Na prawach rękopisu

POLITECHNIKA WROCŁAWSKA
WYDZIAŁ MECHANICZNO-ENERGETYCZNY

HYDROTHERMAL CARBONIZATION AND PLASMA GASIFICATION OF SEWAGE SLUDGE

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Doctoral thesis

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Abstract

Hydrothermal carbonization (HTC) is recognized as an energy-saving thermochemical conversion method that increases the dewatering capacity of sewage sludge and allows it to be converted into economically valuable products. This process helps reduce the amount of sewage sludge waste produced and stored by converting it into less hazardous forms.

In this study, selected sewage sludge after the dewatering process was tested under HTC conditions. Sewage sludge samples were collected from the Municipal Sewage Treatment Plant in Aarhus, Denmark, and the Janówek Municipal Sewage Treatment Plant, located in Wrocław (3 types of sludge from Denmark and one from Poland). Sewage sludge samples, classified as primary, secondary, and anaerobic digested material, were subjected to hydrothermal carbonization (HTC) under various process conditions in a 450 mL reactor. The tests were carried out for temperatures of 180, 200, 250, and 300 ^{0}C and residence times of 5 minutes and 1 hour. The obtained research results showed the great importance of selecting the HTC process conditions for various source materials to optimize energy recovery (in the form of hydrocarbon or syngas) while considering the economic and environmental elements of the process. The gas phase produced in the HTC process consists mainly of CO_2, but the solid product of the process is characterized by a higher calorific value, improved grindability, and hydrophobic properties compared to the feed material. The hydrochar obtained after dehydration and drying was used in the plasma gasification process. For this purpose, a laboratory setup was constructed, complete with a fixed bed plasma gasification reactor with a length of 125 mm, an internal diameter of 50 mm, and an external diameter of 65 mm. The products obtained after the plasma gasification process were synthesis gas and plasma ash. The resulting ash was also processed into new, valuable products in the form of tiles that can be used in construction.

Streszczenie

Karbonizacja hydrotermalna (HTC) jest uznawana za energooszczędną metodę konwersji termochemicznej, która zwiększa zdolność odwadniania osadów ściekowych i pozwala przekształcić je w cenne gospodarczo produkty. Proces ten pomaga w ograniczaniu ilości wytwarzanych i składowanych odpadów w postaci osadów ściekowych poprzez przekształcenie ich w mniej niebezpieczne formy.

W niniejszej pracy badaniom w warunkach HTC poddano wybrane osady ściekowe po procesie odwadniania. Próbki osadów ściekowych pobrano z Miejskiej Oczyszczalni Ścieków w Aarhus w Danii oraz Miejskiej Oczyszczalni Ścieków Janówek, zlokalizowanej we Wrocławiu (3 typy osadów z Danii i jeden z Polski). Próbki osadów ściekowych, sklasyfikowane jako materiał pierwotny, wtórny i po fermentacji beztlenowej, poddano karbonizacji hydrotermicznej (HTC) w różnych warunkach procesu w reaktorze o pojemności 450 ml. Badania przeprowadzono dla temperatur 180, 200, 250 i 300 °C oraz czasów przebywania wynoszących 5 minut i 1 godzina. Uzyskane wyniki badań wykazały duże znaczenie doboru warunków procesu HTC dla różnych materiałów źródłowych, dla odzysku energii (w postaci biowęgla lub syngazu), biorąc jednocześnie pod uwagę elementy ekonomiczne i środowiskowe procesu. Wytwarzana w procesie HTC faza gazowa składa się głównie z CO_2, jednak stały produkt procesu charakteryzuje się wyższą wartością opałową, polepszoną podatnością na przemiał właściwościami hydrofobowymi w porównaniu z materiałem wsadowym. Otrzymany po odwodnieniu i suszeniu biowęgiel wykorzystano następnie w procesie zgazowania plazmowego. Do tego celu zbudowano stanowisko laboratoryjne z reaktorem do zgazowania plazmowego o długości 125 mm, średnicy wewnętrznej 50 mm i średnicy zewnętrznej 65 mm. Produktami otrzymanymi po procesie zgazowania plazmowego był gaz syntezowy i popiół. Otrzymany popiół przetworzono także w nowe, wartościowe produkty w postaci płytek ceramicznych, które mogą znaleźć zastosowanie w budownictwie.

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1. Introduction

A byproduct of wastewater treatment called sewage sludge is becoming more problematic. Sewage sludge contains different amounts of water, organic materials, and organic and inorganic contaminants, such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) [1,2]. Sewage sludge may contain biological activity, thus when using it, that must be taken into account. Because of this, sewage sludge deactivation and stabilization have been extensively studied [3–8] using a variety of thermal utilization routes, including thermal hydrolysis [9], hydrothermal carbonization (HTC) [10–12], HTC integrated with anaerobic digestion [13,14], torrefaction [15,16], pelletizing [17], pyrolysis and co-pyrolysis [18,19], gasification [20–23], and combustion [24].

A multitude of environmental, health, and safety concerns have led to regulations surrounding sewage sludge at both the national and European Union (EU) levels. Certain national regulations are stricter than the standards outlined by EU legislation [25–27]. Based on official Eurostat statistics [28], Figure 1 depicts the amount of sewage sludge produced in each EU member state as well as the amount now used for incineration and cultivation. There are over 60,000 wastewater treatment facilities dispersed throughout Europe [29]. Because of the material's high moisture content, the locations of these facilities may not always be optimal from a logistical standpoint when applied to agricultural applications (land spreading). The allowable limitations on heavy metal content—20 mg/kgdry of Cd, 1000 mg/kgdry of Cu, 16 mg/kgdry of Hg, 300 mg/kgdry of Ni, 750 mg/kgdry of Pb, and 2500 mg/kgdry of Zn—as well as their application to agriculture are outlined in European Council Directive 86/278/EEC [30]. The danger of microplastics for agricultural usage should also be carefully considered [31].

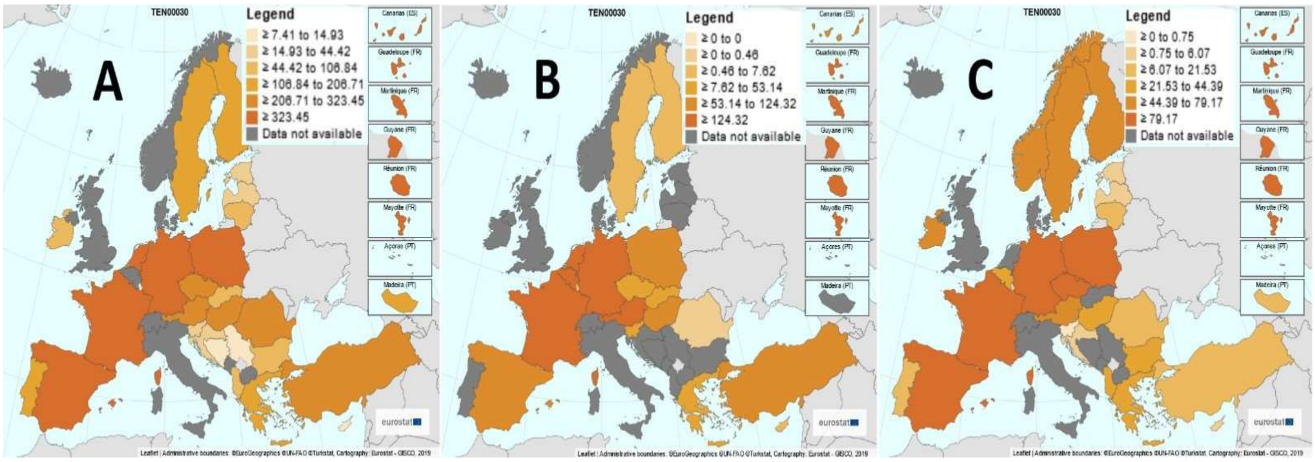


Figure1.1 Sewage sludge production and disposal from urban wastewater (unit–thousand tons of dry mass) in 2016 based on the Eurostat Database [28]: (**A**) sewage sludge production (total); (**B**) sewage sludge utilization by incineration; (**C**) sewage sludge disposal by agricultural use (data for later years not reported by many countries).

On an EU level, the following regulations are significant [26, 27]:

- 2000/60/EC, the Water Framework Directive
- Directive 91/271/EEC (modified on December 17, 2013, by Council Directive 2013/64/EU) The Waste Landfilling Directive (99/31/EC) and the Integrated Pollution Prevention and Control Directive (96/61/EC)
- The 86/278/EEC Sludge Use in Agriculture Directive.

According to Rulkens [100], sludge is a complex, heterogeneous mixture of inorganic materials like silica, heavy metals, proteins, peptides, liquids, polysaccharides, phenols, aliphatic, aromatics, and furans, as well as organic materials like pathogens and other microbiological pollutants. The term "primary sludge" refers to the sludge that remains after mechanical processing (screening, grit removal, sedimentation) in a typical wastewater treatment process. It has a high concentration of suspended and dissolved organics and ranges from 93.5 to 93% water. After biological treatment, secondary sludge also referred to as waste-activated sludge, or WAS—contains a high concentration of microbial cells and a total solids concentration that can range from 0.8% to 1.2%, depending on the process type [102]. The most popular sludge treatment method is anaerobic digestion, which uses hydrolysis, acidogenesis, acetogenesis, and methanogenesis to convert organic materials into biogas (mostly CH_4 and CO_2) [101]. Even with its widespread use, a sizable quantity of reliable only 20–30% of organic matter is mineralized following anaerobic digestion [100]. Although these solids were formerly believed to be environmentally benign, their application to arable land may very well be a significant source of greenhouse gas emissions, point pollutant sources for lead, cadmium, mercury, and copper, contribute to environmental acidification and pose a toxicological risk due to the presence of pathogens [99]. Significant emissions of methane, nitrous oxide, ammonia, and nitrate are produced by the microbiological processes (mostly anaerobic decomposition, nitrification, and denitrification) that take place on land-applied sludge. The application of sludge on land reduces emissions of N_2O, NH_3, and NO_3, and balances the use of industrial nitrogen-containing fertilizers; but, CH4 emissions are still projected to be higher, at 6.3 kg ton−1 of applied sludge [99]. Therefore, applying secondary sludge directly to the ground might not be the best method for recovering nutrients and might even be a waste of a renewable energy source. The process known as hydrothermal carbonization (HTC) densifies the carbon in a given biomass by heating it in water above the saturation pressure and causing a sharp drop in water's dielectric constant, which makes the water both an organic solvent and a reactant. Numerous processes, such as hydrolysis, dehydration, dehydrogenation, decarboxylation, demethanation, and oxidation, are used to carry it out. According to Lucian et al [87] and Lucian and Fiori [88], HTC is carried out in 80–95% water, which makes it the perfect processing method for wet biomasses like sewage sludge. It not only causes the solid to become less dense in terms of volume and energy but HTC has been demonstrated to significantly increase the dewaterability of sewage sludge [89],

According to He et al. [86], Hydrothermal Carbonization (HTC) has become a viable method for the efficient reduction of sludge and the valorization of key products. However, drying is necessary for other thermochemical processes like pyrolysis and gasification. HTC is a pre-treatment method that works well with wet organic waste, like sludge, because it requires a lower temperature than pyrolysis and gasification. HTC is performed in water. HTC creates hydrochar, a sterile, stable, carbon- and energy-rich material that can be made sustainably from a variety of wet organic waste streams. It can be used as a soil amendment, adsorbent in soil or water remediation, or as a renewable biofuel [90] [91] [92]. The subsequent reduction in the bulk and volume of the initial waste biomass, requiring less disposal space, is another significant benefit of HTC; nevertheless, current research on HTC is mostly focused on the manufacture of value-added products from waste streams [90]. According to Funke and Ziegler [93], [94], [88], the HTC process involves heating biomass to 180 to 250 in a suspension with water under saturated pressure for several hours. This process turns biomass into hydrochar, which is easily separated from the wastewater from the HTC process because of its reduced surface polarity. alternatively, as sources for the recycling and reclamation of phosphorous [90][86][95][89]. The energy value of the hydrochar made from sewage sludge was the subject of numerous studies. However, the elevated level of moisture in the air could cause a significant amount of water to be processed for every unit of mass of dry feedstock, which results in low thermal efficiency of the HTC process, which is defined as the ratio between the High Heating Value (HHV) of dried hydrochar and the thermal energy used by the process [88].

The most influential factor in the HTC process is temperature, higher temperatures cause reactions to occur more quickly, which directly affects the kinetics of the reactions and determines the properties of the water, which causes ionic reactions to occur primarily in the subcritical region [96][97][98]. Additionally, temperature influences specifically the quantity of starting feedstock molecules that are hydrolyzable (below 180 carbonization is difficult to achieve). Ultimately, rising temperatures raise the hydrochar's carbon content, which in turn raises its energy content and caloric value, but generally lowers the hydrochar yield, raising the temperature and accelerates the rate of decarboxylation and dehydration. Thus, the O/C and H/C ratios that involve the hydrochar's increased carbon content [103][97][98]. Furthermore, increased temperatures result in higher yields of liquids and gases, with a drop in hydrochar output as a result of some of the char produced degrading [103].

According to LeChatelier's principles, pressure influences reactions. As a result, as reaction pressure rises, reactants with fewer moles of energy simultaneously experience a shift in reaction equilibrium toward the solid and liquid phases, resulting in a decrease in the rate of dehydration and decarboxylation reactions. Most people believe that pressure is an indirect measure due to its strong temperature dependence, the process requires pressure to keep water in the liquid phase to develop HTC. For example, if a closed system containing water and biomass is heated above 100^{o} C, the resulting pressure will be higher than the saturated vapor pressure because gases will form as a result of decarboxylation. According to [103][93][97], water is kept in a liquid form.

The residence duration has a significant impact on energy and heat consumption, making it particularly useful for practical processing design. It typically impacts the harshness of the process and lasts anywhere from a few minutes to several hours. Numerous writers have documented that extending the HTC process's residence time typically raises the hydrochar's carbon content and, as a result, the solid product's calorific value. Furthermore, residence time is said to lower the hydrochar yield in numerous publications, encouraging the synthesis of greater amounts of water-soluble chemicals [103][93][98]; [97]. According to [98], extended residence times can cause fragments that were solved in the liquid phase to polymerize, resulting in the creation of secondary hydrochar with a poly-aromatic structure. Residence time has a significant impact on the production of secondary hydrochar, particularly for lignocellulose feedstock, as dissolved monomers necessitate lengthy polymerization. However, residence time enables the regulation of the degree of polymerization of the soluble monomers during the process, while temperature influences the behavior of non-dissolved monomers [98].

The primary goal of gasification is the conversion of solid fuel into gas [32, 33]. H_2, CO, CO_2, and N_2 make up the majority of the "producer gas" that is produced when air is utilized as a gasification agent [34–36]. There are also hydrocarbons, the most important of which is methane out of all the non-condensable gases [37, 38]. There are also more complicated condensable molecules, phenols, toluene, naphthalene, benzene, and other aromatic chemicals [39–42]. Tars are commonly defined as compounds having an atomic mass greater than benzene [43–46]. Numerous materials have been the subject of in-depth research on gasification [47–54].

For many years, there has been a thorough examination of the gasification of sewage sludge and the subsequent use of producer gas. Werle found that when the amount of hydrogen in the producer gas from sewage sludge increased, so did the laminar flame speed [55]. Spark-ignition engines might use this type of gas [56]. However, Szwaja et al. [57] state that a 40% methane addition to producer gas from sewage sludge is necessary to achieve sufficient performance from a spark-ignition engine.

Werle and Dudziak claim that the majority of the tars created by gasifying sewage sludge are composed of phenols and their derivatives [58]. Pawlak-Kruczek and others [59] suggested predicting the possible severity of tar deposition issues in gas coolers by using a tar-deposition diagram. With the use of this instrument, the research showed that the amount of tars with melting points above 40 °C was decreased by a considerable torrefaction of sewage sludge before steam gasification [59]. Regarding the thermal utilization of sewage sludge, gasification has been suggested as a viable substitute for incineration. Certain studies have even suggested this thermal method, which might result in gas-powered facilities that produce zero carbon dioxide emissions [60].

There is very little information about commercial sewage sludge gasification plants in the literature. By Montouris et al. [61], a case study on the commercial-scale gasification of sewage sludge for the Greek island of Psittaleia was carried out utilizing the GasifEq equilibrium model. It was shown that producing net power using plasma gasification of sewage sludge was possible [61]. 2.85 MW of power might be produced, according to the calculation, which was done for a hypothetical factory with a processing rate of 250 tons per day (moisture content 68%) [61]. Several research groups conducted successful experiments with two-step plasma processing units [62,63], demonstrating the concept's general applicability in a laboratory setting and the possibility of reducing the tar level to 90 mg/mN3 [63]. According to Brachi et al. [64], a real wastewater treatment facility that serves an equivalent of 1.2 million people in Southern Italy may find it economically possible to gasify sewage sludge and then burn the gas in a CHP unit.

Using plasma technology, entrained flow plasma gasification transforms a variety of feedstocks, including biomass, industrial waste, and municipal solid waste, into syngas, or synthetic gas. here I used sewage sludge. This approach has several benefits.

Elevated Temperatures and Energy Economy

At temperatures typically above 3,000 degrees Celsius, entrained flow plasma gasification operates at extraordinarily high temperatures. This high temperature makes it easier for feedstocks to break down efficiently into syngas.

Because complex organic compounds are broken down by the high temperatures produced by the plasma, the process is energy efficient.

Syngas Generation

Syngas is the main by-product of entrained flow plasma gasification, which is a hydrogen and carbon monoxide mixture. Syngas is an important resource that can be utilized to make chemicals, fuels, and other useful goods.

Pure and Low Emissions

By using plasma gasification instead of conventional burning techniques, hazardous emissions are reduced. Pollutants and dangerous materials are destroyed in part because of the elevated temperatures and regulated environment. The impact on the environment can be decreased by designing the process to catch and recover specific contaminants.

A comparatively small amount of inert, vitrified residue—often referred to as slag—is left over from the operation. There is less need for landfills because this stable slag can be utilized to make building materials.

Recovering Energy

A high-temperature plasma method makes it possible to recover energy from the fuel effectively. You can use this recovered energy to heat other industrial operations or to produce power.

Reduced Emissions of Greenhouse Gases

Entrained flow plasma gasification can help reduce greenhouse gas emissions by preventing the release of methane from landfills and lowering the dependency on fossil fuels by turning waste into syngas and recovering energy.

Possibility of Treating Hazardous Waste

Plasma gasification is a good method for treating hazardous waste because of its high temperatures and regulated settings, which allow for the breakdown and conversion of dangerous compounds into less damaging components.

1.1 Objective

This Thesis is mainly a combination of Two Supplements and work performed during the doctoral study. The overall aim of the Thesis is to investigate and give a useful solution for sewage sludge for energy production and characterize the behavior of sewage sludge. For this purpose, the novel technique of Plasma Gasification is used as well as Hydrothermal Carbonization.

