Gasification of sewage sludge under fluidized bed condition

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DECLARATION

I hereby, declare that this manuscript, entitled “*Title of your Master Thesis*”, is the result of my own work except for quotations and citations, which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or intentional institution.

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Abstract

Gasification of sewage sludge (SS) is a thermochemical process that converts sludge particles into syngas, providing an environmentally acceptable alternative to the usual methods of SS disposal, such as landfilling, agricultural land application, and incineration. The present study investigates the gasification of SS in a fluidized bed. Specifically, it explores the influence of several important operation parameters which is temperature, equivalence ratio (ER), and steam-to-fuel ratio (S/F) on the product syngas composition. The experiments were carried out at 650°C, 750°C, and 850°C; ER of 0.2, 0.3, and 0.4; and S/F ratios of 0.5, 1, and 1.5. In total, 36 experiments were performed. This study demonstrates a direct correlation between temperature and hydrogen and carbon monoxide production levels and an inverse correlation between temperature and carbon dioxide and methane formation rates. Aerobic activity has a positive influence on organic matter degradation, identified the value of 0.2 as the optimal ER, which yielded the highest yields of hydrogen and carbon monoxide. It further promoted water-gas shift reactions, which increased hydrogen generation as S/F increased, but the optimal S/F that led to the highest hydrogen production was above the range used in this study. The experimental data was further validated with Aspen Plus process simulation which showed similar correlation between trends of operating parameters with syngas composition, however simulation results showed higher hydrogen generation compared to experimental results.

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List of Abbreviations & Symbols (Example)

P	Static pressure
T	Temperature
SS	Sewage sludge
ER	Equivalence ratio
S/F	Steam to fuel ratio
H_2	Hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
N_2	Nitrogen

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Chapter 1 – Introduction

1.1. Background

The global population growth and urbanization has triggered the significant increase of wastewater discharge, which led to growing demands for municipal wastewater treatment plants. These treatments generate considerable quantities of sewage sludge as an end product, which raises significant issues in terms of safe, sustainable and economical disposal methods. Currently, about 160 million tonnes of dry sewage sludge is generated globally each year and this number is increasing with population growth [1]. Landfilling, incineration, and agricultural application are conventional disposal methods scrutinized for their related greenhouse gas emissions, heavy metal pollution potential, odor nuisance, land use requirements, and growing regulators [2].

The most widely adopted sewage sludge management method is land disposal—popular for its reasonably low cost—followed by land application. The use of SS in agriculture is considered a source of nutrients, due to its content of macroelements (Ca, K, PO_4) and microelements (Fe, Zn, Cu, Mn) [3]. However, the presence of alongside pathogenic microorganisms in SS brings a serious threat to environmental health due to heavy metals in the sewage sludge. Incineration is another management practice; though it helps to reduce large quantities of SS through the destruction of pathogens—there are many carbon emissions leading to air pollution. These disadvantages reflect urgent need for alternative methods which aims at sustainable technologies for sewage sludge treatment.

Gasification is one of the promising thermal treatment processes for converting sewage sludge into syngas with the least pollution, which has been regarded as a potential way to enhance the sewage sludge valorization. Whether based on advanced technologies or other environmental measures, these have proven inadequate in allowing for realisation of all principles of circular economy or waste-to-energy operations in the context of efficient waste management strategies in place.

1.2. Motivation

The generation of municipal wastewater treatment leads to an increasing volume of sewage sludge (SS), which poses a considerable challenge and gives a chance for sustainable waste management. Yet, because of the increasing environmental impacts of landfilling, incineration, and agricultural application, the development of new, economically successful of waste management alternatives remain urgent and mandatory [4].

One of the most promising techniques aiming at reducing waste volume is thermochemical gasification [5], whereby organic matter is converted into a gas mixture known as syngas that serves as a valuable fuel for heating, electricity production, or chemical synthesis. It not only increases energy recovery but also reduces the yield of pollutants such as NO_x and dioxins compared to traditional combustion or anaerobic digestion technologies [6].
Gasification complements circular economy strategies in that it allows for energy and nutrients to be recovered from waste.

However, comprehensive experimental studies coupled with process modeling taking into consideration important parameters such as temperature, equivalence ratio (ER), and steam-to-fuel ratio (S/F) are scantily available especially with air+steam environment. This integration is important for syngas quality optimization, reactor stability and ultimately process efficiency. Motivated by these challenges and opportunities, this study is undertaken to systematically improve the understanding of sewage sludge gasification in fluidized bed systems through targeted experiments complemented with advanced process models, ultimately to help drive the development of efficient, scalable, and sustainable SS gasification technologies.

1.3. Research Objectives

This study investigates the gasification of sewage sludge in a bubbling fluidized bed reactor, focusing on key parameters such as various gasifying agents (air, air-steam and steam), bed temperature, ER, and S/F ratio and their effect on syngas composition. A systematic parametric study was conducted to identify optimal conditions that enhanced syngas yield and its quality. In addition, the Aspen Plus model was built to gain a deeper understanding of the process, providing valuable insights into efficiency improvements and performance optimization. By integrating both experimental and simulation approaches, this study offers a comprehensive perspective on advancing gasification technology. Steam gasification of sewage sludge, in particular, is a less investigated area compared to other biomass feedstocks. While most earlier research has concentrated on using various biomass waste under oxygen and air as gasifying agents, this study assesses steam-assisted gasification and a systematic parametric study. The research advances the technology of sewage sludge gasification and holds particular relevance for the central asian region, in particular to Kazakhstan, wherein circular economy initiatives and sustainable waste-to-energy solutions are urgently needed to be addressed.

The specific objectives of this study are as follows:

- To investigate the effects of reactor temperature, equivalence ratio, and steam to fuel ratio on syngas composition and tar formation.
- To conduct mass balance analysis across different operational conditions.
- To analyze the characteristics of the residual ash, with emphasis on its composition,
- To develop and validate a simulation model using Aspen Plus to predict syngas composition.
- To identify optimal gasification conditions that maximize syngas quality and process efficiency while minimizing environmental risks and operational challenges.

1.4. Constraints

In Scope

- The study is limited to the gasification of dry municipal sewage sludge. Other types of biomass are not considered.
- Experiments are performed using a lab-scale bubbling fluidized bed reactor.
- The research focuses on manipulating temperature (T), equivalence ratio (ER), and steam-to-fuel ratio (S/F) only.
- The study includes the analysis of non-condensable gas composition, mass balance, and ash characterization, particularly elemental analysis of ash.
- A steady-state process model is developed using Aspen Plus.

Out of Scope

- Detailed drying analysis of SS.
- The use of catalysts or any additions to the feedstock.
- Tar analysis.
- Life Cycle assessment (LCA), and economic feasibility.

Chapter 2 – Literature Review

2.1. Overview of Sewage Sludge Management

SS is the residual semi-solid material that is produced as a by-product of municipal and industrial wastewater treatment. The rapid development of urbanization, industrial establishment, and waste disposal infrastructure across the globe has led to a considerable global generation of sewage sludge of about 160 million tons/year [1]. Managing and disposing of this byproduct poses significant technical, environmental, and economic challenges.

Sewage sludge is highly heterogeneous, being composed of a complex mixture of organic matter, inorganic solids, microbial biomass, heavy metals, and multiple trace contaminants, and its composition highly depends on previous use. Characterization of the sludge depends considerably on the kind of influent wastewater and the treatment process used [7]. Moreover, its thermal conversion is more complex than that of biomass, mainly due to its high moisture content (which can be 70% to 90%) and high ash content.

Existing sludge management methods comprise landfilling, land-based application, with an emphasis on nutrient recovery, incineration, composting and-with increasing popularity-thermochemical conversion technologies. Although this casein was generally done as the main way of sludge refuse materials or for biowaste utilization practices like biomethanation & anaerobic processing through the use of landfilling, constraints such as decreased readily available area and also possible leachate contamination danger along with methane discharges served to rebut against this method. At the same time, however, the use of agricultural application is encountering increasing limitations due to growing concerns about heavy metal accumulation as well as emerging pollutants such as pharmaceuticals and microplastics [8].

Owing to such trade-offs, incineration merely achieves volume reduction (achieves removal of pathogen agents but entails high cost in terms of energy, moreover, because of pollutant such as dioxins and furans, requires advanced flue gas cleaning system). Akin alternative methods such as composting biodigestion prove more eco-friendly but have limitations with space needed,time taken and associated smell.

But not some conventional processes did not have an economic feasibility resulting in fewer industrial implementations compared to thermochemical ones which are not gaining momentum through these comparative records [8]. Therefore, the viewpoint that we hold on sewage today is completely different; sewage is no longer merely considered disposal burden through which waste has to be thrown, but has come to potentially mean renewable source from which valuable materials can be captured to shift role towards sustainability ethos.

2.2. Thermochemical Conversion of Sewage Sludge

Thermochemical conversion is one of the most promising technologies and has become a feasible alternative to conventional sludge disposal processes, such as sewage sludge energy recovery. High-temperature chemical processes convert organic matter to valuable carriers of energy, typically in oxygen-limited or devoid environments. In general, the main thermochemical process that can be applied to sewage sludge includes combustion, pyrolysis, and gasification; all of which have different operating conditions, product factors, and environmental impacts.

Combustion is the most common thermal method that directly converts feedstock into heat through complete oxidation. Although the process can decrease volume and inactivate pathogens, its thermal energy efficiency for high-water-content materials such as sewage sludge is comparatively low. Moreover, a large amount of nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter, and trace organic pollutants such as dioxins and furans [9] are produced during this process. This then necessitates considerable investment into flue gas treatment systems to comply with current emissions standards, making it economically difficult to justify.

