure conditions on the RDF gasification in the atmosphere of steam and carbon dioxide. Energies. 14(22): 7502.

[9] M.C. Samolada, A.A. Zabaniotou. (2014). Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for a sustainable sludge-to-energy management in Greece. Waste Management. 34(2): 411-420.

[10] S.S.A. Syed-Hassan, Y. Wang, S. Hu, S. Su, J. Xiang. (2017). Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. Renewable and sustainable energy reviews. 80: 888-913.

[11] S. You, Y.S. Ok, D.C. Tsang, E.E. Kwon, C.-H. Wang. (2018). Towards practical application of gasification: a critical review from syngas and biochar perspectives. Critical Reviews in Environmental Science and Technology. 48(22-24): 1165-1213.

[12] K. Śpiewak. (2024). Gasification of Sewage Sludge—A Review. Energies. 17: 4476.

[13] C. He, C.-L. Chen, A. Giannis, Y. Yang, J.-Y. Wang. (2014). Hydrothermal gasification of sewage sludge and model compounds for renewable hydrogen production: A review. Renewable and sustainable energy reviews. 39: 1127-1142.

[14] S.N. Reddy, S. Nanda, A.K. Dalai, J.A. Kozinski. (2014). Supercritical water gasification of biomass for hydrogen production. International Journal of Hydrogen Energy. 39(13): 6912-6926.

[15] R. Rauch, J. Hrbek, H. Hofbauer. (2016). Biomass gasification for synthesis gas production and applications of the syngas. Advances in Bioenergy: The Sustainability Challenge. 73-91.

[16] N. Gao, K. Kamran, C. Quan, P.T. Williams. (2020). Thermochemical conversion of sewage sludge: A critical review. Progress in Energy and Combustion Science. 79: 100843.

[17] U. Arena. (2012). Process and technological aspects of municipal solid waste gasification. A review. Waste Management. 32(4): 625-639.

[18] N. Nipattummakul, I.I. Ahmed, S. Kerdsuwan, A.K. Gupta. (2010). Hydrogen and syngas production from sewage sludge via steam gasification. International Journal of Hydrogen Energy. 35(21): 11738-11745.

[19] M. Modell, Gasification and liquefaction of forest products in supercritical water. In *Fundamentals of thermochemical biomass conversion*, Springer: 1985; pp 95-119.

[20] Y. Matsumura, T. Minowa, B. Potic, S.R.A. Kersten, W. Prins, W.P.M. van Swaaij, B. van de Beld, D.C. Elliott, G.G. Neuenschwander, A. Kruse, M. Jerry Antal Jr. (2005). Biomass gasification in

near- and super-critical water: Status and prospects. Biomass and Bioenergy. 29(4): 269-292.

[21] L. Jiang, S. Hu, Y. Wang, S. Su, L. Sun, B. Xu, L. He, J. Xiang. (2015). Catalytic effects of inherent alkali and alkaline earth metallic species on steam gasification of biomass. International Journal of Hydrogen Energy. 40(45): 15460-15469.

[22] K. Fijalkowski, A. Rorat, A. Grobelak, M.J. Kacprzak. (2017). The presence of contaminations in sewage sludge–The current situation. Journal of environmental management. 203: 1126-1136.

[23] P.M. Lv, Z.H. Xiong, J. Chang, C.Z. Wu, Y. Chen, J.X. Zhu. (2004). An experimental study on biomass air–steam gasification in a fluidized bed. Bioresource Technology. 95(1): 95-101.

[24] L. Qian, S. Wang, D. Xu, Y. Guo, X. Tang, L. Wang. (2016). Treatment of municipal sewage sludge in supercritical water: A review. Water Research. 89: 118-131.

[25] A. Kruse. (2008). Supercritical water gasification. Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy. 2(5): 415-437.

[26] R.R. Bora, R.E. Richardson, F. You. (2020). Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: a comprehensive review. BMC Chemical Engineering. 2(1): 8.