- Selection of Sewage Sludge and Hydrothermal Carbonization at different temperature

- Dewatering and characterization of Sewage Sludge
- Made an Experimental setup for Plasma Gasification
- Investigation of the result after Plasma Gasification
- Use of residues after Plasma Gasification experiment

1.2 Thesis Structure

This Thesis is organized into five main chapters. It starts with an introductory chapter containing the main objectives of doctoral study as well as the thesis contribution to sustainability. This chapter is a brief overview of Energy and material recovery from sewage sludge and the importance of Hydrothermal Carbonization and Plasma Gasification.

Chapter 2 contains the summary of materials, facilities, and methods used in the experimental studies.

Chapter 3 Presents and discusses the results of the works performed within the doctoral study. Subchapter 3.1 is based on the work conducted within this segment where the characterization of sewage sludge was performed. Subchapter 3.2 covers the Dewatering after Hydrothermal Carbonization results. Subchapter 3.3 is based on the summary of results from plasma gasification of sewage sludge. Subchapter 3.4 covers the elemental analysis of Ash after and before Plasma gasification. In addition, Subchapter 3.5 discusses the analysis of SEM/EDX. Subchapter 3.6 discusses the analysis of tiles which are made of ash and clay.

Chapter 4 closes the thesis with a compilation of the overall concluding remarks and recommendations for future work.

1.3 Thesis Contribution to Sustainability

Sustainable Development Goals (SDGs) 7, 9, and 13, which are either directly or indirectly related to renewable energy and the environment, are the focus of the study because they are related to energy efficiency and the global environment. Hopefully, the advancement of research, such as that which is offered here, offers a chance to create action plans that can incorporate more ecologically conscious tactics to promote sustainability.

SDG 7 seeks to guarantee that everyone has access to modern, affordable, dependable, and sustainable energy [104]. Over the past ten years, waste gasification systems have become remarkably popular, enhancing energy efficiency, growing the use of renewable energy in the electrical sector, and facilitating access to electricity [105]. Waste gasification can provide the production of renewable fuels and clean technologies for the co-generation and supply of energy, gas, and heat. Residential gasification is underused and can be framed as a real solution to inequalities in access to reliable energy, especially in rural and peri-urban areas of the world [106]. Although many efforts to improve the energy system have shown some improvements, there is still a long way to go, as there is a huge gap to be achieved in terms of reducing the costs associated with implementing gasification plants to supply these demands; stagnant progress being seen in terms of providing incentives [107]. To successfully develop society.

SDG 9 is focused on creating resilient infrastructure, encouraging inclusive and sustainable industrialization, and encouraging innovation [104]. To meet future needs, industries, and infrastructure must be modern and sustainable. challenges to unleash dynamic and competitive economic forces. Gasification functions by giving trash a value and extending its useful life in the economy, in line with the ideas of the circular economy [108]. Gasification plants present a huge potential, particularly for emerging nations that are compelled to invest more in research and innovation and strengthen their industrial sectors [109]. In addition to providing new opportunities, the establishment of an organized network of small-scale gasification enterprises would address logistical issues. Urgent action is required to combat climate change and its effects, according to SDG 13 [104]. Since CO_2 and other greenhouse gas emissions from the environment have reached all-time highs, it is becoming more and more important to put plans in place to reduce these emissions. An excellent example is plasma gasification, which outperforms other waste management techniques and produces cleaner syngas, which can be used to manufacture several different commodities, most of which are derived from sources that rely on fossil fuels [110-112].

Technologies used in the treatment and valuation of sewage sludge include hydrothermal carbonization (HTC) and plasma gasification, which support sustainability in several ways-

- Waste Volume Reduction: The amount of sewage sludge produced is greatly decreased by both approaches. HTC accomplishes this by turning the sludge into hydrochar, a substance rich in carbon, whereas plasma gasification turns it into syngas, a combination of carbon monoxide, hydrogen, and solid waste (slag). This decrease lessens pollutants in the environment and eases the load on landfills.
- Energy Production: Using plasma gasification, organic material in sewage sludge is transformed into syngas, which can be utilized as a feedstock for chemical production or as a means of creating energy. Similar to this, the high calorific value of the hydrochar generated from HTC makes it suitable for use as a solid fuel, aiding in energy recovery and lowering dependency on fossil fuels.
- Nutrient Recovery: Phosphorus and nitrogen, which are plentiful in sewage sludge, can be recovered more easily through hydrothermal carbonization. By using these nutrients as fertilizers, we may complete the cycle of nutrients and lessen our reliance on artificial fertilizers.
- Greenhouse Gas Emission Reduction: Both technologies can lower greenhouse gas emissions by turning sewage sludge into electricity or other products. Fossil fuel offsets, a decrease in landfill methane emissions, and the possibility of carbon sequestration by soil application of hydrochar all contribute to this.
- Toxicity and Pathogen Reduction: High temperatures are applied to the sewage sludge during both processes, which aid in the destruction of pathogens and the breakdown of hazardous

organic compounds. This results in the creation of by-products that are safer, easier to handle, and have a wider range of uses.

- Diverse Product Generation: HTC's hydrochar has several uses, such as soil amendment, carbon sequestration, and replacement of activated carbon. Syngas from plasma gasification can be further processed to yield a wide range of compounds and fuels.

Hydrothermal carbonization and plasma gasification of sewage sludge are potential technologies in the route toward sustainability since they handle waste management challenges, aid in the production of renewable energy, and facilitate the recovery of precious resources. However, depending on the precise procedures, feedstock properties, and operating circumstances, these technologies' efficacy and environmental impact may differ. To optimize their sustainability benefits, ongoing research, technology advancements, and thorough lifetime assessments are therefore crucial.

1.4 Energy and Material Recovery from Sewage Sludge

With its advantages for the environment and the economy, energy and material recovery from sewage sludge are essential parts of sustainable waste management. The following are the main elements of recovering materials and energy from sewage sludge:

Recovering Energy

- Anaerobic Digestion: This extensively utilized process creates biogas (mostly methane and carbon dioxide) as microorganisms break down organic waste in the absence of oxygen. Biogas can be converted to biomethane for use as fuel or used to produce heat and electricity.
- Incineration: Heat and power can be produced by incinerating sludge. The heat produced is used to dry the incoming wet sludge, and any extra heat can be used to create power or district heating.
- The thermal processes of gasification and pyrolysis turn organic materials into char and syngas, which are a mixture of hydrogen, carbon monoxide, and other hydrocarbons. The pyrolysis oil can be processed into chemicals or fuels, and the syngas can be utilized to produce energy.
- Hydrothermal Processes: These methods, which include hydrothermal carbonization and hydrothermal liquefaction, turn sludge into fuel-grade hydrochar, oil, or gas.

Content Recuperation

- Nutrient Recovery: It is possible to extract and utilize as fertilizer certain nutrients found in sewage sludge, such as potassium, phosphorus, and nitrogen. Nutrient recovery techniques include struvite precipitation, ammonia stripping, and ash leaching.
- Soil Amendments: Often known as biosolids, treated sewage sludge is applied to agricultural land as a soil conditioner, enhancing soil structure, retaining moisture, and supplying nutrients.

- Metals Recovery: From sewage sludge, sophisticated treatment techniques can extract rare earth elements and trace metals. These can be recycled and applied to several industries, such as agriculture and electronics.
- Water Recovery: Water from sludge can be collected and treated further for reuse, hence lowering the need for freshwater sources. Procedures like dewatering and drying accomplish this.
- Carbon Sequestration: You can sequester carbon and lower greenhouse gas emissions by adding hydrochar (from hydrothermal carbonization) or biochar (from pyrolysis or gasification) to the soil.

1.5 Importance of Hydrothermal Carbonization

The process of hydrothermal carbonization (HTC) of sewage sludge has become increasingly important in the last few years because of all its advantages, both economically and environmentally. The following are the main points emphasizing its significance.

(I) Waste Management and Reduction

- Volume Reduction: HTC greatly lowers the amount of sewage sludge, improving the effectiveness of waste management.
- Stabilization: By stabilizing the biomass, it lowers the possibility of offensive odors and the spread of pathogens.

(II) Recovering Energy

- Production of Biofuel: The procedure produces hydrochar, a solid with a high carbon content that can be utilized as a renewable fuel and provide a long-term energy source.
- Energy Consumption Reduction: HTC uses less energy since it operates at a lower temperature than other thermal treatments like gasification and pyrolysis.

(II) Environmental sustainability

- Greenhouse Gas Reduction: HTC can lower emissions of methane, a strong greenhouse gas, by keeping waste out of landfills.
- Carbon Sequestration: When used as a soil amendment, hydrocarbon sequesters carbon, which helps to slow down global warming.

(IV) The fourth is nutrient recovery

- Fertilizer Production: By helping to recover important elements like phosphorus and nitrogen, HTC can help produce fertilizers that work well.
- Soil Improvement: The application of hydrochar as a soil supplement can enhance soil quality, water retention, and fertility.

(V) Financial gains

- Cost-Effective Treatment: By treating sewage sludge, HTC can be a less expensive option than more costly disposal techniques.
- Revenue Generation: HTC's byproducts, like hydrochar, can be sold to bring in extra money.

(VI) Pollutant Reduction

- Lowers Toxic Substances: By lowering the levels of heavy metals and other pollutants in sewage sludge, HTC can contribute to the safer use and disposal of the final products.

(VII) Flexibility and Versatility

- Suitable for a Range of Biomasses: HTC's versatility in waste management is enhanced by its capacity to treat organic wastes other than sewage sludge.
- Integration with Current Infrastructure: It can be included in waste treatment facilities already in place, improving the functionality of the systems in place.

The method can assist in adhering to strict environmental requirements concerning the disposal and treatment of trash, as well as policy and regulation compliance. It also meets regulatory standards.

In conclusion, the benefits of hydrothermal carbonization of sewage sludge include improved waste management, resource recovery, economic advantages, and environmental benefits. Technologies like HTC are essential to attaining the global shift towards more sustainable practices.

1.6 Importance of Plasma Gasification

Sewage sludge is a result of wastewater treatment that can be managed creatively with the help of plasma gasification, a modern waste treatment method. The effectiveness of this procedure and its advantages for the environment are drawing attention. To treat sewage sludge in particular, plasma gasification is important for several reasons.

(I) Effective Reduction of Sludge

- Volume Minimization: By significantly lowering the amount of sewage sludge produced, plasma gasification relieves strain on landfills.
- High-Temperature Treatment: The process's high temperatures guarantee the organic matter's full breakdown, which effectively reduces sludge.

(II) The second is energy recovery

- Syngas Production: The procedure turns sewage sludge into syngas, a useful energy source that can be utilized as a feedstock for chemical synthesis or to generate electricity.
- Renewable Energy Source: By producing syngas from sewage sludge, you may lessen your reliance on fossil fuels.

(III) Advantages for the Environment

- Decreased Greenhouse Gas Emissions: Plasma gasification lowers methane emissions, a major greenhouse gas, by removing sludge from landfills.
- Safe Removal of Dangerous Contaminants: The procedure is safe for the environment because the high temperatures kill microorganisms, poisons, and pharmaceutical residues.

(IV) Resource Recovery

- Nutrient and Metal Recovery: The procedure makes it possible to extract nutrients and metals from the sludge, which may then be utilized again in a variety of ways.
- Slag Utilization: By using the generated inert slag in the building, less new material will be needed.

(V) Waste Management Advances

A Novel Approach to Sludge Management Plasma gasification is a cutting-edge approach to managing sewage sludge that is in line with contemporary waste-to-energy projects.

(VI) Encouragement of a Circular Economy

Transformation of Waste into Valuable Resources: Plasma gasification promotes the ideas of a circular economy by transforming sludge into energy and other beneficial products.

In conclusion, the potential for plasma gasification of sewage sludge to effectively manage waste, recover energy, lessen environmental effects, and support sustainable waste management methods makes it significant. It is an innovative method of addressing the growing problem of disposing of sewage sludge in an inexpensive and environmentally responsible manner.

2. Materials and methods

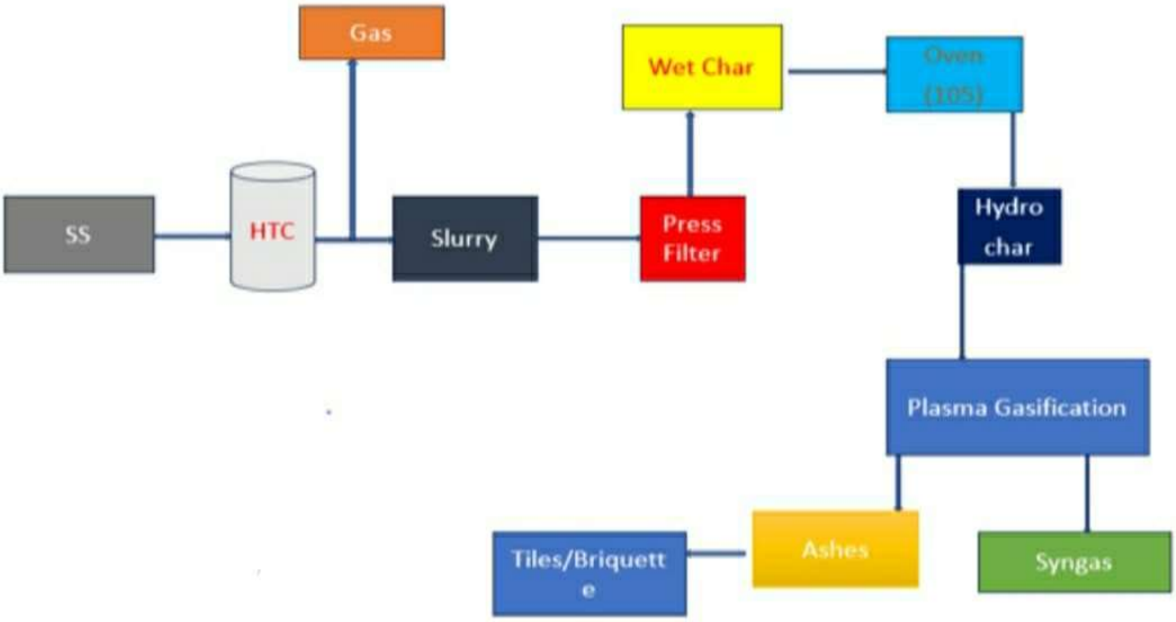


Figure 2.1 Flow chart of the experiment

2.1 Feedstock

Sewage Sludge samples were collected from the Municipal wastewater Treatment plant, in Aarhus, Denmark, and The Janówek Municipal Wastewater Treatment Plant, located in Wroclaw, Poland. There are anaerobic digestion reactors in the Janówek factory. A rotating drum dryer is used to dry the sludge following anaerobic digestion. At the dryer's exit, samples of pre-dried sewage sludge were collected. Four types of sewage sludge collected from Denmark (3 types) and Poland (1 type) based on their calorific value, the name is- Primary, secondary, and AD digestive Sewage Sludge Before utilization the samples were allowed to settle to remove excess water, and a sample of settled sample was stored in a 25-litre bucket in a refrigerator at 4 °C. To ensure a homogenous sample for each run, the whole sample was mixed with a mortar paddle attached to an electric drill, and 200 grams was extracted for processing. For Polish Sewage Sludge use 1 kg for processing.

Table 2.1.1 Calorific Value and Moisture Content of Sewage Sludge

S. no.	Sample Description	Calorific Value (MJ/Kg)	Moisture %
01	Primary Sewage Sludge	17.868	87.6
02	Secondary Sewage Sludge	17.076	85.9
03	AD digestive Sewage Sludge	12.723	89.2
04	Janowek Sewage Sludge	15.7	80

2.2 Hydrothermal Carbonization of Sewage Sludge

HTC has therapeutic applications. HTC facilitates hydro-thermal dewatering, which uses the slurry's water to mineralize, deoxygenate, and flocculate the carbon that is there. During this process, hydrolysis will break up organic compounds, while aldol condensation and intermolecular dehydration will make them more aromatic. Through intramolecular dehydration and keto-enol tautomerism, the compounds subsequently aromatize to form a bigger aromatic macromolecule with a hydrophobic core and a lower surface area. The leading dehydration reaction removes a significant portion of the hydroxyl groups of these macromolecules, which are referred to as hydrochar. Because these hydroxyl groups create hydrogen bonds with water, the hydrochar's vicinal water becomes available and decreases because of a decrease in surface area and hydrogen bonds [65]. When HTC is applied to sewage sludge, the hydrothermal reactions that take place kill the dead bacterial cells, converting the bound water to free water and enhancing the dewaterability [66]. Following the dewatering process, most of the interstitial and vicinal water in the sludge turns into free water and ends up in the hydrochar slurry, from which 80–90% of the residual water may be readily extracted [65]. The resulting carbon-rich hydrochar can be utilized again in agriculture as a soil addition for nutrient enrichment, among other uses.

In addition to the two main products—hydrochar and the aqueous phase—the HTC process also yields a gas phase. Carbon dioxide (CO_2) makes up most of this gas phase [66].

Moreover, HTC can contribute to P recycling since P binds to hydrochar during HTC conversion, making P easier to recover from HTC-converted sludge and potentially reusable in agriculture.

HTC leads to the following improvements of the processed fuel (concerning the feedstocks)

- Improved mechanical dewatering (decreased amount of heat required for drying)
- Higher CV (Calorific Value) of the processed fuels
- Increased carbonization of the product (higher C content = making coal in ½ hour instead of millions of years)
- Improved grindability
- More hydrophobic (in comparison to feedstocks)

HTC in Batch Parr reactor

An HTC reactor with a capacity of 450 mL was used for the procedures. 200 grams of well-mixed sewage sludge were added to the reactor during the HTC process. The reactor was then attached to a PID controller (Parr Controller 4836), sealed, weighted, and placed within the reactor heating jacket. After that, the PID controller was heated and adjusted to the appropriate reaction temperature. In this work, the dewatering potential of temperature was evaluated using four reaction temperatures: 180, 200, 250, and 300 °C. The influence of hold temperature was evaluated using two desired residence times: 5 minutes and 1 hour. On the PID controller, residence time was measured from the moment the required reaction temperature was attained. The reactor was taken out of the heating jacket and put in a bucket of cold water to chill the contents when the treatment period was up. The gases were released into the fume cupboard through the opening of the gas valve, which occurred when the reactor's interior temperature reached room temperature. The reactor was weighed, and the gas yield was calculated from the mass differential. After the reactor was opened, the solid and its entire contents were moved to the pressure filter that is detailed below.24 distinct HTC procedures were used in this study, and various environmental factors including temperature and residence time were considered.