Alternatively, pyrolysis thermally decomposes sludge anaerobically between 300–700°C to give three major products: biochar, bio-oil and syngas. While pyrolysis can result in valuable solid and liquid outputs, there are difficulties in utilizing it for sewage sludge as its liquid production rate is too low, and it incorporates heavy metals and halogens among some other contaminants, which are either preserved in the biochar or pollute the produced oil [10]. The composition of raw materials can also vary, which magnifies the effect on process stability and product quality.

Gasification typically happens at 700–1000°C under strictly controlled circumstances with trace amounts of oxygen or steam. This process also transforms organic material to syngas, a flammable mixture mainly consisting of H_2, CO, CO_2,and CH_4, that could be used for heating applications or electricity production or as building blocks for the generation of liquid fuels and chemicals [11]. Gasification emissions are orders of magnitude lower than those of combustion with byproduct formation much easier to handle. Furthermore, the syngas energetic value is further improved by process optimization, especially steam as the gasifying agent.

Conventional thermochemical conversion processes utilized to treat sewage sludge are proprietary thermal conversion technologies that require high moisture content & high ash & low heating value nonbiodegradable materials, while gasification is also suitable for treating wet feedstocks with high ash suitable for fluidized bed systems, as these systems give fairly uniform temperature distribution, feedstock adaptability and good mixing properties [12], which further provides opportunities such as biomass co-gasification and catalyst use to be studied for improving conversion efficiencies and reducing tar generation.

On a broader scale, thermochemical conversions, especially gasifications, not only emerge as solutions with new methods of waste management strategy by integrating recurring waste into the energy generation but also more closely approach renewable energy elements. With respect to the increasing engagements on the concepts of circular economics integrated with assessment of energy recovery from waste streams, it is paramount that alternative sustainable means for energy recovery as sludge processing routes should be given priority in terms of applications in future.

2.3. Fundamentals of Gasification

Gasification is a thermochemical method performed at high temperatures to convert carbonaceous materials into a combustible gas mixture called syngas. This process takes place in an oxygen controlled environment using air, steam, or pure oxygen and usually functions at temperatures of 700°C to 1000°C, with the composition of syngas obtained is sensitive to the type of input and operating conditions, but typically can contain large quantities of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and small amounts of the other hydrocarbons [13]. Gasification is a series of complex physical and chemical reactions, which can be divided into four main stages:

- Drying: In the first stage, moisture is removed from the feedstock at temperatures < 200°C; although non-reactive in nature the dryer employs energy input and is an important step that can significantly influence the overall thermal efficiency.
- Pyrolysis: In this reaction the dried biomass or sludge is thermally reduced in the absence of oxygen which leads to the formation of char and tar along with the release of volatile compounds. Pyrolysis usually occurs at temperatures between 300 and 600°C [14].
- Oxidation (Partial Combustion): Here is where small amounts of air or oxygen are mixed with remaining carbon and volatiles resulting in CO and CO_2 creation followed by heat burn-off, which causes heat that can be used for promoting later-endothermic responses—this is an important part in sustaining thermal balance all along the process.
- Reduction: The last stage features endothermic reactions between residual char (C) and oxidants (CO_2 and H_2O) resulting in syngas production between:
  Boudouard reaction: $C + CO_2 \rightarrow 2CO$
  Water-gas reaction: $C + H_2O \rightarrow CO + H_2$
  Water-gas shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$
  Methanation: $CO + 3H_2 \leftrightarrow CH_4 + H_2O$ [15]

Thus, their respective equilibrium is affected by different variables; such as operating temperature, equivalence ratio (ER), the selection of the gasifying agent, in other words: which gasifying agents are applied air versus steam/air ratios, residence times during processing durations corresponding with feedstock types; as a rule, usually providing higher hydrogen & carbon monoxide yields at higher temperatures and lower-temperature conditions with higher steam presence directing towards methane & tar formations instead [15].

This is particularly important, as equivalence ratio, which is the ratio of the actual air-to-fuel compared to the stoichiometric air-to-fuel requirement, typically takes a range of values around 0.20–0.40, which show significant oxidation but adequate (>0) levels during gasification are maintained [15].

Moreover, the choice of the types of the gasifying agent used influences both the composition of syngas and its heating value. Air-based gasification systems are more widespread due to their cost-effectiveness, but lead to dilution with nitrogen that lowers calorific values. However, the steam based methods are suitable for hydrogen production with reduction of dilutive effects that accept more heat input [16]. Considering sewage sludge specifically, its persistent high ash content, presences of heavy metals and inherent heterogeneity create specific challenges. But, this process can provide syngas having heating values ranging between 4−8 MJ/Nm3 utilized for applications such as thermal energy generation or power production, or provides substrates to synthetic fuels production[17].

2.4. Influence of Operating Parameters

Process parameters in SS gasification in a fluidized bed reactor, including temperature, equivalence ratio (ER), and steam-to-fuel ratio (S/F), have a considerable effect on both process efficiency and the characteristics of its byproducts. Because syngas composition is dependent on all of these factors, its knowledge is of utmost importance for the optimization of energy recovery and the minimization of unwanted by-products.

Khan et al. (2022) have explored the effect of operating variables, including temperature, on syngas yield and technical performance of the fluidized bed reactor system. As a result, the highest concentration of H_2 and CO was 21 vol% and 46 vol%, respectively, at 800°C [18]. According to the Śpiewak et al. (2024), higher bed temperatures enhanced endothermic reactions, such as the Boudouard reaction and steam reforming, leading to increased production of CO and H_2, which are the main components of syngas [19]. Chen et al. (2022) found that an increase of the gasification temperature from 750°C to 900°C has significantly enhanced syngas production, by improving H_2 and CO concentrations while reducing tar formation [20]. Conversely, lower temperatures tend to result in incomplete gasification, leading to the production of tar and char fractions that can hinder further downstream processes. A careful optimization of gasification temperature is essential for achieving a balance between maximizing syngas production and minimizing tar formation, and ensuring the sustainability of sewage sludge gasification processes (related mainly to the melting of the ash under reductive conditions). Equivalence ratio, the ratio between the actual oxygen supply to the stoichiometric requirement for complete combustion, is another critical parameter in the gasification. Lower ER values lead to an oxygen-lean environment that favors high yields of H_2 and CO, while suppressing heat production by oxidation [21]. In contrast, higher ER conditions promote more extensive (heat releasing) oxidation, which increases the formation of CO_2 and water vapor, ultimately reducing the calorific value of the produced syngas [22]. Steam-to-fuel ratio (S/F) also strongly influences the syngas composition, tar formation, and overall conversion efficiency. Increasing the S/F generally enhances the water–gas shift reaction ($CO+H_2O \leftrightarrow CO_2+H_2$), which raises the H_2 content in the produced syngas while simultaneously reducing tar and residual char by promoting steam reforming ($C_xH_y+xH_2O \rightarrow xCO+(y/2+x)H_2$) and heterogeneous water gas ($C+H_2O \rightarrow CO+H_2$) reactions (Qin et al., 2011) [23]. However, excessive steam can also dilute the calorific value of the syngas, emphasizing the need for an optimal balance. In the study of Pala et al. (2016), authors demonstrated that an optimal S/F not only maximizes cold gas efficiency but also improves the H_2/CO ratio, thereby enhancing fuel quality for downstream applications [24]. The interplay between these operating parameters is complex and requires careful optimization. For instance, while higher temperatures and appropriate S/F ratios can enhance H_2 production, they must be balanced against the ER to prevent excessive oxidation or char formation.

For this reason, the operating parameters of fluidized bed gasification processes using sewage sludge in order to maximize both yield and quality of syngas need to be optimized. Such a comprehensive grasp of these parameters and their influences is necessary if you're going to make headway in adopting cost-efficient and sustainable gasification technologies; therefore, more fundamental research and process-scale experiments are needed.

2.5. Syngas Quality and Utilization

2.5.1. Syngas Composition and Quality

Several factors affect the quality of syngas generated in appears gasification of SS such as the type of gasifier used, operational parameters, feedstock characteristics, etc. Syngas generally contains a combination of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and a range of trace gases. Its energy content and suitability for further applications are greatly influenced by the characteristics of the particular composition used.

In a study by Migliaccio et al. (2021) carried out fluidized bed gasification of sewage sludge with an operating temperature of 850°C and oxygen/fuel equivalence ratios of 0.1 to 0.2, produced syngas with H_2 and CO rich compositions [25]. Interestingly, higher ER and higher temperature in elevated conditions simultaneously improved calorific value while lowering tar, a main contamination factor, which prevents efficient utilization of syngas via Fischer–Tropsch synthesis reactions [25]. In a study by Vincenti et al. (2023), utilized almond-shell biomass to compare olivine to K-feldspar in a fluidized bed gasifier environment [26]. K-feldspar performed more favorably than alternative materials, giving higher yields of H_2 and CO and lower tar and metal contaminants.

2.5.2. Utilization of Syngas:

The specific application of synthesis gas (syngas): Synthesis gas application significantly affects the composition.