Table 2.2.1 *Different parameters for the HTC processes*

HTC			HTC		
Temperature (°C)	Residence Time	Name of the sample	Temperature (°C)	Residence Time	Name of the sample
180	5 minutes	Primary SS, Secondary SS	180	1 hour	Primary SS, Secondary SS, AD Digestive
200	5 minutes	Primary SS, Secondary SS, AD Digestive	200	1 hour	Primary SS, Secondary SS, AD Digestive
250	5 minutes	Primary SS, Secondary SS, AD Digestive	250	1 hour	Primary SS, Secondary SS, AD Digestive
300	5 minutes	Primary SS, Secondary	300	1 hour	Primary SS, Secondary

		SS, AD Digestive			SS, AD Digestive

Importance of residence time

One crucial factor is the residency duration, which can be anywhere from five minutes to many days. Shorter residence times—five minutes or an hour—are the focus of several investigations to develop bio-coal for combustion applications. Reactor throughput can be effectively increased by shorter residence times, notwithstanding the possibility of kinetic restrictions and aromatization prevention. According to Funke (2010) [67] and Hashaikeh (2007) [68], among other writers, HTC can be divided into two stages: the first stage involves hydrolysis and dehydration events, while the second stage involves aromatization and polymerization reactions. The aromatization of the hydrolysis and dehydration fragments are the second-stage processes. To encourage the aromatization of the particles that end up in the liquid phase, the reactor must be kept at a specific temperature. If the residence duration between 180 and 250 °C is increased, the amount of nitrogen will decrease. It is thought that the reactions become more severe with a longer residence duration. Equation (1) (Hoekman et al., 2017) [69] describes how the severity factor, which is used to quantify hydrolytic depolymerization processes, is related to temperature and pressure conditions and is the logarithm of the reaction ordinate. It is possible to produce similar compounds by using higher temperatures and shorter residence times, or by using lower reaction temperatures and longer residence times (Smith et al., 2019) [70].

$$\text{Serverity factor} = \log\left(\text{t} \cdot \exp\left[\frac{(\text{temp } (^\circ\text{C}) - 100)}{14.75}\right]\right) \tag{1}$$

HTC in another reactor

HTC was carried out in an autoclave (Figure 2.2.1) that had a 4000-cc working volume and could sustain 150 bar of pressure and 200 °C of heat. A stirrer is included with the autoclave (Figure 2.2.1). It was not used in the studies, though. In each experiment, an autoclave vessel was first filled with 500 ml of freeboard after 1000 g of sewage sludge was placed inside. Water was then added up to the marking point. After the autoclave was sealed, band heaters on a heating mantle warmed the autoclave vessel. The process temperature was measured and managed by a PLC controller using a K-type thermocouple. Once the installation had cooled down, the products were drained using a clean fabric filter and colander. After the material was drained, it was dried.

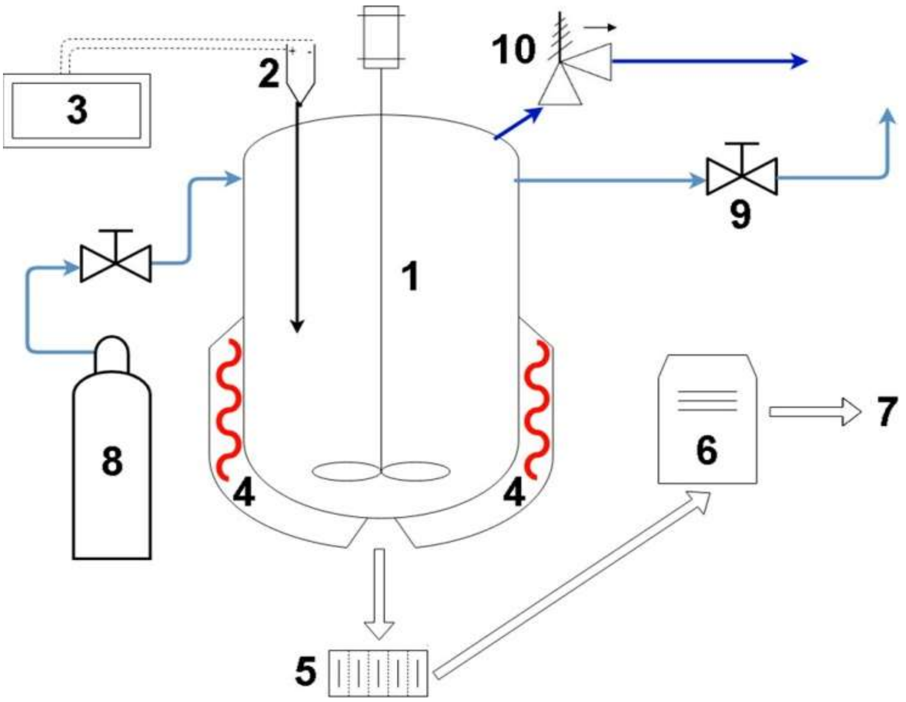


Figure 2.2.1 Diagram of the experimental hydrothermal carbonization (HTC) rig (1–Autoclave; 2–type K thermocouple; 3–PLC controller; 4–heating mantle, with band heaters; 5–draining; 6–dryer; 7–analysis of dry sample; 8–nitrogen for purging; 9–purging valve; 10–pressure relief valve).

***Table 2.2.2** Different parameters for the HTC process of Janowek Sewage Sludge*

Temperature	Residence Time	Name of the Sample
200	4 hours	Janowek Sewage Sludge

The lower temperature range that is typical of the HTC process was the focus of the investigation [71]. Since the residence time affects the output of an installation of a particular size, it was thought to have significant significance for commercial installations. This appears to be in good agreement with reported values for HTC of sewage sludge that is used by commercial HTC reactors [72].

As usual metrics, mass yield (Ym) and energy yield (Ye) were employed to evaluate productivity and performance [73, 74-76]. One of the indirect ways of assessing mass yield was the Weber method [73].

$$Y_m\text{Weber} = 1\text{-}VM_{\text{feedstock}}/1\text{-}VM_{\text{product}} \quad (2)$$

where: *Ym*– mass yield (further part of the subscript indicating a method); *VM*–respective volatile matter content of feedstock and product, $\%_{dry}$

Moreover, the mass yield was also assessed, using a well-established ash tracer method, used for indirect assessment of mass losses, during various thermal conversion processes [77]

$$Y_{m\ ash\ tracer} = A_{feedstock} / A_{Product} \tag{3}$$

where *Ym*–mass yield (further part of the subscript indicating a method);*A*–respective ash content of feedstock and product, dry basis, $\%_{db}$

A well-established formula was used for the calculation of the energy yield [75, 78, 79]:

$$Y_e = Y_m HHV_{product}/HHV_{feedstock} \tag{4}$$

where Y_e–energy yield; *HHV*–respective higher heating value of feedstock and product, MJ/kg

Ash yield was used, as suggested by Wnukowski et al. [80] and Mościcki et al. [81], as a typical indicator of the inorganic's behavior during the HTC process:

$$Y_a = Y_m A_{Product}/A_{feedstock} \tag{5}$$

where: Y_a–ash yield

2.3 Dewatering after Hydrothermal Carbonization

Using a 240 mL batch pressure filter running at 0.1 MPa, a pressure regulator, a 44 cm2 filtration area, and an on/off pressure valve to initiate and terminate the filtration, the silt was filtered. The filter mesh was a Fisher brand QL100 filter paper. After pre-weighing the filter housing without sediment and then again with sediment, it was placed above a Kern balance that was linked to a data logger (Kern Balance Connection), which allowed the weight change to be recorded every second and allowed the rate of dewatering to be calculated. To determine their dewatering behavior, 200 g of raw sediment was tested in addition to the HTC samples.

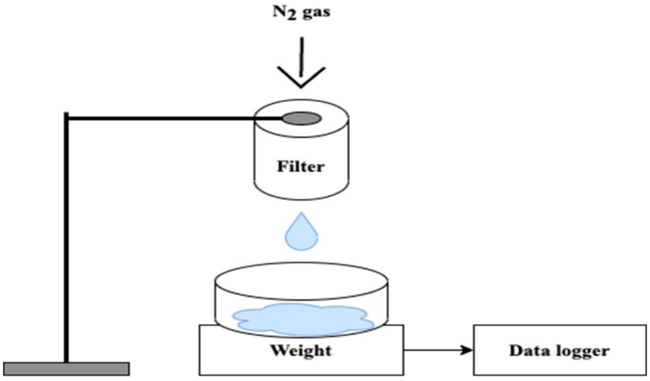


Figure 2.3.1 *Schematic of filtration*

The filtrate was collected for additional analysis following the filtration process. The filter cake was then recovered, moved to an evaporating dish that had already been pre-weighed, and the filter housing and filter cake were weighed. Following the sample's drying, the mass reduction was determined as the remaining water mass, the specific cake resistance was computed using the filtration logging data, and the rotary drum filter's filtration capabilities were assessed. The Kozeny-Carman equation (Biller et al., 2018) [82] applies the following equation (1), which characterizes the pressure loss of the system including the laminar flow across packed beds:

$$\frac{(-\Delta P)_f}{L} = 180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu v_s}{D_P^2}, \tag{6}$$

In situations where the systems are comparable to capillary tubes, Darcy's law is employed as the cake resistance phrase. A function that connects the filtrate volume and rate can be created by correcting the equation (Biller et al., 2018) [82]. Equation (2) follows, assuming that the liquid suspension is uniform throughout the experiment.

$$\frac{\partial \theta}{\partial V} = \frac{\mu \alpha w}{A^2(-\Delta P_t)} \cdot (V + V_e) \tag{7}$$

Where:

$\frac{\partial \theta}{\partial V}$ = *Inverse of rate*$\left[\frac{s}{m^3}\right]$;

μ = *Viscosity* $[Pa \cdot s]$;

α = *Specific resistance of the cake*$\left[\frac{m}{kg}\right]$;

w = *Weight of the solids in suspension divided by the volume of liquid in this suspension*$\left[\frac{kg}{m^3_{water}}\right]$;

A = *Filtration area*$[m^2]$;

V = *Variable volume of filtrate* $[m^3]$;

V_e = *Volume equivalent to the resistance of pipes and filter media*$[m^3]$

This linear relation between $\frac{\partial\theta}{\partial V}$ and V from the equation above can be used to calculate an estimate of the specific cake resistance, α. Data from the filtration tests were used to calculate the numerical derivative $\frac{\partial\theta}{\partial V} \approx \frac{\Delta\theta}{\Delta V}$ to determine its linear correlation with V. Using the calculated specific cake resistance, the filtration rate of a continuous rotary drum filtration system can be estimated using equation (3).

$$V = \frac{2}{3\alpha w}\left(\frac{2\alpha w(-\Delta p)}{\mu}\right)^{\frac{1}{2}} f^{\frac{3}{2}} t_c^{\frac{1}{2}} A \tag{8}$$

Where *w* is the combined solids content in the sludge; Δp is the differential pressure applied to the filtration system (1 bar); *f* is the fraction of the time t_c in which a thin slice of filter area stays in contact with the slurry (50%); t_c is the time for one cycle (30 s, at 2 rpm) and *A* is the filter area (8.38 m^2) (Biller et. al, 2018) [82].

2.4 Experimental facilities

2.4.1 C, H, N, S analysis

After hydrothermal carbonization (HTC), sewage sludge must be thoroughly characterized to comprehend the changes it experiences and to ascertain whether it is suitable for a range of uses. In essence, the HTC process turns wet sewage sludge into a carbon-rich substance known as hydrochar. The following are the main goals for its characterization:

Structure and Carbon Content: evaluating the stability of the carbon structure and the degree of carbonization in hydrochar. This is important for uses such as as a possible fuel source or soil amendment. Finding the concentration of nutrients that are crucial for agricultural applications, such as potassium, phosphorus, and nitrogen, is known as "nutrient content."

Existence of Heavy Metals and Contaminants: Determining and measuring the presence of any hazardous materials to assess threats to the environment and human health.

The PerkinElmer Series II 2400 CHNS/O Analyzer is depicted in the image you have provided. The content of carbon, hydrogen, nitrogen, sulfur, and oxygen in organic and other materials can be measured with this equipment. Here is a basic explanation of its features and operation:

Operational Procedure

- Sample Preparation: A tin (or comparable) capsule is used to seal a tiny, precisely weighed sample.

- Combustion: Next, in the presence of oxygen, the sample is burned at a high temperature, releasing gases as a result.
- Gas Conversion: All combustion products are converted to simple gases such as N_2, CO_2, H_2O, and SO_2 by passing the combustion gases via a reduction tube and other reagents.
- Gas Separation: A chromatographic column is used to separate these gases.
- Detection: Next, a thermal conductivity detector (TCD), which provides a signal according to each gas's concentration, finds the gases.
- Quantification: The percentage of C, H, N, S, and O in the sample is calculated by processing the detector's data.

Details

- Temperature of Combustion: To guarantee that the sample is completely burned, the furnace runs at a high temperature, frequently higher than 900°C.
- The detection limits of these instruments are usually in the parts per million range, meaning that they can detect CHNS/O elements at very low concentrations.
- Sample Size: May differ, but often a few milligrams is enough for analysis.
- Analysis Time: Depending on the sample and the exact methodology, a single analysis may take a few minutes or more.

Typically, a CHNS/O Analyzer diagram would look like this.

- Sample Loader: The location of the sample.
- The furnace used for combustion is where the sample is burned.
- Chemicals in the reduction tube break down the combustion gases into simpler molecules.
- Gas Chromatography Columns: Distinguish the various gases generated during burning.
- The thermal conductivity of the gases, which fluctuates with their concentration, is measured by the detector (TCD).
- Data System: Computes the elemental composition and stores the detector signal.

2.4.2 Thermogravimetric analyzer

The TGA/DT Pyris Diamond, manufactured by Perkin Elmer, was used. The conditions of the experiment with nitrogen and oxygen are 50-105 ^{0}C at 30 ^{0}C/minute, hold for 5 minutes at 105^{0}C, 105-900^{0}C at 10^{0}C/Minute, and Hold for 10 minutes at 900^{0}C.

A PerkinElmer Pyris Diamond TG/DTA, a thermogravimetric/differential thermal analyzer, is depicted in the picture. Below is a broad summary of the features and operation of this kind of instrument:

Operational Procedure

- Sample Preparation: A small quantity of the sample material is ready and put into the instrument's sample pan.
- Heating and Cooling: By a predetermined schedule, the device progressively raises or lowers the sample's temperature.
- Data collection: The device monitors the sample's mass (thermogravimetric analysis, or TGA) and its absorption or release of energy (differential thermal analysis, or DTA) in response to temperature variations.
- Data analysis: Using the data gathered, a thermogram depicting changes in mass and heat flow is made. This thermogram can be examined to ascertain characteristics like moisture content, temperatures at which things break down, thermal stability, and heat of reaction.
- The temperature range of these devices is usually quite broad, ranging from below room temperature to 1000°C or more.
- Sensitivity: A TG/DTA balance can pick up weight variations in the microgram range.
- Heating Rate: Variable; can be carefully adjusted to temperatures that are appropriate for the sample and the analysis.
- Control of Atmosphere: Depending on the needs of the experiment, either reactive or inert gases can be used to regulate the sample environment.
- Software: Includes analysis software to decipher the data and determine the sample material's thermal characteristics.

In terms of the diagram, it usually comprises of the following essential elements.

- a furnace to heat or chill the specimen.
- a balance for tracking variations in weight.
- A pan or holder for samples.
- temperature sensors that measure heat accurately.
- a technique for controlling the gases in the surrounding air of the sample.
- an output system that is linked to data interpretation software.

2.4.3 Microwave Plasma atomic emission spectroscopy (MP AES)

The analytical method known as Microwave Plasma Atomic Emission Spectroscopy (MP-AES) is used to analyze components in different samples quantitatively. It's a kind of atomic emission spectroscopy where the excitation source is a microwave-induced plasma.

Overall MP-AES Operating Procedure

- Desolvation: The solvent in the aerosol evaporates in a desolvation chamber, leaving behind tiny droplets of the sample.
- Excitation: A microwave source creates the plasma into which the droplets are introduced. The atoms in the sample are excited by the plasma's high-energy environment.
- Emission: When excited atoms return to their ground state, they release light at distinctive wavelengths.
- Detection: A spectrometer divides the emitted light into its constituent wavelengths, which are then picked up by a detector (often a charge-coupled device, or CCD).
- Data processing: The concentration of components in the sample is quantified by measuring the intensity of light emitted at wavelengths.

General MP-AES Specifications

- Plasma Origin: Plasma generated by microwaves.
- Detector: For multi-element analysis, a CCD detector is usually used.
- Spectral Range: Generally, spans the range required to study the elements of interest (usually from 190 to 900 nm), depending on the architecture of the spectrometer.
- Resolution: Enough to distinguish between the atomic emission lines of various elements, although dependent on the spectrometer's grating and slit width.
- Sensitivity: Able to identify element concentrations in parts per billion (ppb).
- Sample Throughput: This can vary, although contemporary systems are built for fast analysis times per sample and comparatively high throughput.

MP-AES Simplified Diagram

The following elements might be included in a simplified diagram:

- The nebulizer and spray chamber are included in the sample introduction system.
- Microwave Generator: Generates the necessary microwave energy to form the plasma.
- Plasma Torch: The area of excitation of the sample.
- Spectrometer: Distinguishes the wavelengths of light.
- Detector: Gathers light emissions and transforms them into an electrical signal.
- Computer: For analyzing and processing data.

2.4.4 Atomic absorption spectroscopy (AAS)

An "Analyst 400" PerkinElmer Atomic Absorption Spectrometer (AAS) is depicted in the picture. With the use of atomic absorption spectroscopy, one can determine the amounts of various elements in a sample by examining the light that each element's vaporized atoms absorb.

How an Atomic Absorption Spectrometer Operate

- Sample Introduction: A nebulizer that produces a fine mist is usually used to introduce a liquid sample into the apparatus.
- Atomization: The sample mist is evaporated to create ground-state atoms when it enters a flame or a graphite furnace.
- Light Absorption: The vaporized sample is penetrated by a light beam whose wavelength corresponds to the element of interest. A portion of this light is absorbed by the element's atoms.
- Detection: A detector measures the light intensity drop brought on by absorption, and this measurement is used to determine the element's concentration in the sample.
- Data Analysis: To determine the element's concentration, the instrument's software examines the data and compares the absorption to calibration curves.

Features of the Analyst 400

- Detection Method: Depending on the particular configuration, vapor, furnace, or flame.
- Elemental Range: Able to analyze various non-metals as well as a broad spectrum of metals.
- Sensitivity: Depending on configuration, it can identify concentrations as low as parts per million (ppm) or as high as parts per billion (ppb).
- Wavelength Range: Generally, encompasses the range required to analyze the majority of interesting aspects.
- Light source: electrodeless discharge lamps or hollow cathode lamps designed specifically for the element under test.

An AAS's Simplified Diagram

An AAS's basic schematic would normally show the following:

- System of Sample Introduction: In this system, a sample solution is presented.
- Nebulizer: Produces an aerosol from the liquid sample.
- Atomizer: The device that turns the sample aerosol into atoms, either by flame or graphite furnace.
- Monochromator: Separates the particular light wavelength that the element absorbs.

- Light Source: Produces light with a particular wavelength.
- Detector: Determines the light's intensity both before and after it enters the sample.
- Computer/Readout: For processing the data and showing the findings.

2.4.5 Scanning Electron Microscopy with energy dispersive X-ray spectroscopy (SEM/EDX)

SEM-EDX or SEM-EDS or scanning electron microscopy combined with energy-dispersive X-ray spectroscopy, is a potent analytical method for determining the morphology and elemental makeup of materials.

Electron Microscopy (SEM) for Scanning

SEMs are a kind of electron microscope that uses a concentrated electron beam to scan a sample and create images of it. The sample's atoms and electrons interact to produce signals that reveal details about the composition and surface topography of the sample. The following are the main benefits of SEM:

- High Magnification and Resolution: Compared to optical microscopes, SEMs can attain far greater magnifications and resolutions, making it possible to see structures at the nanoscale scale.
- Depth of Field: SEM has a large depth of field, which gives the sample a three-dimensional look and enables a more realistic understanding of the structure.
- Surface Imaging: SEM is extremely useful in a variety of disciplines, including materials science, biology, geology, and more. It is especially skilled at studying surface features.

X-ray energy-dispersive spectroscopy (EDX, often known as EDS)

An analytical method called elemental analysis or chemical characterization of a material is called EDX. Inner-shell electrons may be dislodged from the material when the SEM's electron beam collides with it. After that, as outer-shell electrons occupy the vacancy, the atom releases X-rays. These X-rays' energy is indicative of the element from which they were released. EDX entails:

- Elemental Identification: X-rays are gathered by EDX detectors, which then compare the energy levels of the radiation to elements listed in the periodic table. EDX is largely a qualitative method of analysis, but it can also yield semi-quantitative data about the sample, such as an estimate of the relative abundance of various elements.
- Mapping: The distribution of elements within the scanned area of the sample is displayed visually in elemental maps, which may be made using EDX.

SEM-EDX In tandem

When combined, SEM and EDX offer a thorough study of the sample by connecting the elemental data from EDX with the visual, topographical data from SEM. This combination enables scholars to:

- Ascertain the phase or particle composition seen in the SEM pictures.
- Determine which materials include inclusions or impurities.
- Draw a map of the elemental distribution on the sample's surface. This method is commonly applied in fields where knowledge about the surface and composition of a material is essential, such as forensic science, research and development, quality control, and failure analysis.

  A "Thermo Scientific Prisma E" device, which appears to be a scanning electron microscope (SEM) based on the context. SEMs are strong tools for capturing detailed pictures of a material's surface.

Typical SEM Operating Procedure

- Electron Generation: A high-energy electron beam is produced using an electron cannon.
- Beam Focusing: The electron beam is finely focused using electromagnetic lenses.
- Mechanism of Scanning: A raster pattern is created as the electron beam moves across the specimen's surface.
- Signal Collection: A variety of signals, such as secondary electrons, backscattered electrons, and distinctive X-rays, are produced when the electron beam hits the object.
- Image Formation: Detectors gather these signals and utilize them to create an image.
- While backscattered electrons can provide compositional information, secondary electrons are usually utilized to image the topography.
- Vacuum System: To prevent air molecules from interfering with the electron beam's path, the entire procedure takes place in a vacuum.
- Display and Analysis: An image is created on a computer display by processing the signals. The surface composition and structure of the material under examination can be seen in the photograph.

General SEM Specifications

- Resolution: SEMs can have resolutions better than one nanometer, depending on the apparatus.
- Magnification: Varying, usually between around 10x to more than 500,000x.
- Field emission gun (FEG), tungsten filament, or lanthanum hexaboride (LaB6) are examples of electron sources.

- Detectors: X-ray detectors for elemental analysis, backscattered electrons, and many kinds of secondary electron detectors.
- Accelerating Voltage: 0.5 to 30 kV is the typical range, though it can vary.

An SEM's simplified diagram

- An SEM's simplified diagram would look like this:
- The electron source is called an electron gun.
- The electron beam is focused and controlled by electromagnetic lenses.
- Sample Chamber: The area in which the sample is kept.
- Detectors: Gather various signal kinds for analysis and imaging.
- The vacuum system keeps the SEM operating at the necessary pressure.
- Computer/Display: Produces the picture and makes additional analysis possible.
- Field emission gun (FEG), tungsten filament, or lanthanum hexaboride (LaB6) are examples of electron sources.
- Detectors: X-ray detectors for elemental analysis, backscattered electrons, and many kinds of secondary electron detectors.
- Accelerating Voltage: 0.5 to 30 kV is the typical range, though it can vary.

2.4.6 Bomb Calorimeter

The increased heating value was computed by ISO 1928 using the IKA C2000 basic bomb calorimeter. We applied the isoperibolic approach. Perkin-Elmer 2400 analyzer was used for the final analysis by Polish standard PKN-ISO/TS 12902:2007. To calculate the gross calorific value of solid and liquid combustibles, calorimetric measurements can be carried out using the IKA C2000 basic bomb calorimeter in compliance with ISO 1928.

Complete Operation of a Bomb Calorimeter

- Sample Preparation: The calorimeter bomb's crucible is filled with a predetermined amount of the sample.
- Oxygen Filling: Next, oxygen is pumped into the bomb at a high pressure.
- Assembly: After sealing the bomb, it is put inside the calorimeter vessel that has been filled with a certain amount of water.
- Ignition: The sample is electrically ignited, and in the presence of oxygen, it burns up.

- Temperature Measurement: A thermometer or temperature sensor is used to measure the temperature change in the water within the surrounding vessel as a result of the heat from combustion.
- Computing: The sample's calorific value is determined by measuring the water's mass, specific heat capacity, and temperature change. Adjustments could be made for the production of nitric acid and heat exchange with the environment.

The IKA C2000 basic bomb calorimeter specifications are as follows:

- Measurement Range: Usually capable of obtaining a highly accurate measurement of a sample's calorific value.
- Sensitivity: Excellent ability to pick up on minute temperature variations.
- Oxygen Fill Pressure: Typically, a high pressure—often about 30 atm—is applied when filling oxygen.
- Sample Size: Depending on the material being examined, this is often a few grams.
- Precision: Extremely high precision to guarantee precise calculation of the calorific value.

2.5 Plasma Gasification of Sewage Sludge

Background and Objectives

The remaining semi-solid substance left over after wastewater treatment presents serious disposal and environmental issues. This material is called sewage sludge. While some processes, like incineration, can be expensive and emit toxic emissions, traditional methods, like landfilling and ocean dumping, have significant ecological implications.

Sewage sludge is a result of wastewater treatment that can be managed creatively with the help of plasma gasification, a modern waste treatment method. The effectiveness of this procedure and its advantages for the environment are drawing attention. Here is a thorough explanation of the goals of sewage sludge plasma gasification:

- **Need for Sustainable Solutions:** Stricter wastewater treatment laws and growing urban populations are driving up the volume of sewage sludge, which calls for effective and sustainable treatment methods.
- **Technology:** Plasma gasification is a sophisticated thermal process that turns solid waste into vitrified slag and organic materials into synthetic gas (syngas) using a plasma torch. At temperatures beyond 2300 ° C (for small plasma reactor0.5 kg) and 3,000°C (for 15 kg

feedstock capacity), plasma—a highly ionized or electrically charged gas—can completely decompose organic compounds.

- **Volume Reduction:** A major goal of plasma gasification is to drastically cut the amount of sewage sludge produced. A limited quantity of inert slag is left behind when the process turns organic components into syngas, reducing the mass of the waste.
- **Energy Recovery:** An important source of energy is the syngas generated during the process of plasma gasification. It can be used as a feedstock for making chemicals or as a means of producing power. Its main components are hydrogen and carbon monoxide. This helps the healing process become more energy independent.
- **Environmental Protection:** Because plasma gasification operates at significantly higher temperatures than typical incineration, it produces fewer toxic pollutants such as furans and dioxins. The procedure is made with the environment in mind, minimizing the ecological impact of disposing of sewage sludge.
- **Resource Recovery:** Resources can be recovered thanks to the method. As a byproduct of gasification, vitrified slag can be utilized to make building materials, which helps with sustainable resource management.
- **Regulation Compliance:** Plasma gasification aids in meeting the ever-tougher environmental standards about emissions and waste management.
- **Innovation and Efficiency:** When compared to conventional approaches, technology offers a more efficient approach to waste management. In the framework of the circular economy and sustainable urban management, it is regarded as a progressive approach.

In summary, the process of plasma gasification of sewage sludge is consistent with international initiatives aimed at energy recovery, sustainable waste management, and environmental preservation. It provides an effective, hygienic, and cutting-edge technological response to the problems associated with conventional sewage sludge disposal techniques.

There are two different kinds of gasification technologies: entrained flow gasifiers and fixed bed gasifiers. Each has unique properties and working theories. The following are the main distinctions between fixed bed gasifiers and entrained flow gasifiers-

1. Feedstock Flow

Entrained Gasifier Flow

The feedstock, which can be trash, biomass, or coal, is fed into entrained flow gasifiers as fine particles suspended in a high-velocity gas stream.

Effective gasification is achieved when the feedstock is thoroughly mixed and reacts quickly with the surrounding gas due to its entanglement in the gas flow.

Fixed Bed Gasifier

The feedstock is usually placed within fixed-bed gasifiers in a stationary bed or layer.

As the feedstock descends, the gasification reactions go from the top to the bottom of the bed, with gasification happening at various points along the bed.

2. The temperature at Operation

Entrained Gasifier Flow

Works at temperatures that are normally over 1,500 degrees Celsius (2,732 degrees Fahrenheit).

The efficient conversion of feedstock into syngas is facilitated by the high temperatures attained through the use of a plasma torch or other heat sources.

Fixed Bed Gasifier

Runs at a lower temperature than gasifiers with entrained flow.

Temperatures during gasification reactions are typically lower than those in entrained flow gasifiers.

3. Staying Time

Entrained Gasifier Flow

Due to the gas stream's high velocity, feedstock particles have a brief residence period in the gasifier.

The feedstock can be converted into syngas quickly and effectively thanks to its short residence period.

Fixed Bed Gasifier

longer dwell period while the feedstock particles pass through the stationary bed.

Longer residence times have the potential to promote more thorough gasification reactions, but they may also cause more tar to develop.

4. Flexibility of Feedstock

Entrained Gasifier Flow:

Ideal for a variety of feedstocks, including as waste materials, biomass, and coal.

The adaptability of entrained flow gasification is facilitated by its capacity to handle a wide range of feedstocks.

Fixed Bed Gasifier

The fixed bed gasifier's particular design and configuration determine which feedstocks are suitable for it. Certain feedstock types are better suited for particular types of fixed-bed gasifiers, and modifications may be required for various materials.

5. Formation of Tar

Entrained Gasifier Flow

Tends to create less tar because of the high temperatures and brief residence time, which reduce the number of secondary reactions that result in the creation of tar.

Fixed Bed Gasifier

Fixed bed gasifiers have longer residence times, which may increase the generation of tar and necessitate more cleaning procedures.

The process of breaking down raw material molecules into their constituent elements at high temperatures and atmospheric or increased pressures is known as gasification [113]. The aforementioned intricate procedure needs to be executed with a gasifying agent present, such as steam, air, oxygen, carbon dioxide, or even combinations of these [114-116]. Synthesis gas is produced when the raw material is exposed to a sub-stoichiometric oxygen level. This gas mostly consists of hydrogen, carbon monoxide, methane, carbon dioxide, branched hydrocarbons, tars, and a very small amount of nitrogen [117]. Among its uses are the production of heat, the combustion of this gas in engines to generate electricity, and its use as a raw ingredient in chemical synthesis [118]. Condensable organic molecules called tars are produced during the gasification process. Single to five-ring aromatic hydrocarbons make up most of the hydrocarbons found in tar species, which span a broad range of hydrocarbons [119]. Pyrolysis, which is the process of the high temperatures of the plasma breaking bonds in organic molecules, destroys the organic chemicals found in trash. Through the steam reforming reaction, these ingredients are transformed into synthesis gas—a clean-burning fuel mostly composed of CO, CO_2, and H_2—when steam is introduced into the process chamber. Other waste components that don't volatilize are changed into a molten state, which cools to create vitrified glass that is stable. When the vitrification process is managed, the resulting vitrified glass is stable against substances found in the environment and chemicals and has a strong resistance to the hazardous substances bonded to the glass leaching, demonstrating potential downstream applications [120]. Over 99% of the universe is made up of plasma, the fourth state of matter [118]. It is made up of neutrals, ions, and electrons in both excited and fundamental states. Electrostatic neutrality characterizes plasma from a macroscopic perspective. It is electrically conductive and does include free-charge carriers, though. Applying energy to a gas causes it to restructure its atoms' and molecules' electronic structures, producing excited species and ions, which is how plasma is formed [121]. The utilization of plasma produced from an electrical energy source in atmospheric settings is described in detail [122]. The electrons in the gas that have the highest mobility receive energy from the electric field. This electronic energy is then transmitted to neutral species through collisions, which fall into two categories: elastic and inelastic collisions. These collisions are governed by the rule of probability. Certain species have extended lifetimes since energy is only transferred by collisions, but most stimulated species are very short-lived and only attain their fundamental state. [123][124] state that there are two main types of plasma: thermal and non-thermal. As a result, thermal plasma also referred to as hot plasma, is described as possessing a local thermodynamic balance, which means that all of the plasma's constituents—neutrons, ions, and electrons—have a temperature that is constant along the electric arc's column [123]. Local thermodynamic equilibrium plasma (LTEP) is another name for these. Collisions, not radiation processes, must control chemical transitions and reactions in LTEP. Moreover, micro-reversible collision phenomena are required. As a result, there needs to be an inverse equilibrium for every kind of collision (kinetic equilibrium, excitation/deexcitation, ionization/recombination) [125]. The local gradients of plasma attributes (temperature, density, and thermal conductivity) must be minimal enough for a particle within the plasma to reach equilibrium, and the diffusion time must be at least as long as essential for the particle to attain balance [122]. The temperature of electrons in non-thermal plasma, often referred to as cold plasma or non-local thermodynamic equilibrium plasma (non-LTEP), is, therefore, higher than the temperature of heavy components, like ions and neutral particles [124]. The plasma temperature, also known as the gas temperature, is fixed due to the significant mass difference between electrons and heavier particles, as stated in [122]. The temperature differential increases with increasing LTEP production. The plasma's state—whether it is in LTEP or not—is significantly influenced by the supply's power density. Low power supply density or pulsed power supply (e.g., microwave plasmas) are preferred for non-LTEP, whereas high power density typically causes LTEP (e.g., arc plasmas). A plasma torch, generator, or plastron is a type of thermal and electrotechnical apparatus. In terms of applicability, it is an extremely versatile tool. Today, plasma torches are utilized in continuous steel casting, alloy and ceramic deposition (plasma spraying), welding, melting, and refining of metals, as well as in extrusive metallurgy. Hospital and industrial waste, inertization of hazardous chemicals, and layers and surface-protective metals [126-131]. Moreover, it is used in the production of compounds (such as acetylene and calcium carbide) and the thermal breakdown of materials (such as methane, ethanol, and other fuels to make hydrogen) and novel ceramic materials (such as carbides, nitrides, and oxides). Additionally noteworthy are the applications of plasma torches in waste treatment [132], biomass gasification [133], spheroidization and ceramic phase shift, heat treatment of surfaces, and the recovery of metals from metallurgical fines [118,134] in the reformation of polluting gases [135]. Applications about environmental issues have grown in importance recently [136]. Paredez Angeles [134] claims that there are a few fundamental categories under which plasma torches can be categorized. The most common method of producing plasma is using direct-current electric arc torches, alternating-current electric arc torches, radiofrequency plasma, high-frequency plasma, and ultra-high frequency plasma. plasma at high frequency, ultra-high frequency, radiofrequency, and current. Usually, a direct-current electric arc torch is utilized for conversion. Plasma gasification setups can take on a vast array of torches in terms of both form and arrangement.

One can have a plasma torch made up of one or more non-transferred DC or AC plasma torches, or a plasma torch made up of two non-transferred reverse polarity DC plasma torches, depending on the feedstock and equipment parameters. Induced coupled plasma (ICP) torches are recognized to have certain limitations. Firstly, plasma is hard to ignite at low frequencies (less than 150 kHz). Because of this, the majority of ICP torches uses a high-temperature hollow cylinder in conjunction with an inert and readily ionized gas. susceptor that is filled with the waste substance. A frequency even higher than 150 kHz is used by several ICP torches to ignite the inductively coupled plasma [118]. Second, adding waste material straight into an ICP torch makes it very difficult to maintain the plasma within. Furthermore, the presence of volatiles in the material increases the amount of gas inside the torch. As a result, there is little usage of ICP torches for processing trash inside the torch vessel. This method is used in non-transferred arc plasma torches, such as non-transferred AC and plasma torches with DC arc. With plasma torches, a range of gases have been employed, such as O_2, N_2, Ar, CH_4, C_2H_2, and C_3H_6. LTE discharges can be used to describe classical arc torches. Low-power pencil torches feature a non-LTE discharge—they create a “chemically rich environment” that is employed for low-temperature applications—whereas high-power pencil torches are characterized by relatively high temperatures and are used for applications where heat is required (welding, cutting, spraying, etc.). The cathode and anode electrodes, the gas passage tube, the gas inlet chamber or vortex chamber, the arc stabilization system, and the electrode are the fundamental components that make up the plasma torch chilly [137].

Within an evacuated chamber, the cathode and anode assembly produce the electrical structure known as the electric arc. Thermionic discharge is an electrical discharge that forms when the cathode heats up and some electrons move from the cathode surface towards the anode. The electrons that the cathode emits will collide with the gas molecules when it is delivered into this chamber, ionizing the gas and producing more free electrons to carry out the bombardment process [123]. Godoy [136] asserts that regardless of the arc's length or current, the voltage drop in the electrodes depends on the kind of gas and material utilized to create the plasma. The arc that forms has a voltage depending on the kind, composition, and conditions of the surrounding atmosphere in which the arc is functioning. There are two different kinds of electric arcs: the free electric arc, where natural convection is used to exchange heat with the surrounding gas, and the restricted electric arc, where forced convection is used to exchange heat with the surrounding gas. The plasma torch is more efficient than a free arc because of its roughly six-fold higher temperature [134], which is why it is frequently employed with a restricted arc [137]. Depending on how much they rely on the electrical arc being used, plasma torches can be categorized as non-transferred, transferred, overlapped, or mixed arc. Cathode erosion directly affects the equipment's durability in non-transferred arcs, where the cathode and anode are housed in the same body [136], frequently with tubular and concentric geometries [123]. This kind of arc is typically employed in pyrolysis, melting, refining, reduction, and decomposition processes [138]. When working with a transferred arc, the apparatus uses one electrode on the torch—often the cathode—and the other electrode on the material to be handled [138]. Metals are typically cut using this kind of electric arc [137].

To enable the synthesis gas to reach the energy recovery system, the gas cleaning subsystem must successfully remove moisture, heavy metals, suspended particles, and acid gasses (HCl, SOx). For that reason, A standard gas cleaning system includes the following components-

(a) water quenches to quickly cool the hot, unclean synthesis gas and prevent the production of complicated compounds like dioxins. The quench is used to make sure that dioxins and furans cannot develop. The purpose of the quench is to use an injected water spray to cool the gasses. The typical temperature range for an off-gas outlet is 70–90 ° C.

(b) A packed bed tower scrubber that neutralizes acid gasses by dipping it in a caustic solution. Additionally, the moisture in the gas condenses in the solution when the cold cleaning solution is used.

(c) Particulate removal using a venturi scrubber.

(d) H_2S is extracted using an H_2S absorber and subsequently extracted for sulphur recovery.

(e) Heavy metal and other fine particle entrapment filters. [85]

As seen in Figure 2.5.1 Entrained flow plasma gasification is used in this experiment. sewage sludge was gasified using specially designed equipment. The gear was outfitted with a plasma torch that produced plasma by utilizing N_2. Stainless steel was used to construct the reactor wall, and the refractory was ceramic. A K-type thermocouple that was placed into the top revisory hole was used to measure the temperature at the refractory's edge. The reactor's gasification process involved an entrained flow with a residence time of around one second. The Municipal Wastewater Treatment plant in Janówek in Wrocław, Poland) provided pre-dried sewage sludge. There are anaerobic digestion reactors in the Janówek factory. A rotating drum dryer is used to dry the sludge following anaerobic digestion.