- Gas turbine or engines can directly burn syngas, enabling you to produce power and heat. The efficiency of these energy conversion processes depends on calorific value which in turn depends on the concentration of hydrogen (H_2) and carbon monoxide (CO).
- Syngas can be converted to synthetic liquid fuels, like diesel and methanol, via Fischer-Tropsch synthesis. The catalytic efficacy is dependent on the H_2/CO ratio in the system.
- Synthesis gas used as a precursor for hydrogen. Using water-gas shift reactions followed by CO_2 separation techniques, it is possible to generate a high-concentration hydrogen stream. A study by Chen et al. (2021) but observed that hydrogen production was elevated during comparative tests in a pilot-scale fluidized bed gasifier equipped for co-gasification of sewage sludge and industrial wastewater sludge[27].
- Methanation Process: Syngas mainly consists of carbon monoxide and hydrogen, thus, it can be transformed through methanation into Renewable Natural Gas (RNG) that can be injected into the natural gas grid or used as vehicle fuel. Methane production rate in this step critically depends on optimal balance maintaining in H_2/CO composition which should be above 2 for better synthesis [28].

2.5.3. Challenges and Considerations:

Although the generation of syngas from sewage sludge is promising, there are certain challenges pertaining to its generation:

- Syngas Cleansing and Conditioning: Tar, ammonia as well as heavy metals complicate the cleanup and conditioning processes required for certain applications. Advanced gas cleaning technologies must be properly applied in order to fulfill purity requirements for a wide range of applications.
- Syngas Yield: Maximizing the syngas yield requires the optimization of operating parameters such as temperature, equivalence ratio (ER), and material selection for the bed. There remains a need for continuous research to design efficient and scalable gasification systems with a special focus on sewage sludge.

Overall, sewage sludge to energy via fluidized bed reactor gives a better solution to waste utilization, while providing a potential energy resource. By making better syngas production processes and addressing challenges, we can help move forward with renewable energy projects.

2.6. Ash Behavior and Challenges

2.6.1. Characteristics of Ash in Sewage Sludge Gasification

The gasification of sewage sludge (SS) in fluidized bed reactors results in the production of ash with distinct properties influenced by the feedstock's composition and the operational parameters of the gasification process. Notably, SS typically contains high levels of phosphorus (P), along with other inorganic elements such as potassium (K), calcium (Ca), iron (Fe), and aluminum (Al). These constituents play a significant role in determining the behavior of ash during thermal conversion.

Recent studies have highlighted that co-gasifying SS with K-rich agricultural residues, such as wheat straw or sunflower husks, can lead to the formation of K-bearing phosphates. These compounds are of particular interest due to their potential as plant-available fertilizers. Hannl et al. (2023) demonstrated that the co-gasification process facilitates interactions between P from SS and K from agricultural residues, promoting the formation of such valuable phosphates [29].

2.6.2. Challenges in Ash Management

Managing ash derived from SS gasification presents several challenges:

1. Ash Fusion and Agglomeration: The melting behavior of ash can lead to agglomeration within the fluidized bed, disrupting reactor operation. The presence of low-melting-point compounds, especially when co-gasifying with certain biomass types, exacerbates this issue. Understanding the ash fusion characteristics is crucial to mitigate operational problems.
2. Phosphorus Recovery: While P is a valuable nutrient, its recovery from ash is complicated by its association with other elements. The speciation of P in ash determines its availability for reuse as a fertilizer. Co-gasification strategies aim to enhance the formation of plant-available P compounds, but achieving consistent results requires precise control over feedstock composition and process conditions [25].
3. Heavy Metal Contamination: SS often contains heavy metals that can become concentrated in the ash, posing environmental risks. Effective strategies are needed to immobilize or remove these contaminants to ensure the safe application of ash-derived products.

2.6.3. Strategies for Ash Utilization

To address these challenges, several strategies have been proposed:

- Blending SS with K-rich biomass can enhance the formation of beneficial ash compounds, such as K-bearing phosphates, improving the fertilizer potential of the ash [29].

- Adjusting gasification parameters, including temperature and ER, can influence ash characteristics, reducing agglomeration tendencies and promoting the formation of desirable mineral phases [29].

- Post-gasification treatments, such as selective leaching or thermal processing, can be employed to extract valuable elements like P or to stabilize heavy metals, facilitating the safe reuse or disposal of ash [29].

2.7 Research Gaps and Justification for This Study

Research Gaps:

1. While gasification of sewage sludge (SS) with other biomass types has been investigated, comprehensive studies on the synergistic effects, particularly with various agricultural residues, remain scarce. Understanding these interactions is crucial for optimizing gasification performance and syngas quality.
2. Recent advancements in gasification technologies, such as chemical looping gasification, have shown promise for efficient SS conversion. However, there is a noticeable gap in research regarding the application of these innovative technologies to SS, especially in fluidized bed reactors.
3. Although various modeling approaches have been applied to SS gasification, there is a lack of integrated simulations which favors experimental results. These models are essential for accurately predicting reactor behavior and optimizing operational parameters.
4. The behavior of ash during SS gasification poses operational challenges, including agglomeration and deposition. While some studies have addressed ash characteristics, research on effective strategies for ash utilization and mitigation of associated issues is still limited.
5. Comprehensive life cycle assessments (LCAs) and techno-economic analyses (TEAs) specific to SS gasification processes are underrepresented in current literature. These evaluations are vital for determining the sustainability and economic viability of gasification technologies. However, this is out of scope of this research.

Addressing the aforementioned research gaps is imperative for advancing SS gasification technologies. This study aims to explore the gasification of SS, to elucidate effects of operating parameters on gasification efficiency and syngas composition. In summary, this study endeavors to fill critical voids in SS gasification research, contributing to the development of more efficient, sustainable, and economically viable waste-to-energy solutions.

Chapter 3 – Methodology

3.1. Sample preparation

Sewage sludge samples were collected from the wastewater treatment plant (WWTP) of Astana city. The wet sewage sludge samples were dried at 110 °C for one hour until the weight of the sample became constant to remove excess moisture. After drying, samples (Fig. 1) were grinded and sorted through a vibrating screen (Fig. 2) for the desired particle diameter of 400-500 µm as suggested by Khan et al. (2022) [18]. Around 400 g of silica sand with mean particle size of 400 - 500 µm was used as the bed material. Ash content was determined based on the ASTM D7582 standard. Proximate analysis was performed in a muffle furnace and volatile matter content was determined using ISO 18134-3:2023. The ultimate analysis was performed using the UNICUBE® micro elemental analyzer (Table 1). Thermal degradation behavior of sewage sludge pyrolysis was analyzed by using thermogravimetric analyzer under nitrogen environment.

Fig. 1. Grinding of SS

Fig. 2. Vibrating screen

Table 1. Proximate and ultimate analysis of Astana's pre-dried sewage sludge.

Proximate Analysis (wt%)		**Ultimate Analysis (wt%, Dry Ash Free)**	
FC	2.69	Carbon	48.21
VM	62.82	Hydrogen	5.69
Ash	32.22	Nitrogen	5.49
Moisture	2.27	Sulfur	1.62
HHV (daf), (MJ/kg)	18.87	Oxygen (by difference)	38.99

3.2. Bubbling fluidized bed (BFB) gasifier setup

Sewage sludge gasification tests were carried out in a laboratory scale BFB reactor. The inner diameter and height of the riser were 50 mm and 800 mm, respectively. The schematic illustration of the BFB reactor is shown in Fig. 3. Uniform air and steam flow was introduced through the bottom of the reactor and air was controlled using Bronkhorst flow meter, while preheated water was introduced by pump to the bottom of the reactor where it was further converted to steam through reactor temperature. Batch feeding of solid sewage sludge samples were performed from the top of the reactor. The temperature of the reactor was controlled using an external (Nabertherm) electric heater. The produced syngas passed through an isopropanol solution filled in 4 serial impinger bottles, serving as a condenser to filter the syngas from tar and solid particles. Lastly, a gas analyzer (CDL-TeCora ARCMULTI-01, see Fig.5) was used for measuring and recording the syngas composition such as CO, CO_2, O_2, CH_4 and gas chromatograph Agilent/8890 (Fig.4) was used to find out composition of N_2 and H_2. Table 2 shows the main experimental conditions of this study. Each experiment used roughly 20 g of sewage sludge samples. Remaining ash was further analysed for the elements by using XRF Axios Max PANalytical with Omnian method.