At the dryer's exit, samples of pre-dried sewage sludge were collected. Table 2.5.1 offers an experimental matrix for entrained flow plasma-assisted gasification investigations. Different air-to-fuel ratios (AFR) and plasma-gas-to-fuel ratios (PGFR) were used during gasification with Janowek sewage sludge. Utilizing nitrogen density under standard conditions and flow rates determined with rotameters, mass flow rates of plasma gas were computed. Furthermore, air and fine sewage sludge particles (d < 1 mm) entrained from the gasifier's top auger were fed into the reactor throughout the gasification process. The freeboard, which was situated above the hot plasma streams produced by the plasma torches, received the two-phase mixture from the reactor's top. The reactor's bottom was cleaned of the producing gas (see Figure 2.5.1). Plasma torch tangential placements imposed cyclonic flow within the reactor. In the cleaning system, Dichloromethane (CH_2Cl_2) and NaOH are used to clean the syngas in both systems. NaOH is used to reduce sulfur. To analyze separately the components of syngas, an analyzer is used. The percentage of CO, CO_2, CH_4, H_2 was analyzed by the analyzer. The temperature outside the reactor wall (Figure 2.5.1) is measured by an infrared thermometer i.e. 620-680 ^{0}C.

Table 2.5.1 Experimental matrix for plasma-assisted gasification of pre-dried sewage sludge (R-wall indicates refractory wall).

Exp.ID	AFR	PGFR	I	$T_{R\text{-wall}}$
	–	–	A	°C
I	0.43	6.73	100	650
II	0.33	7.36	80	620
III	0.29	6.73	100	680
IV	0.33	7.85	100	680
V	0.29	6.31	80	620

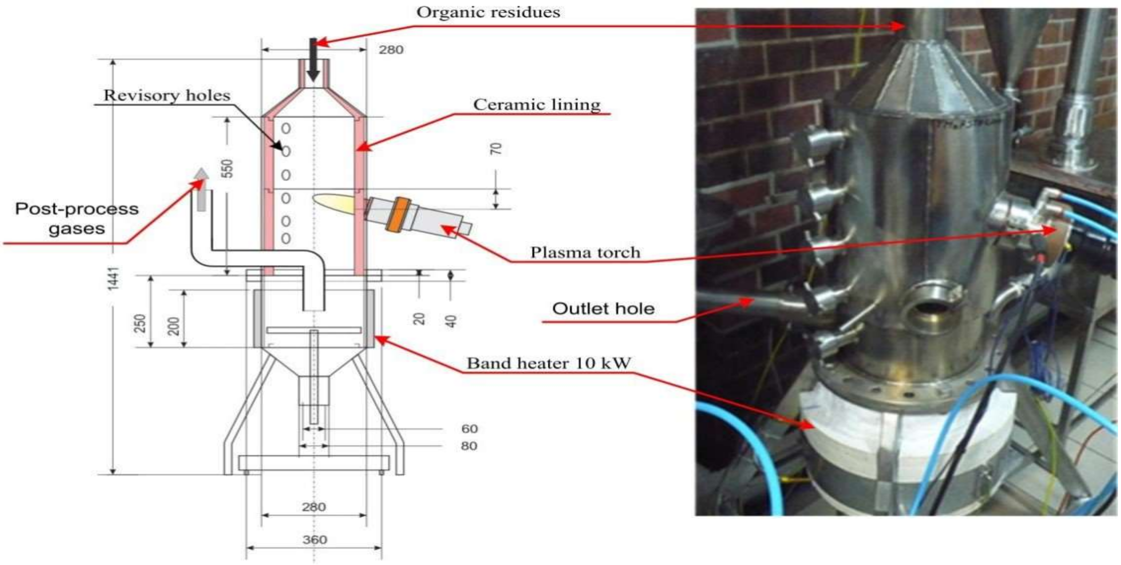


Figure 2.5.1 Experimental rig for plasma gasification of sewage sludge

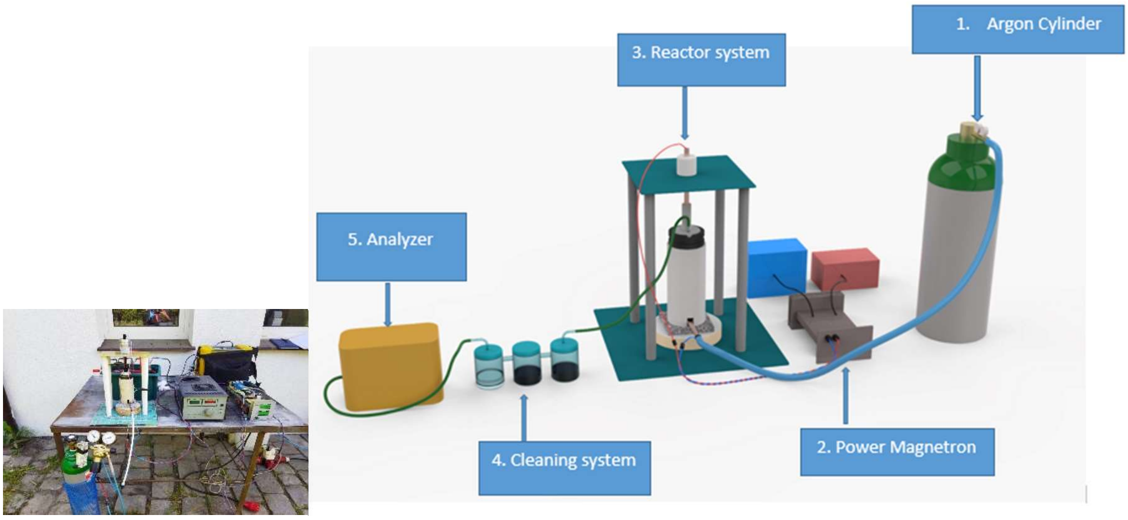


Figure 2.5.2 Experimental setup for plasma gasification of sewage sludge

In Figure 2.5.2 Plasma gasification is a sophisticated thermal process that turns solid waste into vitrified slag and organic materials into synthetic gas (syngas) using plasma. At temperatures beyond 2300 °C (for a small plasma reactor 0.5 kg) plasma—a highly ionized or electrically charged gas—can completely decompose organic compounds.

The goal of the invention is the development of a technology/method for plasma gasification of sludge, chemically and bacteriologically contaminated organic waste (including after their hydrothermal carbonization) using a non-equilibrium LF radio frequency arc plasma, preferably with a plasma channel current in the range of 50-120 kHz, and an AC plasma reactor. preferably with a frequency in the range of 70-100 kHz, the essence of which is the volumetric nature of the action of the plasma in the reaction zone on the processed/processed material while preventing the accumulation of electrostatic charge on the particles of the crushed material and thus its aggregation (merging into larger structures disturbing the plasma process thermal processing. H_2O is used as a gasifying agent to increase the involvement of the present Carbon of Sewage Sludge in the experiment. A fixed-bed plasma gasification reactor is used for this experiment. Different types of sewage sludge are used after different temperatures with different residence time hydrothermal carbonization for this plasma gasification which is it makes unique.

The reactor electrodes (Figure 2.5.4) that produce the plasma are powered by a generator that has a series resonant circuit with a stabilized Q Electric Charge. This is what distinguishes the invention. We convert the system's nature from voltage to current in this way. Arc plasma is used in this experiment. Argon is used for this purpose. The flow of argon is 2.5–3 cubic meters per second. The power of 2-3 KW is used. 23 samples were used as raw material. Synthesis gas is produced in varying amounts. Depending on the size of the samples, 3–4 ml of water is used as a gasifying agent. The reactor length is 125 mm, the inner diameter is 50 mm and the outer diameter is 65 mm in Figure 2.5.3.

Method

In Figure 2.5.2 Firstly particular sample is put in the reactor and some water 3-4 ml then Arc Plasma and Argon are passed into the reactor, the tube which is fixed on the top of the reactor, after a few minutes of the experiment the composition of gases passed through it and the tube is connected with filter glass in which Dichloromethane (CH_2Cl_2) helps to clean it, there is a consecutive chain of filter tube after that the gas is passed in analyzer where the composition of gases collected. The final ash after Plasma gasification is one-third of the initial feedstock. But in some cases, it will be one-fourth of the initial feedstock. The temperature outside the reactor wall is measured by an infrared thermometer i.e. 350-360 ° C.

Novelty

- The invention is characterized by the fact that for the processing of chemically and bacteriologically contaminated organic waste (including after its hydrothermal carbonization), a non-equilibrium LF radio frequency arc plasma in the range of 50-120 kHz is used.

- The reactor length is 125 mm, the inner diameter is 50 mm, and the outer diameter is 65 mm Figure 2.5.3, and the unique design of the rod (300 mm length and 9 mm diameter) Figure 2.5.4 A fixed bed plasma gasification reactor is used for this experiment.
- The plasma channel is generated by a power source with a sinusoidally alternating voltage, preferably with a frequency of 70 - 80 kHz.
- The current of the plasma channel is sinusoidally alternating, continuous during the process, and stabilized to a constant set effective value of current and voltage, which ensures constant plasma power during the process.
- A generator with a series resonant circuit is used to power the reactor electrodes between which the plasma is generated, with a feedback loop and a special fast differential system to control and stabilize the Q system by adjusting the changes like the system from voltage to current. This ensures automated maintenance of the set process parameters - plasma power.
- The subject of the invention is the creation of a concentric reactor for gasification of chemical and biological sludge (including after their hydrothermal carbonization) using high-frequency alternating current plasma (75kHz), the task of which is to prevent the accumulation of electrostatic charge on the dust from the substrate.
- The invention is characterized by the fact that a generator with a series resonant circuit in which Q is stabilized is used to power the reactor electrodes between which the plasma is produced. In this way, we change the nature of the system from voltage to current.
- Water (3-4 ml) is used as a gasifying agent in Figure 2.5.2 setup and CO_2 is used in Figure 2.5.1.
- Plasma temperature inside the reactor is 2300 °C almost.
- Argon gas is used for the experiment. With the flow of 2.5–3 cubic meters per second, the power of 2-3 KW is used.
- Hydrothermal Carbonization firstly is conducted with sewage sludge with one hour and 5 minutes of residence time at 180, 200, 250, and 300 degrees Celsius. Due to this, the carbon is enriched in sewage sludge for Plasma gasification.

The difference between Figure 2.5.1 and 2.5.2

In Figure 2.5.1 the feedstock capacity is 15 kg and it is an Entrained Flow Plasma Gasification System and in Figure 2.5.2 the feedstock capacity is only 0.5 kg and it is a fixed bed system. Based on method and construction figure 2.5.1 also has a difference [83] from figure 2.5.2. The novelty of Figure 2.5.2 experimental setup is mentioned above.

Parts of the Reactor

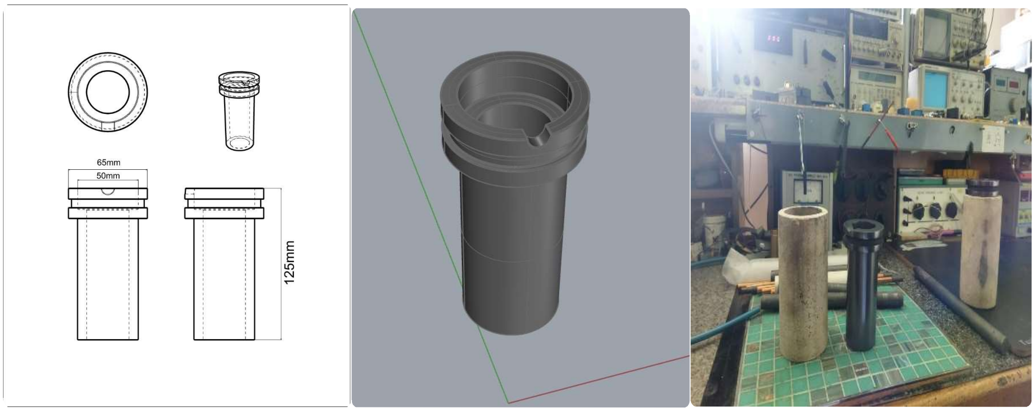


Figure 2.5.3 Reactor cylinder of Plasma gasification setup (Figure 2.5.2)

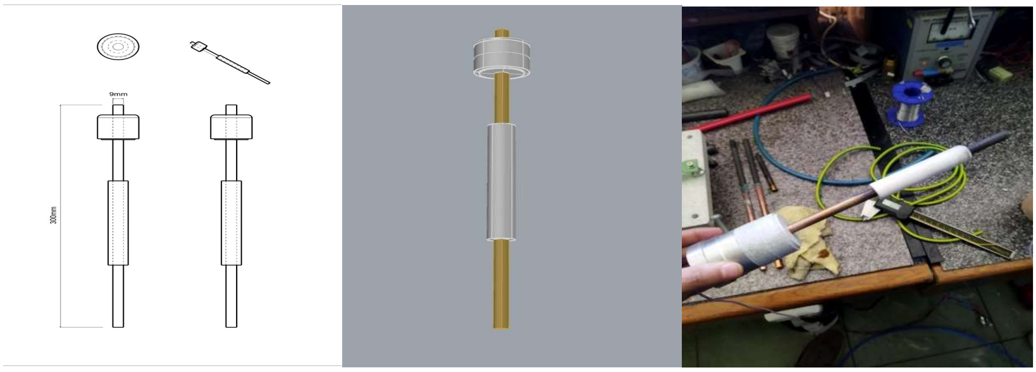


Figure 2.5.4 Rod of reactor system in Plasma gasification setup (Figure 2.5.2)

2.5.1. Gasifying Agent

The most often utilized gasification agents in high-temperature plasma gasification are oxygen, steam, air, and their mixes [139,140]. The effectiveness of air, steam, and steam-oxygen mixes in biomass gasification was compared by Gil et al. [141]. Several authors have proposed that pure steam is the most suitable gasifying agent for increased hydrogen generation since it performs better under operating conditions and in syngas composition (higher H_2 yields and higher LHV) [139,140,142]. Another common application for air is as a gasifying agent. The synthesis gas produced can be utilized to generate heat or electricity, even if its nitrogen content is substantially diluted (LHV typically ranges from 3.5 to 7 MJ/Nm^3) [141-143]. In the co-gasification of wood chips and sewage sludge, Ong et al.[144] investigated various air flow rates and found that raising the reactor's temperature increased flow rates. More energy was released because of the encouragement of exothermic combustion reactions. Additionally, they looked at how the airflow rate affected the composition of the syngas and discovered that when this parameter was raised, the CO concentration increased and the H_2 concentration slightly decreased—possibly because of the promotion of the water-gas displacement reverse reaction. Hernandez et al.'s study [145] supported these findings and demonstrated that adding steam to the air component improves syngas quality by raising H_2 and CH_4 levels. This was examined in [146] as well. Steam gasification of biomass results in the synthesis of gas with a greater H_2 content and heating value (11–20 MJ/Nm^3)[140,147-150]. However, the energy required to raise the temperature is decreased by endothermic reactions [151]. Steam-oxygen gasification accelerates biomass conversion in comparison to steam gasification alone, resulting in a simultaneous rise in CO_2 content and a fall in CO and H_2 content [146,151]. Synthesis gas with a moderate heating value (typically 9–15 MJ/Nm3) can be obtained from O_2-enriched air, but it comes at a higher cost because oxygen generators are needed. Zhou et al. [152] observed great gasification efficiency and enhanced carbon conversion when using oxygen as a gasification agent to treat biomass verifying a reduced LHV for the generated gas. The method of "plasma gasification" involves heating organic materials to extremely high temperatures with a plasma torch to create synthetic gas, or "syngas." The goal of the procedure when it comes to sewage sludge is to convert the complex organic molecules into simpler ones, such as carbon monoxide (CO) and hydrogen (H_2). In this situation, a gasifying agent may play several different roles. CO_2, O_2, and H_2O are used as gasifying agents according to suitability. In Figure 2.5.1 CO_2 is used as a gasifying agent because it helps the Carbon of sewage sludge to decompose easily in Plasma gasification. The goal is to produce syngas and with this syngas, the turbine will run to produce electricity so that the CO_2. is producing a lot in it and this CO_2 is used as a gasifying agent for Plasma gasification. In Figure 2.5.2 H_2O is used as a gasifying agent to increase the involvement of the present Carbon of Sewage Sludge in the experiment.

2.5.2 Ash

Ash from plasma gasification of sewage sludge is not the same as ash from traditional incineration in several ways. Plasma gasification is a technique that turns organic material in sewage sludge into synthetic gas (syngas) by using plasma, a highly ionized or electrically charged gas. What occurs to the ash throughout this procedure is as follows:

- **Volume Reduction:** Because plasma gasification tries to turn as much of the organic material into syngas as possible, it can drastically lower the volume of the original sludge.

- **Change in Composition:** The inorganic and non-volatile elements found in the sludge make up the majority of the ash obtained by plasma gasification. Simpler inorganic compounds can be formed from these components by the extreme heat of the plasma arc.
- **Reduced Organic Content:** The ash produced by plasma gasification usually contains less unburned carbon and other residual organics since it is heated to a higher temperature than traditional incineration.
- **Potential for Vitrification:** Some of the ash may be vitrified—that is, melted at the extraordinarily high temperatures reached during plasma gasification and then solidifying into a glass-like substance upon cooling. By encasing harmful substances in a glassy matrix, vitrification may lessen the likelihood that heavy metals and other pollutants will leach from the material.
- **Toxicity Concerns:** Sewage sludge ash from plasma gasification needs to have its toxicity evaluated, just like conventional ash does. However, some dangerous elements might be better confined due to their increased energy and potential for vitrification.
- **Use as Construction Material:** In certain cases, vitrified ash is utilized as an aggregate in building materials. Its glass-like qualities can offer advantageous qualities like greater durability.
- **Decreased Leachability:** Heavy metals in the slag may be immobilized during the vitrification process, which could result in decreased leachability and make the material safer to dispose of or use in specific applications.
- **Energy Recovery:** The syngas that are created during plasma gasification are a valuable byproduct that may be utilized to manufacture chemicals or electricity, which might potentially balance out the energy spent during the gasification process.
- **Regulatory Aspects:** Ash from plasma gasification cannot be disposed of or reused without following regulations, and it must fulfill specific requirements to be deemed safe for a particular usage.
- **Post-treatment:** The ash may need post-treatment, such as stabilization or more vitrification, before it can be safely disposed of or used, depending on its ultimate composition and intended application.

It's crucial to remember that the feedstock, the particular technology and parameters of the gasification process, and any post-treatment procedures used on the ash can all affect the unique properties of sewage sludge ash from plasma gasification.