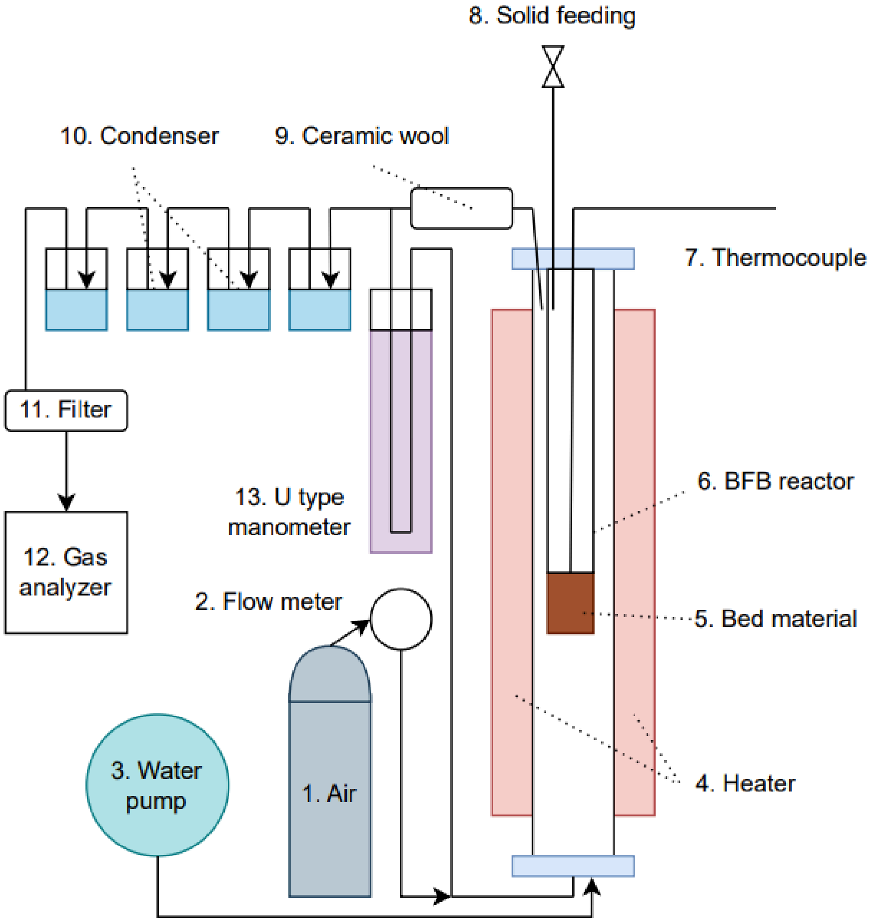

Fig. 3. Experimental setup of the designed bubbling fluidized bed gasifier.

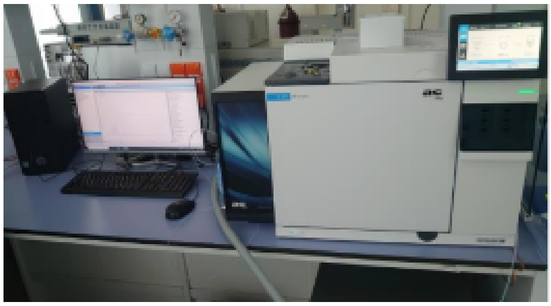

Fig. 4. GC-Agilent/8890

Fig. 5. CDL-T-CORA ARCMULTI-01

In total, 36 unique experiments were conducted for syngas composition analysis according to the design of experiments, see Table 3. These tests were based on three temperature levels (650, 750 and 850 °C), three ER levels, and three gasifying agents. Optional tests were repeated 2 times to avoid outliers.

Table 2: Experimental conditions used for gasification of the sewage sludge

Gasifying agent	Air	Air+steam	Steam
Temperature ºC	650; 750; 850	650;750;850	650;750;850
ER	0.2; 0.3;0.4	0.2;0.3	-
Feed rate (g/min)	20	20	20
S/F	-	0.5;1;1.5	0.5;1;1.5
Bed material	Silica sand (400-500µm)		
Mass of the bed	400 (g)		

Table 3: Design of experiments

№	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T	650	650	650	750	750	750	850	850	850	650	650	650
ER	0.2	0.3	0.4	0.2	0.3	0.4	0.2	0.3	0.4	0.2	0.2	0.2
S/F	-	-	-	-	-	-	-	-	-	0.5	1	1.5

№	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
T	650	650	650	750	750	750	750	750	750	850	850	850
ER	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2
S/F	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5

№	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**

T	850	850	850	650	650	650	750	750	750	850	850	850
ER	0.3	0.3	0.3	-	-	-	-	-	-	-	-	-
S/F	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5

3.3. Model simulation

Fig.6 illustrates process simulation of sewage sludge gasification in Aspen Plus, incorporating a kinetic model to validate syngas composition. The process consists of feedstock preparation, pyrolysis, oxidation, and reduction stages, producing syngas, char, and tar by-products. Peng-Robinson equation of state with Boston-Mathias (PR-BM) model was selected to simulate this process, aligning with other literature [29, 30]. MIXCINC stream class was chosen to specify feed, which contains MIXED, CISOLID, and NC without particle size distributions [31]. The HCOALGEN and DCOALIGT models were used to calculate the heat of formation, heat capacity, and density of the mixture for non-conventional components, such as sewage sludge and ash [29, 31, 32].

The simulation was designed based on the following assumptions: 1) the sewage sludge feed rate was 100 kg/h; 2) the reactor is based on kinetic mechanisms and functions under isothermal conditions; 3) the gasifier operates at atmospheric pressure and uses air and/or steam as gasifying agents depending on experiments; 4) sewage sludge feedstock is non-conventional and converted into conventional elements based on proximate and ultimate analysis; 5) heat and pressure losses were neglected in the system; 6) gases (H_2,CO, CO_2, N_2, O_2, CH_4, H_2O, H_2S) were treated as ideal gases; 7) tar is considered as mixture of benzene, toluene, and naphthalene, and char is carbon and ash.

The process starts with a drying block in the RStoic reactor through removing moisture and the dry biomass is decomposed into conventional components in the RYield reactor based on proximate and ultimate analysis of SS. Following this, pyrolysis reactor (RGibbs) performs thermal decomposition of SS into volatile gases and char. Another RStoic reactor facilitates the cracking process, following the reactions R10-R12 in Table 4 [29].

Gasification block involves two reactors (RPlug) one for complete oxidation and reduction reactions. The feedstock is subjected to high temperatures (650, 750, or 850 °C), breaking down the organic materials into syngas. Herein, a controlled amount of air and steam is supplied to the system, converting carbonaceous material into CO and CO_2. Reactions between carbon and produced gases after combustion lead to formation of syngas such as CO, CO_2, H_2, and CH_4, which includes the Boudouard reaction, water gas shift reaction, and methane reforming reactions [29]. Kinetic model reactions from R1-R9 are shown in Table 4 and unit block functions are provided in Table 5, respectively.

Table 4. Kinetic reactions in gasification block with parameters [29].

No	Reaction	k	E (J/kmol)
	Kinetic model		
R1	$C+0.5O_2 \rightarrow CO$	1.47×10^5	1.13×10^8
R2	$C + O_2 \rightarrow CO_2$	267	1.26×10^8
R3	$H_2 + 0.5O_2 \rightarrow H_2O$	8.83×10^8	9.98×10^7
R4	$CO + 0.5O_2 \rightarrow CO_2$	3.09×10^5	9.98×10^7
R5	$CO + H_2O \leftrightarrow CO_2 + H_2$	2.98×10^{12}	3.69×10^8
R6	$C + CO_2 \rightarrow 2CO$	2100	2.6×10^8
R7	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	2.55×10^{14}	1.25×10^8
R8	$C + 2H_2 \rightarrow CH_4$	8.89×10^{-6}	6.7×10^7
R9	$C + H_2O \rightarrow CO + H_2$	36	1.54×10^8
	Stoichiometric conversion		
R10	$C_{10}H_8 \rightarrow 6.5C + 0.5C_6H_6 + 0.5CH_4 + 1.5 H_2$	-	-

R11	$C_6H_6 + H_2O \rightarrow 1.5C + 2.5CH_4 + 2CO$	-	-
R12	$C_7H_8 + H_2 \rightarrow C_6H_6 + CH_4$	-	-

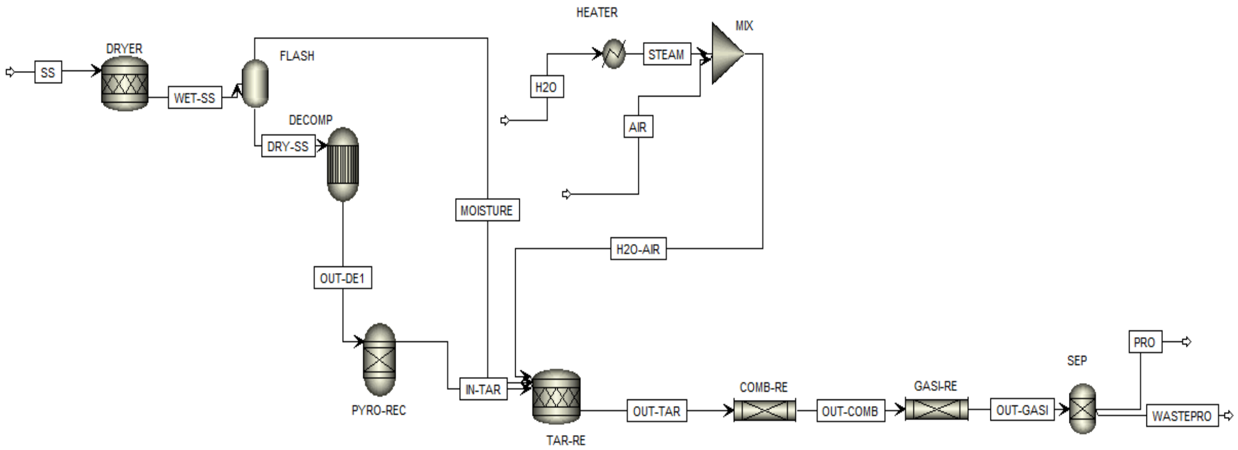

Fig. 6. Sewage sludge gasification simulation in Aspen Plus

Table 5. Unit blocks functions in Aspen Plus.

Unit block	Function
Dryer (RStoic)	Moisture removal from sewage sludge feedstock
Separation (Flash)	Separation of moisture
Decom (RYield)	Conversion of non-conventional components into conventional components
Pyro-rec (RGibbs)	Pyrolysis reactions through minimization of Gibbs free energy to reach equilibrium
Mix (Mixer)	Supply of gasifying agents, such as air, steam, and air-steam
Tar-rec (RStoic)	Cracking tar into light hydrocarbons
Comb-rec (RPlug)	Oxidizing carbonaceous fuel into CO_2 and H_2O

Gasi-rec (RPlug)	Thermochemical conversion under gasification agent into syngas
Sep (Separator)	Separation of syngas products from tar and char

Chapter 4 – Results and discussion

4.1. Thermal properties of samples

Fig.7a shows the thermogravimetric (TG) and differential thermogravimetric (DTG) curves for the dry sewage sludge samples as a function of the temperature at a heating rate of 10°C/min under nitrogen environment. Three main weight loss regions were observed in the TG curve of SS. The initial weight loss of about 3% was related to the loss of physically adsorbed water molecules at temperature lower than 110°C. The maximum rate of moisture loss has occurred at 109°C. Subsequently, there was an endothermic peak which showed the heat absorption. The first major weight loss region occurred in the range of 232–380°C, and reached about 42% of the total weight of SS. In this temperature range, the decomposition of proteins and carboxyl groups occurs, as noted by Migliaccio et al. (2021) [25]. Second major weight loss region was shown between 380 and 500°C, where decomposition of more stable organic components (cellulose, lignin, etc.) takes place [33]. Lastly, in the temperature range 500-800°C, samples showed a weight loss of 12.0% of its original mass, slowly approaching a final residue weight of 40.9%. This stage could be explained by the decomposition of inorganic materials [33]. Fig.7b illustrates TG and DTG curves of SS ash obtained from air gasification at 650°C. The results show that the total weight loss was only 3.5% which can be explained by the residual carbon content in the SS ash. The analysis can be divided into three main stages of decomposition. The first stage is from 210 to 330°C with a mass loss of 0.75%. The second main stage ranged from 330 to 450°C with a weight loss of 1.5%. The third final stage occurred from 450 to 900°C with a weight loss of only 1.3%. According to these results, it can be concluded that the gasification efficiency was high.

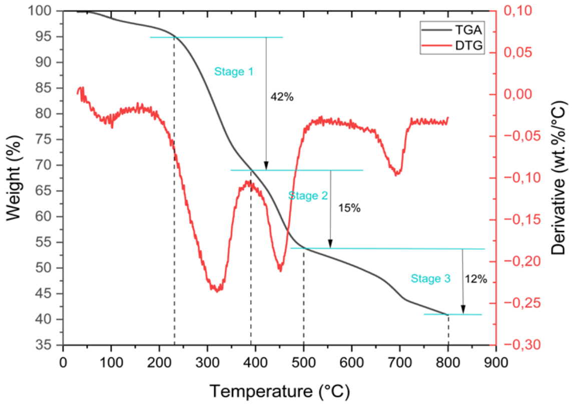

Fig. 7a. TGA analysis of SS under N_2 environment at 10°C/min

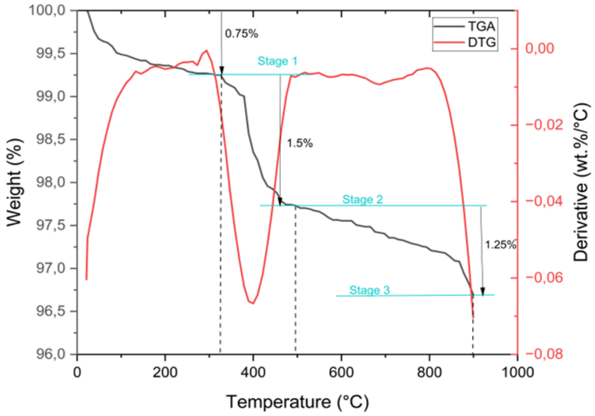

Fig. 7b. TGA analysis of SS ash after air gasification at 650°C under N_2 environment at 10°C/min

4.2. Effect of temperature

At the initial stage, a series of 9 tests were conducted at three temperature levels as 650°C, 750°C, and 850°C under air gasification each repeated for three ER values as shown in Table 2. At 650°C, the produced syngas exhibited relatively low concentrations with a range of values 3.7-4.1 vol% for H2 and 10.0-11.3 vol% for CO, see Fig.8a. At this lower temperature condition, the endothermic gasification reaction, such as the Boudouard reaction, was less effective. As a result, the conversion of carbonaceous materials was incomplete, leading to higher concentrations of CO_2 and CH_4, with the ranged values being around 15.6-17.7 vol% and 5.5-6.1 vol%, respectively. In contrast, the gasification tests at 750°C revealed improved conversion efficiencies. The increased temperature promoted the gasification reactions, resulting in enhanced levels of H_2 and CO yield with a concentration range of 5.5-6.2 vol% and 11.2-12.6 vol%, respectively. Simultaneously, the concentrations of CO_2 and CH_4 decreased to about 14.1-16.4 vol% and 4.4-5.1 vol%, respectively, indicating a shift in reaction equilibria favoring the formation of more energy rich gases. At the temperature of 850°C, the syngas composition showed the highest yields of H_2 and CO, with values rising to roughly 7.8-9.0 vol% H_2 and 14.0-15.2 vol% CO. Correspondingly, the levels of CO_2 and CH_4 were minimized, registering approximately 12.6-13.6 vol% and 3.0-4.6 vol%, respectively. The higher temperature accelerated the endothermic reactions and enhanced thermal cracking of heavier molecules.

Similar results were observed by Khan et al. (2022) where H2 and CO showed maximum concentrations at the temperature of 850 C [18]. The reported values for H_2 and CO were 16.26 vol% and 33.55 vol%, respectively, whereas CO_2 and CH_4 concentrations decreased compared to the results at 700°C. These results clearly demonstrate that temperature is a critical parameter in the gasification process. Increasing the temperature from 650°C to 850°C clearly enhanced the production of combustible gases while reducing the formation of less desirable by-products such as CO_2 and CH_4. The same trend was observed for the tests when gasifying agents were replaced by steam (Fig.8b). Tezer et al. (2023) found that optimal temperatures for sewage sludge gasification typically ranges between 800°C and 950°C, depending on the reactor configuration and feedstock characteristics which supports the results of this paper [33]. The improved reaction kinetics and favorable shift in equilibrium reactions at elevated temperatures not only increase the yields of H_2 and CO but also contribute to a more efficient gasification process, which is essential for the practical application and scale-up of sewage sludge gasification technology.

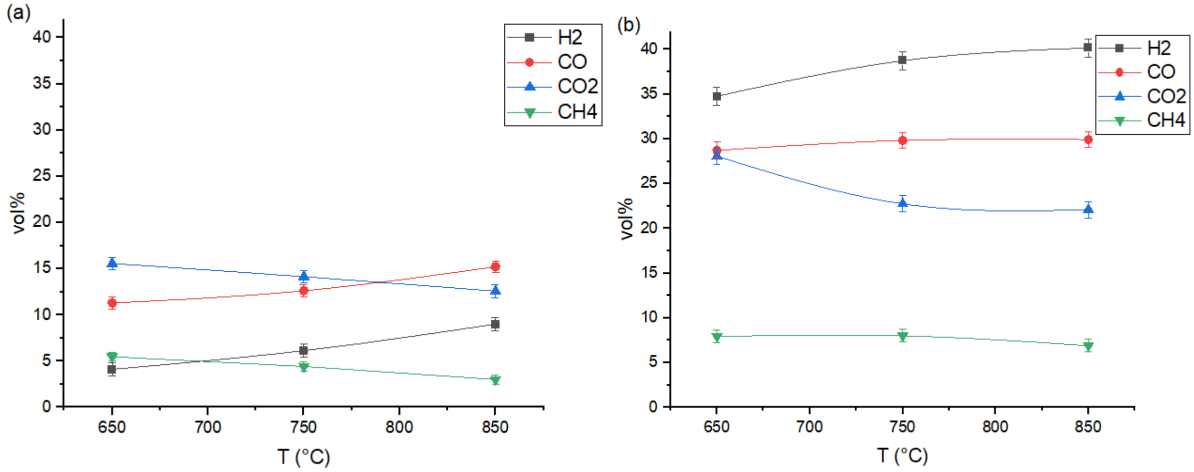

Fig. 8. Graphical representation of results; (a) air gasification at ER=0.2; (b) steam gasification at S/F=1.5

4.3 Effect of equivalence ratio

The ER was systematically varied to assess its influence on reaction pathways and product gas quality. Under lower ER conditions, which create a more reducing atmosphere, the gasification reactions favor the formation of H_2 and CO. For example, for the air+steam gasification tests at

850°C and S/F=1.5, the syngas produced exhibited an composition of approximately 35.6 vol% H_2, 31.4 vol% CO, 28.7 vol% CO_2, and 1.5 vol% CH_4 when the equivalence ratio was maintained at 0.2, Fig.9d. In contrast, when the equivalence ratio was increased to 0.3, a shift toward partial oxidation was observed. Under these more oxidizing conditions, the H_2 and CO contents decreased to around 32.8 vol% and 29.4 vol%, respectively, while CO_2 increased to roughly 30.25 vol% and CH_4 to 1.5 vol%. Same trend was observed for the rest of the experiments, Fig 9a-9c.