2.6 Production of Tiles

The idea of using ash from the plasma gasification of sewage sludge to make tiles is a creative solution to material recycling and waste management. This concept was sparked by the necessity to manage sewage sludge responsibly and the goal of finding uses for its byproducts that add value. Here's a thorough look at the history and goals of this procedure:

- **Background of Sewage Sludge Accumulation:** As a byproduct of wastewater treatment facilities, sewage sludge presents major logistical and environmental issues when it comes to disposal. Sludge is often either burned, landfilled, or utilized in agriculture, all of which have different effects on the environment.
- **Process of Plasma Gasification:** Plasma gasification is a technique that breaks down organic material in the absence of oxygen (pyrolysis) by using extremely high temperatures produced by a plasma torch. When applied to sewage sludge, it converts organic materials into syngas, which is a hydrogen and carbon monoxide mixture and leaves behind an inorganic residue that is sometimes called slag or ash.
- **Waste-to-Energy and Waste-to-Material Concepts:** As the world moves toward more environmentally friendly waste management techniques, researchers are investigating waste-to-energy and waste-to-material strategies, in which waste materials aren't only thrown away but instead are used to produce energy or new materials.
- **Goals of Recycling and Resource Recovery for Ash-Based Tile Production:** The main goal is to recycle the inorganic ash into useful products, adhering to the principles of a circular economy. This ash can be used to make tiles, adding value to what would otherwise be a wasted material.
- **Environmental Sustainability:** By using the ash in the creation of tiles, the demand for landfills is decreased, the negative effects of waste disposal on the environment are lessened, and natural resources that would otherwise be used in tile production are preserved.
- **Economic Viability:** This strategy may help the waste management and tile manufacturing industries financially by turning a waste by-product into a material that can be sold.
- **Innovation in Construction Materials:** Creating tiles out of ash encourages innovation in construction materials by providing maybe special attributes like increased durability or distinctive aesthetic traits.
- **Diminution of Greenhouse Gas Emissions:** This procedure helps to lower greenhouse gas emissions by keeping waste out of landfills and by lowering the need for raw materials.

- **Regulatory Standard Compliance:** The procedure is designed to comply with environmental regulations, guaranteeing that the tiles are safe for use and do not release any hazardous materials.

In conclusion, creating tiles out of the ash left over from the plasma gasification of sewage sludge is a creative solution to the problems of waste management and the manufacture of sustainable materials. It is a prime example of the trend toward novel, sustainable, and profitable waste-to-material approaches. The core of the idea is a ceramic mixture made up of 80–75% clay by weight and 20–25% weight of ashes left over after the plasma gasification of sewage sludge. The final combination is used to manufacture products by pressing them, depending on the amount of ash in it.

2.6.1 Design of Mold

A tile mold is a form or template used in tile manufacture to shape raw materials into tiles. In the tile industry, these molds are essential since they determine the size and shape of the finished product. An outline of several tile mold-related topics is provided below:

Tile Mold Types

- **Molds for plaster:** Traditionally used for handcrafted tiles, molds for plaster draw moisture from the clay and facilitate the easy release of the tile when it has dried.
- **Plastic molds:** They can be produced from a variety of polymers, including ABS, and are robust and moisture resistant. They are frequently used for small-scale production.
- **Metal molds:** Because of their longevity, these molds are typically employed in high-volume production applications. Steel, aluminum, or other metal alloys can be used to make them.
- **Rubber molds:** Provide elasticity and are utilized when complex designs are needed. These molds are often made of silicone.
- **Making of Molds:** Molds can be made by hand or with the aid of specialized machinery such as CNC machines, which are capable of precisely carving solid metal blocks into the shape of the molds that are needed. Molds can be stamped or cast for mass production, which will expedite the manufacturing process and guarantee uniformity.
- **Style and Tailoring:** The size, form, and texture of the intended tile are reflected in the design of the molds. They can be made to fit a variety of aesthetics, from plain, flat surfaces to elaborate relief patterns.

Production Method

To take on its shape, the material (such as clay or concrete) is forced into the mold during the pressing process. In the case of ceramic tiles, the back of the tile may contain ribs or grooves to aid in adherence during installation, while the face design and size are determined by the mold. The raw material is poured into the mold, which is either allowed to set (for cement tiles) or compacted under high pressure (for porcelain tiles). In Figure 2.6.1 the mold is made of metal.

- **Mechanism of Release:** To ensure that the formed tile may be removed without harming the mold or the tile, molds are frequently equipped with a release mechanism or treated with a release agent.
- **Upkeep and Scenario:** Regular cleaning of molds is necessary to get rid of any buildup of raw materials or residues that can compromise the tile's quality. To prolong the life of the molds, especially those composed of less robust materials like plaster or plastic, proper treatment and storage are imperative.
- **Life Expectancy:** A Mold's lifespan is determined by the materials it is built of and the environments in which it is used. Compared to plaster or plastic molds, metal molds are more durable. Fine Molds can create hundreds of tiles before they break or need to be replaced. To sum up, tile Molds are crucial to the tile-making process and come in a variety of materials to accommodate varying production quantities and design specifications. The final tile product's quality and manufacturing efficiency are directly impacted by the material and design of the Mold.

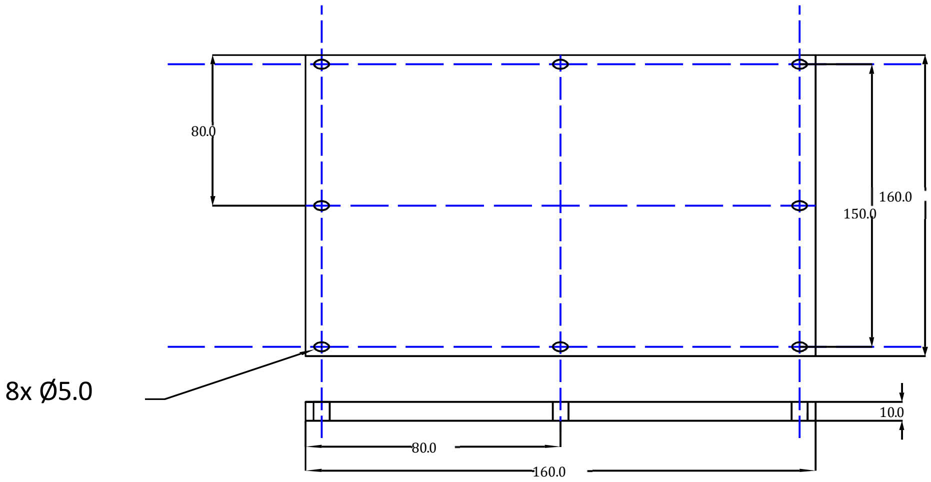


Figure 2.6.1 Mold Diagram

2.6.2 Preparation of tiles

Tile preparation is a multi-step process that starts with raw material preparation, moves on to shaping the tile shape, and ends with applying different finishes. An outline of the typical procedure for creating ceramic tiles, which are among the most popular kinds of tiles, is provided below:

The invention's solution permits the management of ashes that result from the dumping of sewage sludge.

For instance, the ceramic mixture is comprised of 80% gelina clay by weight and 20% by weight of ashes left over from the plasma gasification of sewage sludge. These combinations were used to create rectangular ceramic tiles. Dimensions Length/width/thickness: 12/3.5/2.5 cm. and thick, with a radius of two to three centimeters. 2.5 inches tall in the manner described below. First, a powdered mixture of ash and clay is combined in the mixer. Amorphous silica is added as a binding agent and at least 50–80ml of water is added after the ash and clay mixture have been well mixed into 600 grams in a weight of 5–7 g, ideally 6 g. Up till a paste is formed, the mixture is further combined. To create a consistently saturated, non-agglomerated water paste, the appropriate amount of water is added. Organoleptic assessment is applied to the aforementioned. After that, the paste is put into the mold and compressed with a 25 KN pressure and 1000°C temperature in the oven for 120 minutes increasing 10ºC rate per minute.

(a) Before oven (b) After oven

Figure 2.6.2 Valuable product in which the mixture of sewage sludge ashes and gelina clay i.e. Tiles

Table 2.6.2 Ash particle size for making tiles.

Particle size (Micrometers)	Weight in %
25	4.34
63	11.78
106	54.17
315	14.53
630	4.84
1000	9.83

2.7 Compressive and Water Absorption Test of Tiles

To make sure tiles fulfill industry requirements and are appropriate for their intended use, some tests are essential. The results of these tests aid in determining the tiles' strength, security, and aesthetic qualities. The following is a list of tests carried out on tiles:

2.7.1 Compressive Strength

One key measure of a tile's capacity to support weights without breaking under compression is its compressive strength. The following is a general procedure to check tiles for compressive strength.

Tools Required

- The main piece of equipment utilized to impart a load to the tile until it fails is the compression testing machine.
- Load gauge: Usually found on compression testing apparatuses, it gauges the applied load.
- Calipers or Ruler: To determine the tile's dimensions.
- Balance: If required, weigh the tile.
- Gloves and safety glasses are essential pieces of safety equipment during testing.

Getting ready

- **Conditioning**: Because temperature and moisture content can have an impact on strength, make sure the tiles are at a consistent temperature.
- **measurements**: To precisely determine the compressive strength, measure and document the tile measurements.

Method of Testing

- **Positioning:** Position the tile in the middle of the compression testing machine's plates. To ensure that the weight is distributed uniformly over the whole surface, the tiles should be aligned.
- **Rate of Loading**: Until the tile breaks, apply the weight at a predetermined rate. The rate needs to match the benchmarks (such as ASTM, ISO, or EN) that you are comparing it against.
- **Data recording**: Keep an eye on the load gauge to see the highest load that a tile can support before failing. Compressive strength is computed by dividing the tile's cross-sectional area by the highest load at failure. Megapascals are the standard unit of measurement (MPa).

Security and Precision

- **Safety**: Make sure the testing apparatus is always used safely and that there are protections in place to shield users from flying debris if a tile fails.
- **Calibration**: To guarantee reliable findings, calibrate the testing apparatus regularly.
- **Repeats**: To increase accuracy, run the test on several samples and average the results.

Results Reporting

The maximum load, compressive strength, and any findings regarding the tile's failure mode should all be included in the results, which should be reported in compliance with the testing standards in use.

Standards

For exact testing procedures, consult certain standards for testing ceramic tiles, such as ASTM C165, ISO 13006, or EN standards.

It's crucial to remember that not all tiles require a recognized compressive strength test, even if certain tiles, like floor tiles, might. For example, wall tiles hardly ever experience compressive loads that would require this test. When performing these tests, always refer to the applicable product standards and specifications.

2.7.2 Water Absorption Test

One important quality control tool for figuring out a tile's porosity—which in turn impacts how suitable it is for different applications, particularly in places that are prone to moisture—is the water absorption test. The general steps involved in conducting a tile water absorption test are as follows.

Tools Required

- Balance**:** Perceptive to 0.1% of the weight of the tile.
- Oven: 110°C to 115°C is the temperature range it can hold.
- Water immersion of the tiles is done using the measuring container.
- Calipers or Ruler: If needed, for determining the tile's dimensions.

Procedure for Testing

(I) Weighing the Dry Tile

- To eliminate all moisture, dry the tile in an oven set between 110°C and 115°C for a predetermined amount of time, usually 24 hours.
- To stop the tile from absorbing moisture from the air, let it cool in a desiccator once it has dried.
- Accurately measure the dried tile's mass to the closest 0.1%.

(II) Submersion and Absorption

- Soak the dehydrated tile for a predetermined amount of time—typically 24 hours—in room temperature water.
- Make sure that at least 1 cm of water completely submerges the tile.

(III) Cleaning the Wet Tile and Weighing It

- Remove the tile and use a moist cloth to remove any remaining surface water after the soaking time.
- To stop the moist tile from evaporating, weigh it right away.

(IV) Compute:

- Utilizing the following formula, determine the water absorption as a percentage of the dry weight:

  {Absorption of Water (%) } = {(Wet Weight} - Dry Weight})}100 times {\{Dry Weight}}

Important Points to Remember

- Where tiles can be utilized depends heavily on their rate of water absorption. Tiles that absorb less water, for instance, are typically better suited for outdoor use or bathrooms, whereas tiles that absorb more water can be more suited for interior walls or other dry locations.
- To make sure the tiles fulfill the quality and performance requirements needed for their intended usage, this test is crucial. When done correctly, it aids in the understanding of the tile's applicability and durability for various contexts by both makers and users.

3 Results and Discussion

3.1 Characterization of sewage sludge

The unit for CHNS analysis is mgs. [C 0.001-3.6 mgs, H 0.001-1.0 mgs, N 0.001-6.0 mgs, S 0.001-2.0 mgs]. In Table 3.1.1 The CHNS values obtained above are dry-state sewage sludge after hydrothermal carbonization. A table displaying several sewage sludge (SS) samples treated by hydrothermal carbonization (HTC) at varied temperatures and residence times. For every sample, it provides information on the elemental composition of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). The main, secondary, or AD digestive sludge type, treatment temperature (180–300 degrees Celsius), and residence time (five minutes to one hour) are used to distinguish the samples from one another. For example, the composition of primary SS treated for 5 minutes at 200 degrees is 47.60% C, 6.85% H, 1.32% N, and 1.61% S. According to the kind of SS and the conditions of treatment, the data display differences in elemental composition. Comparisons of these percentages would be necessary for a comprehensive understanding of how temperature and time affect the HTC process and the final material attributes.

For instance, compared to secondary or AD digestive SS under the same conditions, primary SS at 200°C for 5 minutes has a larger carbon and hydrogen concentration. Longer residence times often result in lower hydrogen levels, but they can also raise sulfur content. The alterations show how the HTC processing changed the sludge's organic and inorganic components.

32.89% C, 4.11% H, 2.81% N, and 1.35% S make up the "HTC of secondary SS at 250 degrees plus 1-hour residence" composition.

To analyze and draw conclusions, we would compare the data to comprehend how the temperature and residence time of hydrothermal carbonization (HTC) affect the elemental composition. Increased carbon content and decreased hydrogen and oxygen concentrations are generally the results of higher temperatures and longer residence durations. This indicates a move towards a more carbon-rich material, which is preferred for some purposes such as the manufacturing of biofuel.

The HTC of AD digesting SS, for example, has 25.74% C, 3.16% H, 1.62% N, and 2% S at 300 degrees with a 5-minute residence. The HTC of primary SS, on the other hand, exhibits a greater carbon percentage of 52.34% at the same temperature after a 1-hour residency. Variations in elemental composition are displayed in each entry, demonstrating how process conditions affect the material's characteristics.

Table 3.1.1 Ultimate analysis of sewage sludge after Hydrothermal Carbonization

s.no.	Sample Description	C	H	N	S
1	HTC of primary SS at 200 degrees plus 5 min residence	47.60	6.85	1.32	1.61
2	HTC of Primary SS at 200 degrees plus 1-hour residence	47.96	6.70	1.12	1.98
3	HTC of secondary SS at 200 degrees plus 5 min residence	38.92	5.41	5.12	1.51
4	HTC of secondary SS at 200 degrees plus 1-hour residence	37.35	4.84	4.23	1.45
5	HTC of AD digestive SS at 200 degrees plus 5 min residence	28.23	4.13	2.53	1.88
6	HTC of AD digestive SS at 200 degrees plus 1 hour residence time	25.85	3.50	1.79	1.95
7	HTC of Primary SS at 250 degrees plus 5 min residence	50.06	6.77	1.02	1.94
8	HTC of primary SS at 250 degrees plus 1-hour residence	49.26	5.95	2.04	1.98
9	HTC of secondary SS at 250 degrees plus 5 min residence	37.60	4.64	4.6	1.30
10	HTC of secondary SS at 250 degrees plus 1-hour residence	32.89	4.11	2.81	1.35
11	HTC of AD digestive SS at 250 degrees plus 5 min residence	23.56	2.99	1.48	1.73
12	HTC of AD digestive SS at 250 degrees plus 1-hour residence	23.59	2.95	1.48	1.98
13	HTC of primary SS at 180 degrees plus 5 min residence	47.03	6.60	1.68	1.13
14	HTC of secondary SS at 180 degrees plus 5 min residence	37.70	5.46	5.68	1.48
15	HTC of Primary SS at 180 degrees plus 1-hour residence	47.36	6.67	1.18	0.96
16	HTC of secondary SS at 180 degrees plus 1-hour residence	38.26	5.33	4.52	1.55
17	HTC of AD digestive SS at 180 degrees plus 1-hour residence	24.24	3.50	2.37	1.51
18	HTC of primary SS at 300 degrees plus 5 min residence	51.31	6.62	1.63	2.10
19	HTC of secondary SS at 300 degrees plus 5 min residence	33.80	4.15	2.72	1.45
20	HTC of AD digestive SS at 300 degrees plus 5 min residence	25.74	3.16	1.62	2.00
21	HTC of primary SS at 300 degrees plus 1-hour residence	52.34	6.53	1.74	1.97
22	HTC of secondary SS at 300 degrees plus 1 hour residence time	34.30	4.19	2.63	1.27
23	HTC of AD digestive SS at 300 degrees plus 1-hour residence	25.88	3.01	1.6	1.44
24	HTC of Janowek Sewage Sludge at 200 degrees plus 4 hour residence time	37.57	4.85	6.57	1.69

The data shown in Table 3.1.2 is a comparative elemental analysis of dry sewage sludge before and after HTC treatment, plasma ash, and samples with and without HTC ash after gasification. The principal conclusions are:

The carbon content of dry sewage sludge is greatly increased (from 38.94% to 37.57%) by HTC treatment. Following HTC treatment, the hydrogen level slightly drops (from 5.53% to 4.85%).

After HTC, the nitrogen level slightly decreased (from 7.51% to 6.57%).

Following HTC, the sulfur level slightly decreases (from 1.74% to 1.69%).

Following HTC, the oxygen content drops, suggesting that there may have been deoxygenation reactions during the procedure. In summary, the elemental composition of the sewage sludge appears to be affected by HTC treatment, which tends to enrich the carbon content while diminishing the quantities of hydrogen, nitrogen, sulfur, and oxygen to variable degrees. When utilized in energy recovery procedures, this might improve the sludge's fuel qualities.

Table 3.1.2 Ultimate analyses of Janowek Sewage sludge

s.no.	Sample Description	C	H	N	S	O
01	With HTC ash after gasification	10.37	0.40	1.30	0.82	4.00
02	Without HTC ash after gasification	9.37	0.10	1.41	0.75	0.07
03	Dry sewage sludge after HTC	37.57	4.85	6.57	1.69	15.69
04	Dry sewage sludge before HTC	38.94	5.53	7.51	1.74	21.20
05	Plasma Ash	41.22	1.36	3.32	1.11	6.58

The distinct sewage sludge (SS) kinds of hydrothermal carbonization (HTC) at varied temperatures and residence durations. With residence durations of either five minutes or one hour, it displays the percentage of ash content in primary, secondary, and AD digestion SS at 180, 200, 250, and 300 degrees Celsius. In Table 3.1.3 Ash content typically rises with higher temperatures and longer residence times. This suggests that higher HTC conditions lead to higher inorganic component concentrations or mineralization. The ash percentage in Primary sewage sludge is less as compared to other sewage sludge at different temperatures. 180 and 200 ^{o}C is the better temperature for HTC of primary sewage sludge.

The reactions of primary, secondary, and AD digestive SS types to identical HTC circumstances differ from one another. This implies that the treatment process's final result is highly influenced by the sludge's initial composition.

Finding the ideal HTC settings that strike a balance between energy consumption and the required ash concentration is crucial for effective waste management and resource recovery.