These results indicate that lower equivalence ratios enhance the endothermic gasification reactions, such as R6 and R7 reactions, by maintaining a strongly reducing environment. This promotes a more complete conversion of the feedstock into high energy syngas components. Conversely, higher equivalence ratios tend to favor partial oxidation processes that increase the formation of carbon dioxide and diminish the concentrations of combustible gases, thereby lowering the overall energy content of the syngas. The data also suggest that the maximum hydrogen yield occurred at equivalence ratio 0.2 in these experiments where the balance between complete gasification and controlled oxidation yields the maximum energy output. These trends, which are clearly outlined in the experimental results, highlights the importance of carefully manipulating the equivalence ratio to achieve high process efficiency and energy recovery in sewage sludge gasification. These results are compatible with Werle (2016) where ER values below 0.2 led to incomplete gasification and excessive tar formation, whereas values above 0.4 resulted in excessive oxidation, reducing syngas calorific value [34]. Similarly, Khan et al. (2021) emphasized the role of equivalence ratio (ER), demonstrating that an ER between 0.2 and 0.3 optimized the balance between oxidation and reduction reactions, leading to higher carbon conversion efficiencies and lower tar yield [35]. Furthermore, maintaining an optimal ER has been shown to improve cold gas efficiency and reduce the generation of secondary pollutants, contributing to a more environmentally sustainable process.

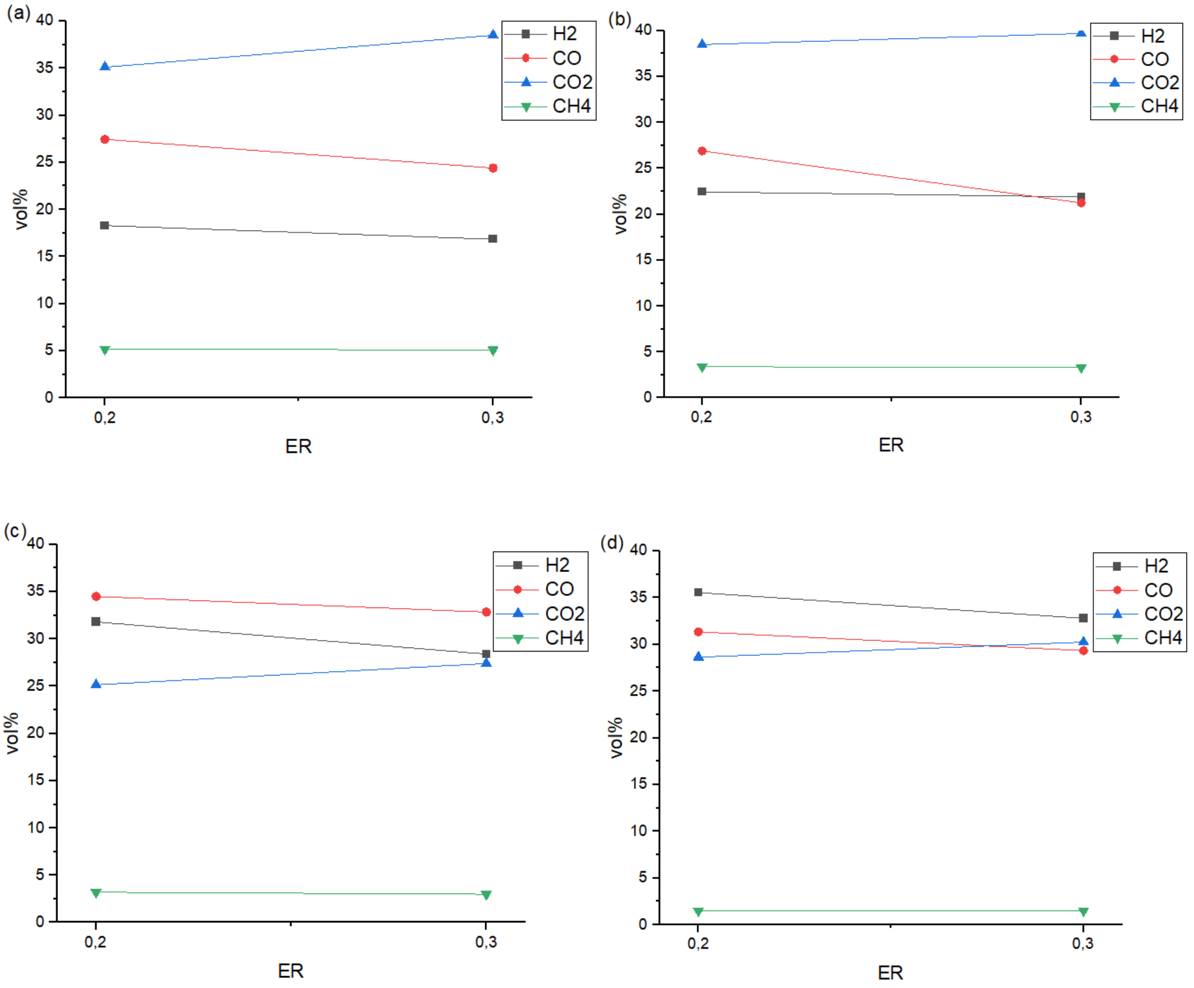

Fig. 9. Syngas composition (a) at S/F=0.5, T=650°C; (b) at S/F=1.5, T=650°C; (c) at S/F=0.5, T=850; (d) at S/F=1.5, T=850°C

4.4. Effect of steam-to-fuel ratio

The investigation into the effect of the S/F on syngas composition reveals a distinct improvement in gas quality as the ratio increases. In the experiments, three different S/F were evaluated: 0.5, 1.0, and 1.5. At the lowest ratio of 0.5, the syngas produced from sewage sludge steam gasification at 650°C exhibited composition of about 29.15 vol% H_2, 34.21 vol% CO, 25.38 vol% CO_2, and 11.24 vol% CH_4, see Fig 10a. With an increase of the steam-to-fuel ratio to 1.0, the additional steam promoted the water–gas shift reaction, which increased the H_2 content to around 33.41 vol% and reduced the CO concentration to roughly 28.69 vol%, while CO_2 increased to 28.9 vol% and CH_4 decreased to about 8.15 vol%, respectively. When the ratio was further increased to 1.5, the H_2 concentration further rose to approximately 34.78 vol%, with a slight increase in CO to 28.74 vol%, a slight drop in CO_2 to about 28.08 vol%, and CH_4 to 7.94 vol%.

These findings demonstrate that an increased steam-to-fuel ratio enhances key gasification reactions, especially the water–gas shift reaction, by providing more steam for the conversion of CO to H_2 [36]. This results in a higher yield of energy rich H_2 and a concurrent reduction in less desirable by-products such as CH_4 and tar precursors. However, Gai et al. (2016) suggest that if the S/F becomes excessively high, it may result in a dilution effect where unreacted steam lowers the overall concentration of combustible gases, thereby diminishing process efficiency [37]. The experiments indicate that an optimal balance is achieved at a ratio of approximately 1.5, where the benefits of increased hydrogen production and reduced tar formation are maximized without significant dilution. Overall, these results highlight the importance of controlling the steam-to-fuel ratio as a critical parameter for optimizing the fluidized bed gasification process of sewage sludge, ultimately leading to improved syngas quality for sustainable energy production.

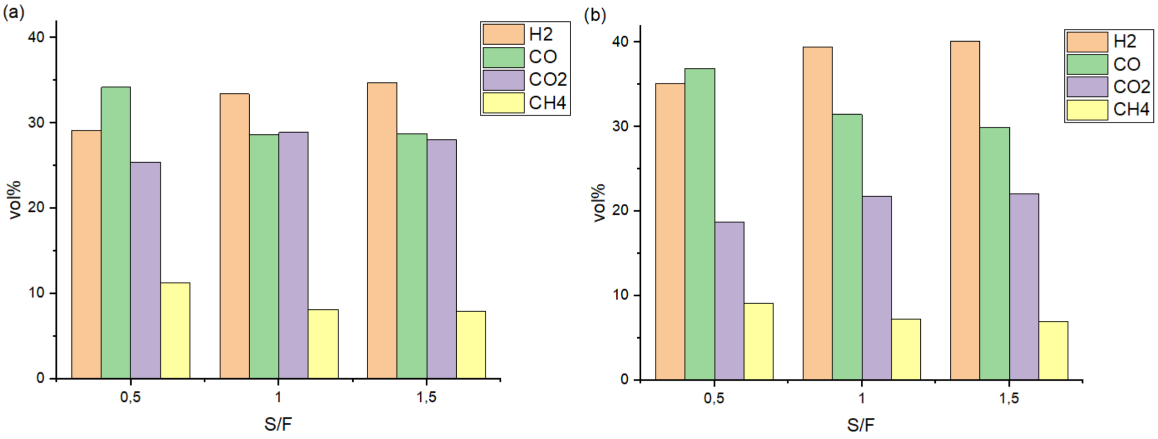

Fig. 10. Graphical representation of steam gasification results at; (a) 650°C; (b) 850°C

4.5. H_2/CO ratio

Tables 6-9 shows results of syngas composition of conducted experiments with H_2/CO ratio. The maximum ratio obtained at test 35 (T=850°, S/F=1) where H_2/CO = 1.39. Second maximum ratio was 1.3 at T=750°, S/F=1.5. According to these results, better ratios were obtained during steam and mixed air+steam conditions where ratio was in the range of 1 and above. This is due to the fact that introduction of steam favors R5 which increases H_2 while reducing CO and thus, introduction of steam and S/F affects this H_2/CO ratio the most making syngas high quality for synthesis of liquid fuel such as methanol. To compare with, air gasification has the results in the range between 0.3-0.6 which shows poor quality of syngas.