It is clear from data analysis that the kind of SS and treatment circumstances have a substantial impact on the ash content. For example, higher temperatures and longer residence times tend to result in a higher percentage of ash. This variation demonstrates how various treatment settings impact the sewage sludge's carbonization process, which is crucial to comprehending the effectiveness and environmental effects of these operations. To accomplish desired results in resource recovery and waste management, the data may be utilized to improve HTC conditions for different kinds of sewage sludge. A Janowek Sewage Sludge sample that was heated to 200 degrees Celsius for four hours. It reveals that there is 58.1% volatile stuff and 32.5% ash content. This suggests that there is a considerable amount of inorganic material (ash) and a high percentage of volatile matter, or flammable components. The ash content may affect the residue's suitability as a soil amendment, while the high volatile matter signals the possibility of energy recovery. The information helps manage waste and recover energy from this sewage sludge by helping to understand its properties.

Table 3.1.3 Proximate Analysis of Sewage Sludge after Hydrothermal Carbonization

S.no.	Sample Description	Ash %	Volatile matter Content %
01	HTC of primary SS at 200 degrees plus 5 min residence	14.16	30.82
02	HTC of Primary SS at 200 degrees plus 1-hour residence	19.12	52.15
03	HTC of secondary SS at 200 degrees plus 5 min residence	38.00	41.22
04	HTC of secondary SS at 200 degrees plus 1-hour residence	41.00	61.62
05	HTC of AD digestive SS at 200 degrees plus 5 min residence	50.76	51.23
06	HTC of AD digestive SS at 200 degrees plus 1 hour residence time	59.99	64.56
07	HTC of Primary SS at 250 degrees plus 5 min residence	21.21	50.08
08	HTC of primary SS at 250 degrees plus 1-hour residence	35.84	81.16
09	HTC of secondary SS at 250 degrees plus 5 min residence	41.26	40.29
10	HTC of secondary SS at 250 degrees plus 1-hour residence	55.19	59.22
11	HTC of AD digestive SS at 250 degrees plus 5 min residence	64.68	76.87
12	HTC of AD digestive SS at 250 degrees plus 1-hour residence	64.40	85.95
13	HTC of primary SS at 180 degrees plus 5 min residence	21.65	59.75
14	HTC of secondary SS at 180 degrees plus 5 min residence	29.38	42.04
15	HTC of Primary SS at 180 degrees plus 1-hour residence	17.41	52.67
16	HTC of secondary SS at 180 degrees plus 1-hour residence	35.66	41.31
17	HTC of AD digestive SS at 180 degrees plus 1-hour residence	57.39	76.20
18	HTC of primary SS at 300 degrees plus 5 min residence	30.26	57.57
19	HTC of secondary SS at 300 degrees plus 5 min residence	54.64	61.77
20	HTC of AD digestive SS at 300 degrees plus 5 min residence	63.31	86.58
21	HTC of primary SS at 300 degrees plus 1-hour residence	28.63	61.06
22	HTC of secondary SS at 300 degrees plus 1 hour residence time	55.35	67.25
23	HTC of AD digestive SS at 300 degrees plus 1-hour residence	65.04	-
24	Janowek Sewage Sludge at 200 degrees plus 4 hour residence	32.50	58.10

Graphical representation of Thermogravimetric Analysis (TGA with Air)

1. HTC of Primary sewage sludge (SS) at 200 ° C plus 5-minute residence time

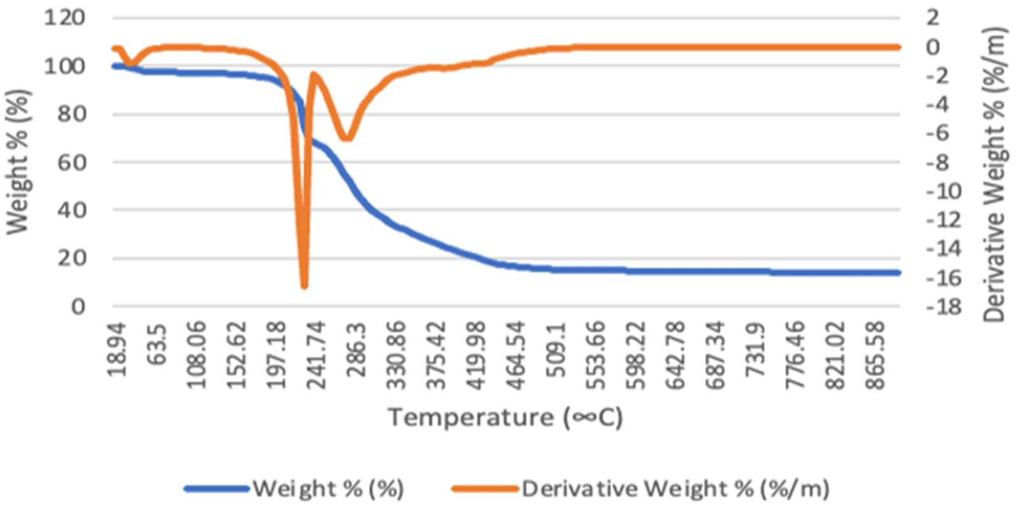


Figure 3.1.1 Graphical representation of Thermogravimetric Analysis (TGA with Air) of HTC of Primary SS at 200 ° C plus 5 min residence time

2. HTC of Primary sewage sludge (SS) at 200 ° C plus one hour of residence time

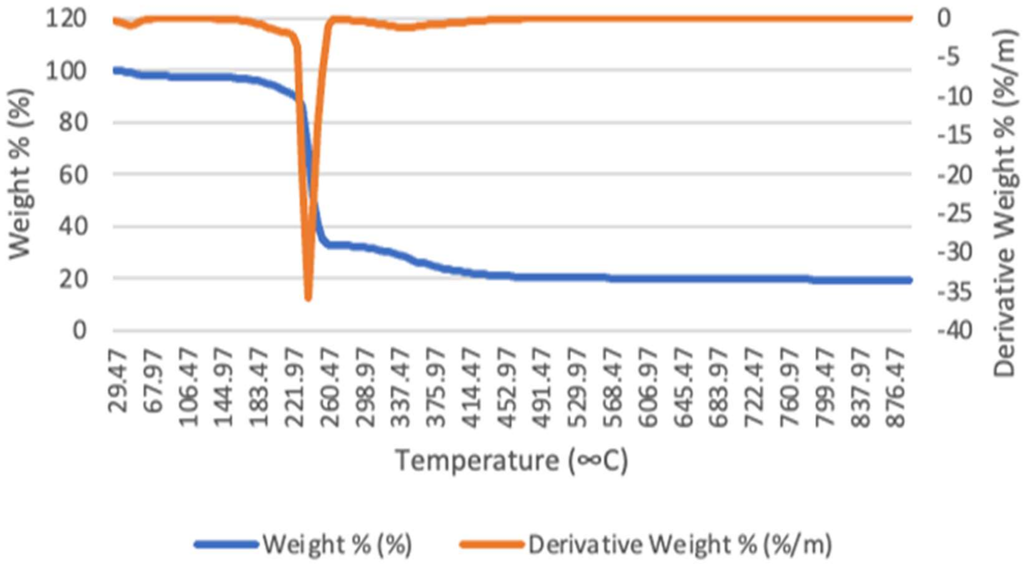


Figure 3.1.2 Graphical representation of Thermogravimetric Analysis (TGA with Air) of HTC of Primary SS at 200 ° C plus one hour of residence time

3. HTC of Secondary sewage sludge (SS) at 200 ° C plus five-minute residence

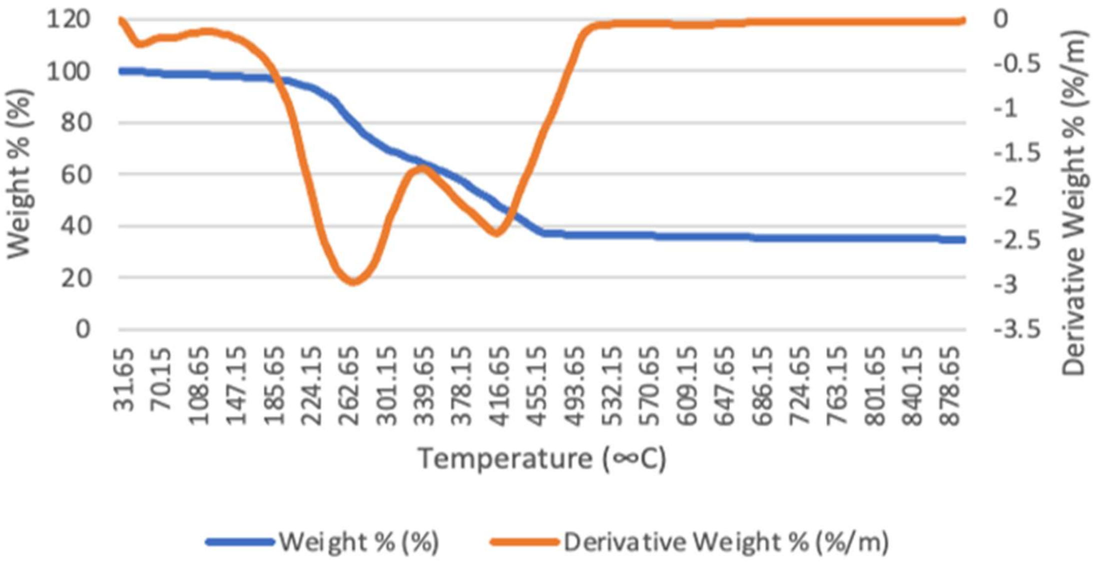


Figure 3.1.3 Graphical representation of Thermogravimetric Analysis (TGA with Air**)** of HTC of Secondary SS at 200 ° C plus five-minute residence

4. HTC of Secondary sewage sludge (SS) at 200 ° C plus one-hour residence time

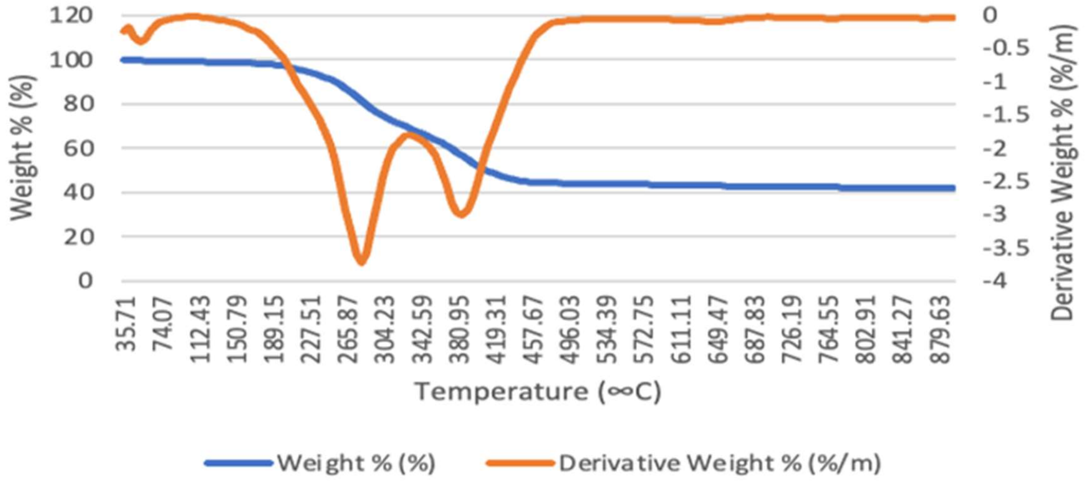


Figure 3.1.4 Graphical representation of Thermogravimetric Analysis (TGA with Air**)** of HTC of Secondary SS at 200 ° C plus one-hour residence time

5. HTC of AD digestive sewage sludge (SS) at 200 ° C plus five min. residence time

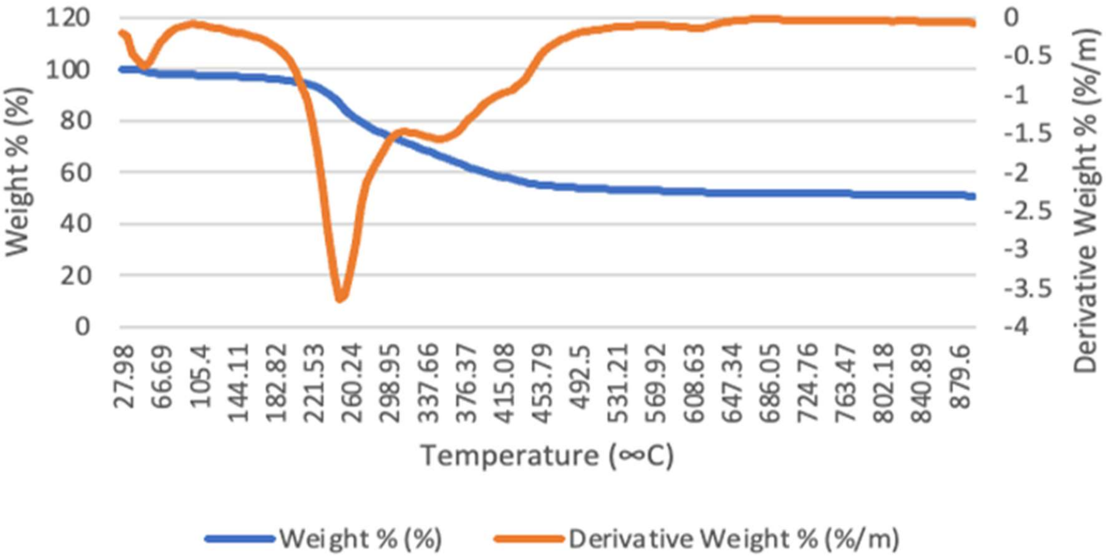


Figure 3.1.5 Graphical representation of Thermogravimetric Analysis (TGA with Air) of HTC of AD digestive SS at 200 ° C plus five min. residence time

6. HTC of AD digestive sewage sludge (SS) at 200 ° C plus one hour of residence time

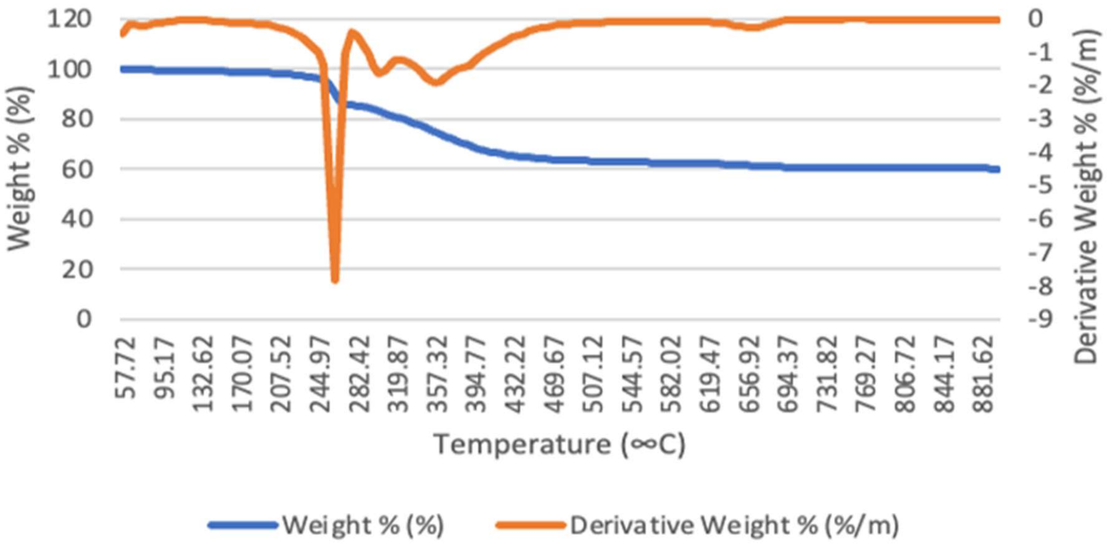
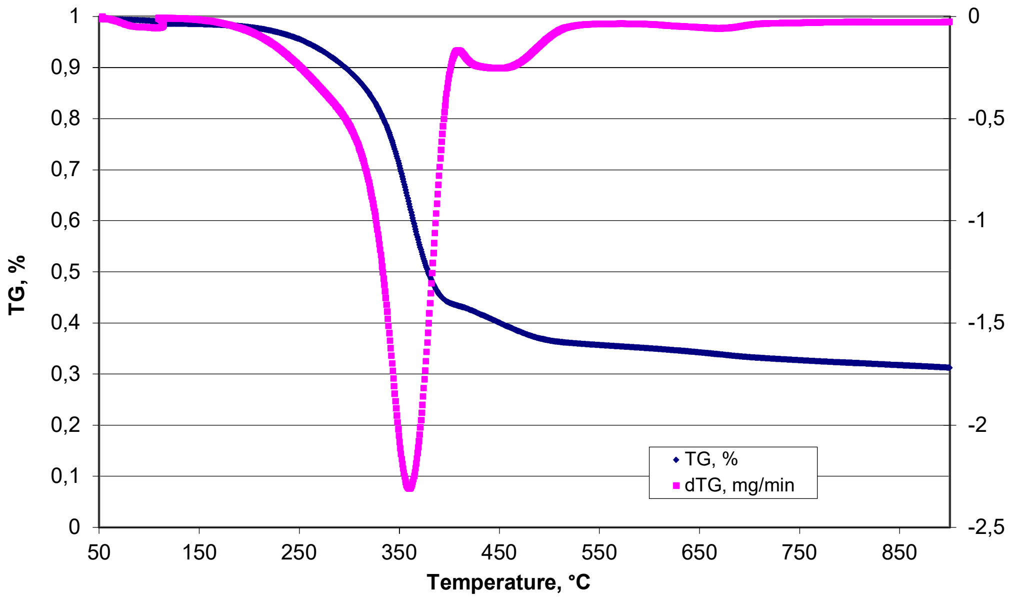


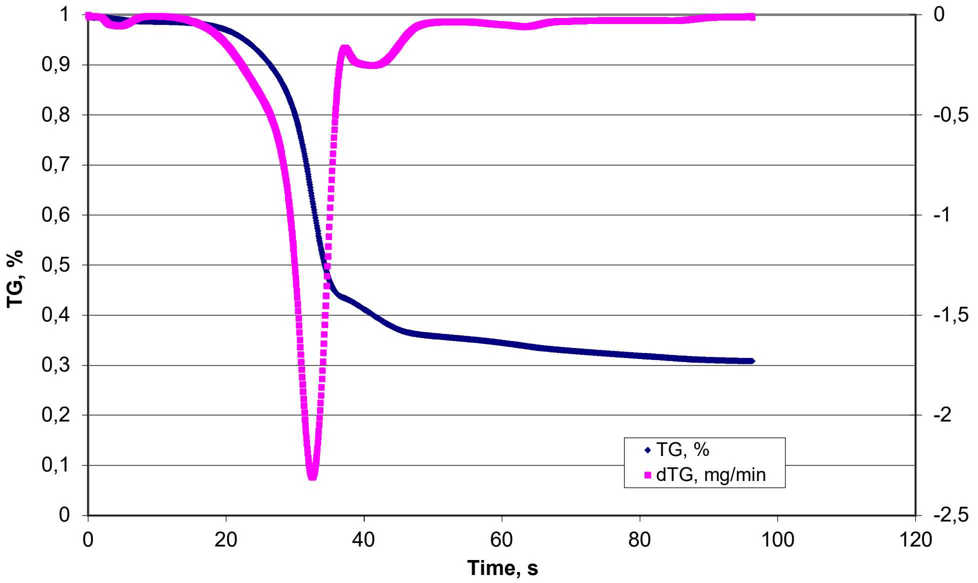
Figure 3.1.6 Graphical representation of Thermogravimetric Analysis (TGA with Air) of HTC of AD digestive SS at 200 ° C plus one hour of residence time

Graphical representation of Thermogravimetric analysis (TGA with Nitrogen)

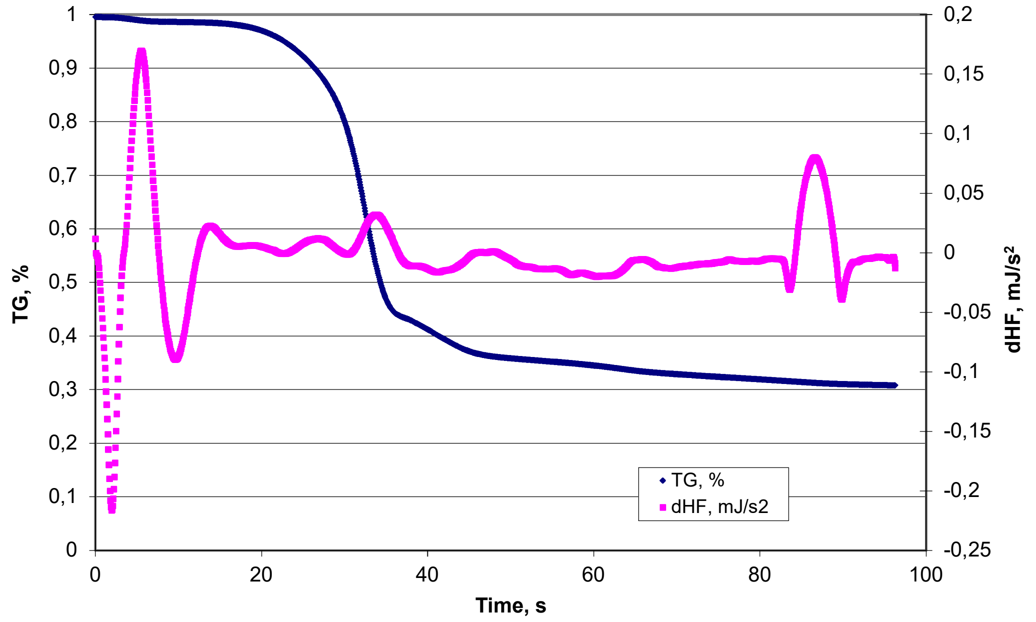
1. HTC of Primary sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time.