Table 4. Composition of syngas obtained from air gasification of sewage sludge under various operating conditions

Gas composition (vol%)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
CH_4	5.48	5.65	6.1	4.43	4.86	5.11	3.02	4.01	4.63
H_2	4.12	3.87	3.65	6.15	5.87	5.52	9.01	8.12	7.84
CO	11.29	10.51	10.02	12.62	11.5	11.18	15.21	14.85	14.02
CO_2	15.57	17.66	16.57	14.14	16.17	16.41	12.57	12.91	13.62
O_2	0.08	0.09	0.15	0.24	0.46	0.85	0.02	0.74	0.59
N_2	63.46	62.22	63.51	62.42	61.14	60.93	60.17	59.37	59.3
H_2/CO	0.36	0.37	0.36	0.48	0.51	0.49	0.59	0.55	0.56

Table 5. Composition of syngas obtained from air+steam gasification of sewage sludge under various operating conditions

Gas composition (vol%)	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18

CH_4	5.2	4.3	3.4	5.1	4	3.3	4.1	3.25	2.45
H_2	18.3	20.15	22.45	16.85	19.65	21.9	25.25	28.5	30.75
CO	27.45	26.75	26.9	24.4	22.55	21.25	30.5	28.65	26.8
CO_2	35.1	37.25	38.5	37.4	38.85	39.7	30.2	32.15	33.35
N_2	14.95	12.55	12.75	16.25	14.95	13.85	10.95	9.45	9.15
H_2/CO	0.67	0.75	0.83	0.69	0.87	1.03	0.83	0.99	1.15

Table 6. Composition of syngas obtained from air+steam gasification of sewage sludge under various operating conditions

Gas composition (vol%)	**Test 19**	**Test 20**	**Test 21**	**Test 22**	**Test 23**	**Test 24**	**Test 25**	**Test 26**	**Test 27**
CH_4	4	3.1	2.3	3.2	2.3	1.5	3	2.2	1.5
H_2	23.4	25.6	28.75	31.8	33.25	35.55	28.4	30.65	32.8
CO	27.7	25.9	24.4	34.5	33.6	31.35	32.85	30.75	29.35
CO_2	32.8	34.15	35.5	25.15	27.05	28.65	27.4	29.1	30.25
N_2	12.1	11.25	10.05	7.4	5.8	5.3	9.35	8.4	7.6
H_2/CO	0.84	0.99	1.18	0.92	0.99	1.13	0.86	1.00	1.12

Table 7. Composition of syngas obtained from steam gasification of sewage sludge under various operating conditions

Gas composition (vol%)	**Test 28**	**Test 29**	**Test 30**	**Test 31**	**Test 32**	**Test 33**	**Test 34**	**Test 35**	**Test 36**
CH_4	11.24	8.15	7.94	10.78	8.23	8.01	9.06	7.26	6.91
H_2	29.15	33.41	34.78	33.56	37.95	38.74	35.12	39.46	40.18
CO	34.21	28.69	28.74	35.14	30.14	29.84	36.94	28.45	27.94
CO_2	25.38	28.9	28.08	19.78	23.57	22.76	18.69	24.76	24.1
O_2	0.02	0.85	0.46	0.74	0.11	0.65	0.19	0.07	0.87
H_2/CO	0.85	1.16	1.21	0.96	1.26	1.30	0.95	1.39	1.34

4.6. Model validation

The Aspen Plus simulation was validated against experimental data, specifically for equivalence ratio of 0.3, bed temperature of 650°C, and steam-to-fuel ratio of 0. The model was developed following a kinetic approach based on the study of Aentung et al. (2024) [29]. Fig.11 demonstrates the comparison of the experimental and simulated syngas composition under air as a gasifying agent.

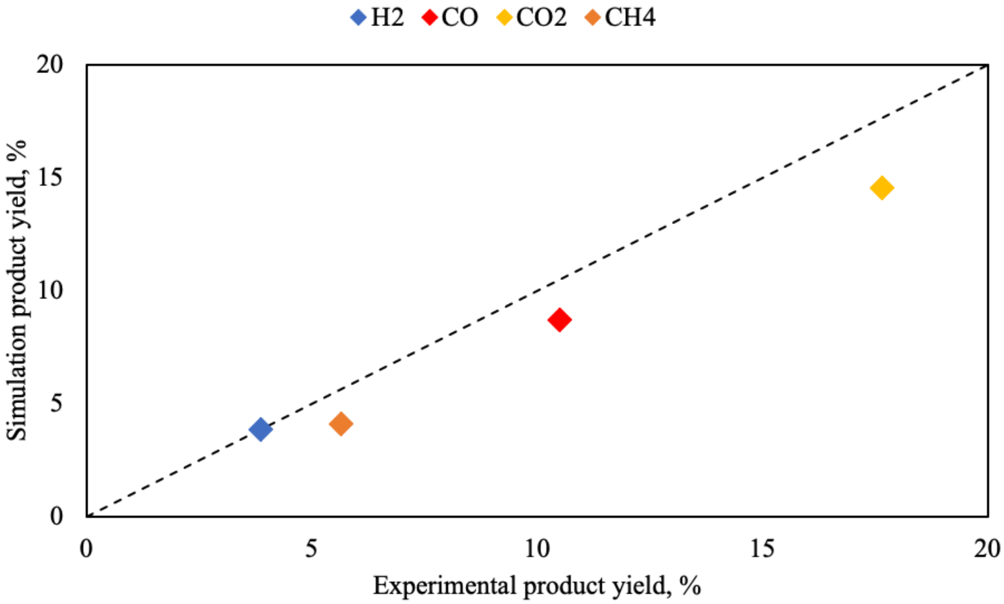

Fig. 11. Comparison of experimental and simulation results under air gasification.

The kinetic model shows a reasonable agreement with the experimental data, with an average error of 2%. The hydrogen yield in the experimental setup (3.87%) was slightly higher than in the simulation (3.82%). This alignment suggests that the model effectively captures the primary reactions influencing hydrogen production, such as water gas shift and steam reforming reactions. Higher deviations occurred for CO_2 and CO. A similar trend was observed in the study of Nikoo and Mahinpey (2008), where authors utilized equilibrium-based gasification models using the RGibbs reactor [38]. The probable reason can be mass transfer in gas-solid reactions, and the work concluded that considering this factor could improve simulation performance [38].

Moreover, simulation underestimated the concentration of CH_4 by 1.57%. This discrepancy can be due to instantaneous pyrolysis and exclusion of particle size distribution (PSD). For instance, a study by Žandeckis et al. (2014) indicated that syngas quality increases with smaller particle size of biomass [39]. Therefore, incorporating detailed particle size distribution in Aspen Plus Incorporating a detailed tar decomposition sub-model that accounts for particle size effects could improve CH_4 predictions in future simulations.

4.7. Sensitivity analysis

Sensitivity analysis was done to investigate the model' response to temperature changes and gasifying agent change. Fig.12. Shows the effect of temperature on composition of syngas under air with ER=0.3. Model results demonstrated good agreement with experimental results within a temperature range of 650-850 °C. Methane concentration was highest at 850 °C equaling 4.99%, which aligned with experimental data (4.01%) and literature. For instance, in the study of. de Andrés et al. (2018), gasification of sewage sludge demonstrated the highest methane output of 5% at 850 °C [32].

Moreover, both results showed an increase in the yield of H_2 and CO with temperature increase while CO_2 concentration decreased. The similar trend was observed in the study of de Andrés et al. (2018) [32]. Syngas production increased with temperature due to more intense volatilization reactions [32]. Also endothermic reactions in the gasification process are more dominant at elevated temperatures [34]. At 850 °C, the higher CO content and lower CO_2 content may be due to the promotion of Boudouard reaction (R9), which converts CO_2 to CO.

While the trend of our experiments and the model for H_2, CO, and CO_2 is same, the values differ. This issue has been a limitation on the modeling as has also been reported in the study of Andrés et al. (2018) [32]. In his work, during the simulation of the results the largest difference were found from the experimental values for carbon conversion [32]. The content of ethane (C_2H_6) and ethylene (C_2H_4) in the syngas was included in the composition. However, our model did not take into account these gases, which may be the cause for these deviations, especially for methane.

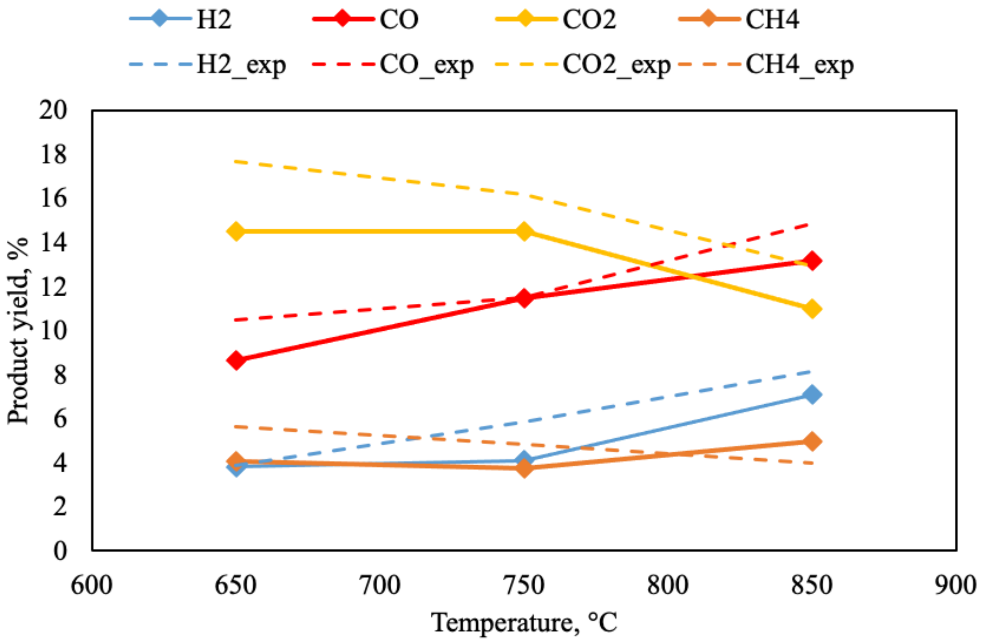

Fig. 12. Effect of gasification temperature on syngas composition

Fig.13 below demonstrates the syngas composition under S/F ratio of 1 and temperature of 650 °C. According to results, there is a higher discrepancy between experimental and simulation results. While CO (26.49% vs. 28.69% experimentally) and CH_4 (8.31% vs. 8.15% experimentally) concentrations align more closely with experimental results, the discrepancies in H_2 and CO_2 require closer analysis. The simulation overestimated the concentration of H_2 by 37.5%. Generally, hydrogen formation is sensitive to steam-to-fuel ratio due to reactions that promote H_2 [40]. Kinetic model employs three reactions, including water gas shift (R5), steam reforming (R7), and water gas (R9), which mainly contribute to the production of hydrogen [40]. Therefore, higher yield of H_2 suggests that these reactions proceeded more extensively in comparison with experimental setup. One possible reason for deviation is that the kinetic model's reaction rate constant may not fully represent the actual experimental conditions, accounting for ideal cases. For example, char reactivity, residence time of steam in the reactor might influence the product yields. Also incomplete gas-solid reactions (R9) in experiments can cause this difference. In terms of CO_2 formation, the model underestimated CO_2 (14.83%) in comparison with experimental one (28.90%), which is linked to reverse water gas shift reaction (R5). Water gas shift reaction is reversible and equilibrium-limited reaction [41]. Therefore, in experiments shift toward CO and H_2O formation is possible.

However, despite the fact that the model results do not closely align with experiments, they are consistent with literature findings. In the study of Aentung et al. (2024), H_2 and CO are dominant products, with approximately 60% and 30% of yield, respectively [29]. Moreover, increasing S/F ratio increases the concentration of CO_2 and H_2 [29].

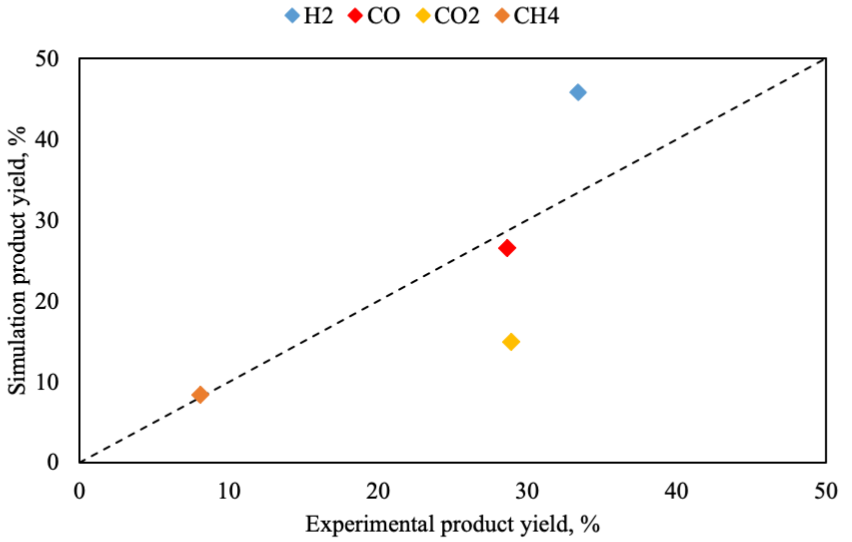

Fig. 13. Comparison of experimental and simulation results under steam at 650 °C

4.8. Mass balance

Table 10 shows the mass balance of focused experiments which were chosen to show the effects of each operating parameter on char, tar and syngas yield. Comparison of test 1 and 3, 7 and 9 shows effect of ER, while comparing tests 1 and 7, 3 and 9 shows effect of temperature. Comparison of tests 34 and 36 shows effects of S/F. According to table 10, syngas generation increases with increase of all operating parameters (T, ER, S/F) due to the thermal cracking and carbon conversion, however the main parameter in syngas yield was temperature because of dramatic increase above 55%. The less tar and char yield occurred in test 36 at 850°C and S/F=1.5. This shows that the steam environment shows better carbon conversion comparatively with air.

Table 10. Results of mass balance.

Test	Char (g)	Tar (g)	Syngas (%)
1	8.12	4.46	37.10
3	7.88	4.41	38.55
7	6.4	2.37	56.15
9	6.45	2.18	56.85
34	6.67	1.99	56.70
36	6.32	1.89	58.95

4.9. Composition of ash and the influence of its elements on gasification

Fig. 14 shows the XRF analysis of sewage sludge ash at 650°C, 750°C and 850°C. This led to significant changes in the inorganic composition, reflecting both the original sludge mineralogy and the thermochemical transformations during gasification.

SiO_2 was the main component of SS ash which shows about 40% composition of the sample. This was due to the sample preparation, since the sample was mixed with silica sand to create a glass sample for XRF, the main component here is silica dioxide. Thus, this component can be neglected from the analysis. CaO is the second abundant content which decreased slightly with increasing temperature, due to the potential participation in high-temperature interactions, such as the formation of low-melting silicates or phosphates. Calcium is known to influence slagging behavior and may react with SiO_2 to form Ca-silicates [42]. Both Fe_2O_3 and Al_2O_3 oxides showed an increasing trend with temperature, especially Fe_2O_3, which became more prominent at 850 °C. This might be attributed to the oxidation of iron-bearing minerals or volatilization of lighter components. Iron oxides are also known to catalyze tar cracking and gas-phase reactions at high temperatures [43].

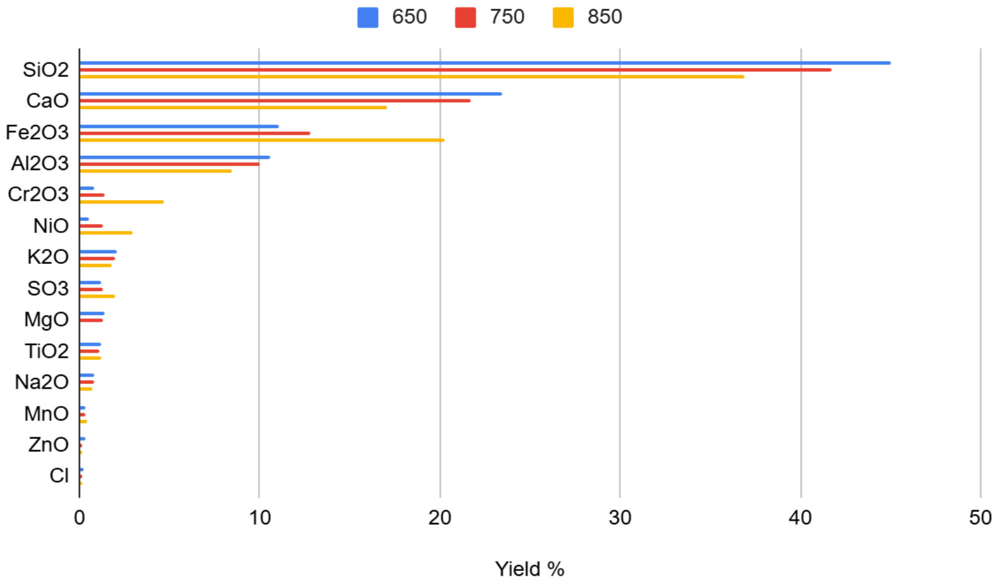

Fig.14. Results of XRF analysis of SS ash oxides

Chapter 5 – Conclusion

This study investigated the gasification of SS in a bubbling fluidized bed reactor, analyzing the effects of key parameters such as gasifying agents (air, air-steam, and steam), bed temperature, equivalence ratio (ER), and steam-to-fuel ratio (S/F) on syngas composition. Experimental results demonstrated that higher bed temperatures (850°C) enhance the production of hydrogen and carbon monoxide while reducing methane and carbon dioxide concentrations. The optimum ER was found to be 0.2, maximizing syngas yield by promoting endothermic gasification reactions. Similarly, increasing the S/F ratio (1.5) improved hydrogen generation through the water gas shift reaction, with a maximum H_2 generation of 40 vol%, but reduced CO concentration which was about 30 vol%. The maximum H_2/CO ratio was 1.39 at 850°C and S/F=1. The experimental findings were validated using an Aspen Plus process simulation model which showed 2% error between experimental and simulation results, captured the general trends in syngas composition but slightly overpredicted hydrogen yields during sensitivity analysis by 37.5% due to idealized reaction kinetics. Sensitivity analysis further confirmed that optimizing operational parameters is crucial for improving gasification efficiency and syngas quality. Despite some discrepancies, the model provided valuable insights for process optimization and scale-up potential.

Overall, this study highlights the potential of fluidized bed gasification as a sustainable valorization pathway for sewage sludge, aligning with circular economy principles. Future work should focus on addressing challenges such as tar formation, syngas contamination, LCA and economic reliability.

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