(a)



(b)



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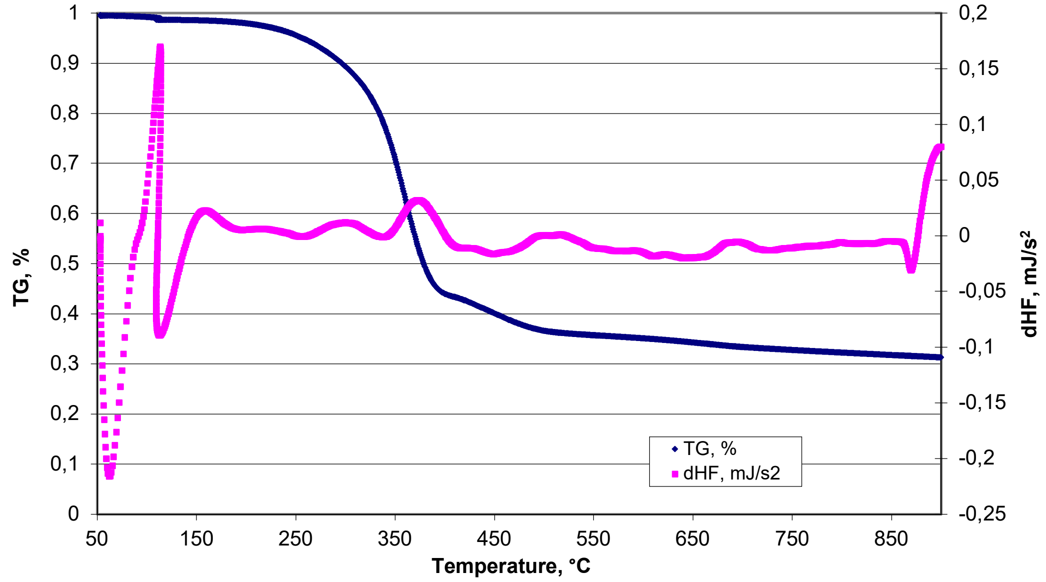
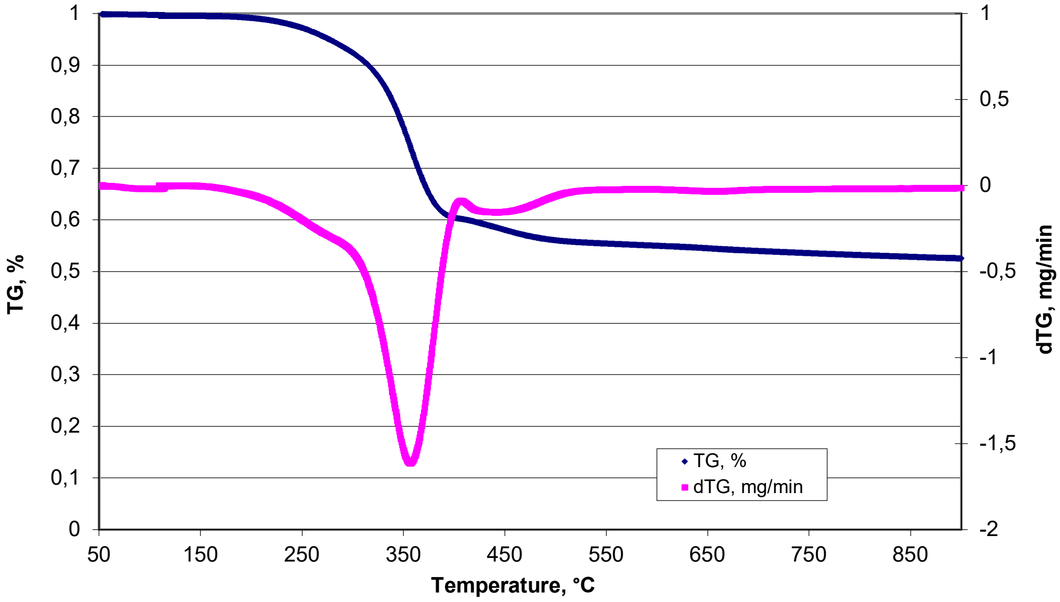


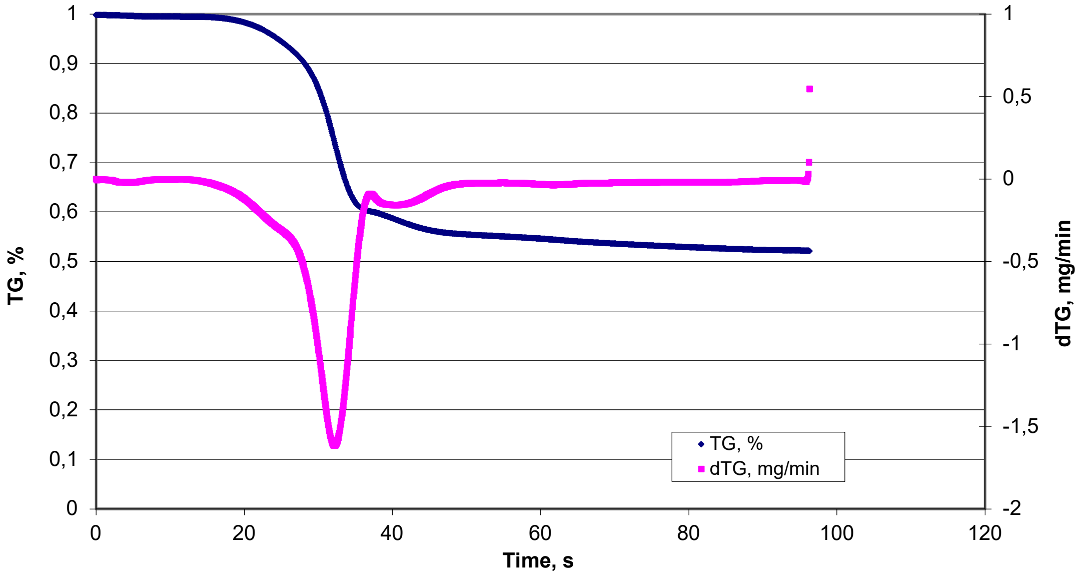
(d)

Figure 3.1.7 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen) of HTC of Primary SS at 200 ^{0} C plus 5-minute residence time (a), (b), (c), (d).

2. HTC of Primary sewage sludge (SS) at 200 ^{0} C plus one hour residence time



(a)



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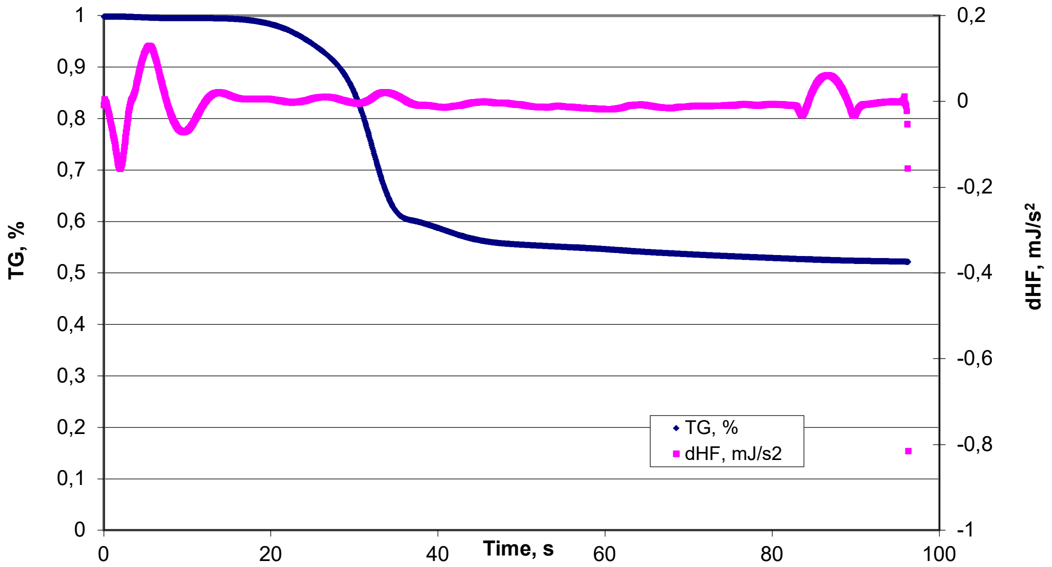

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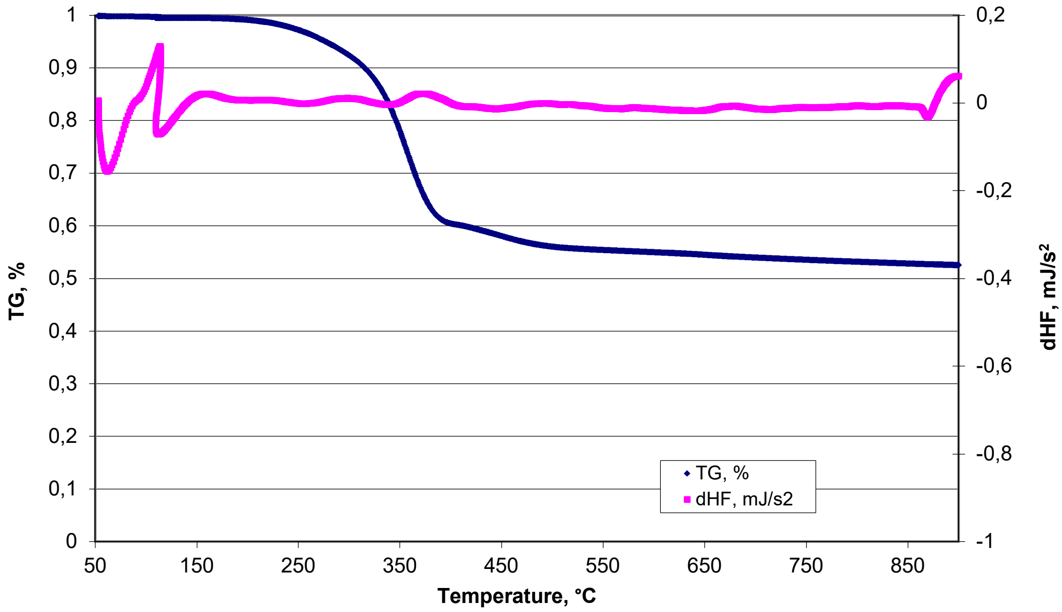
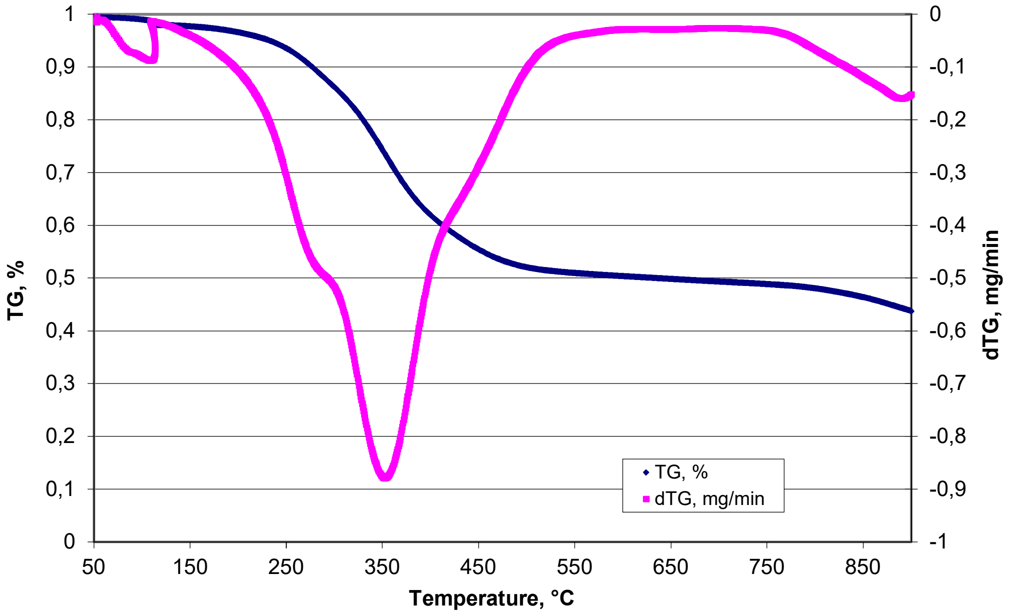


(d)

Figure 3.1.8 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen) of HTC of Primary SS at 200 ^{0} C plus one hour residence time (a), (b), (c), (d).

3. HTC of Secondary sewage sludge (SS) at 200 ° C plus 5-minute residence time



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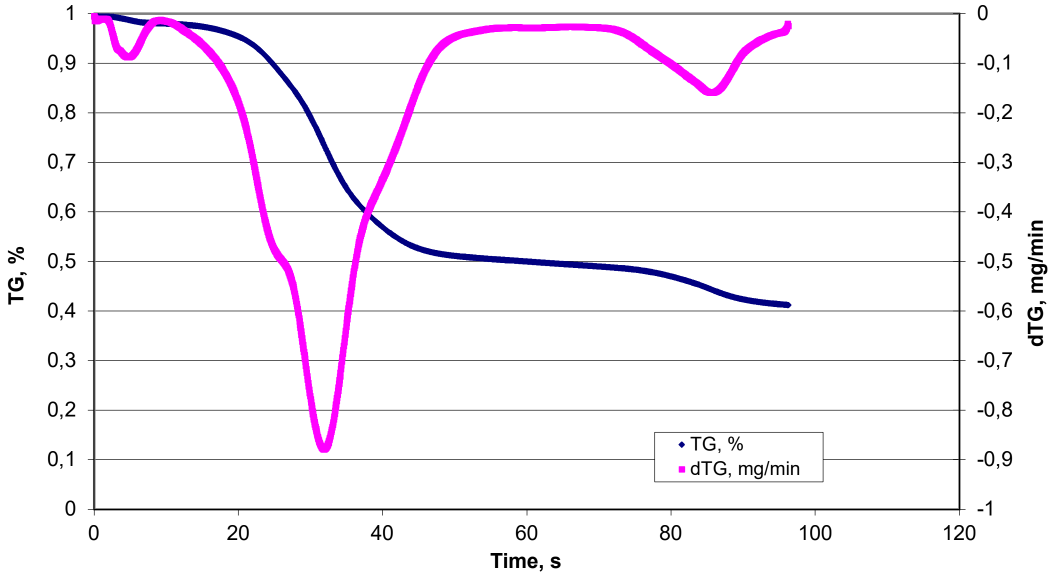

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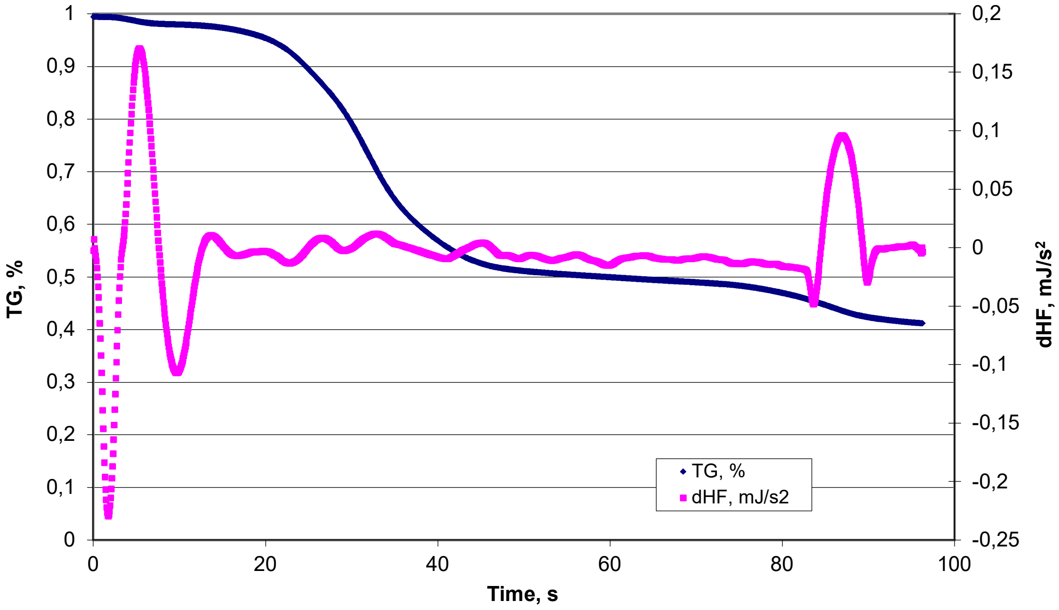

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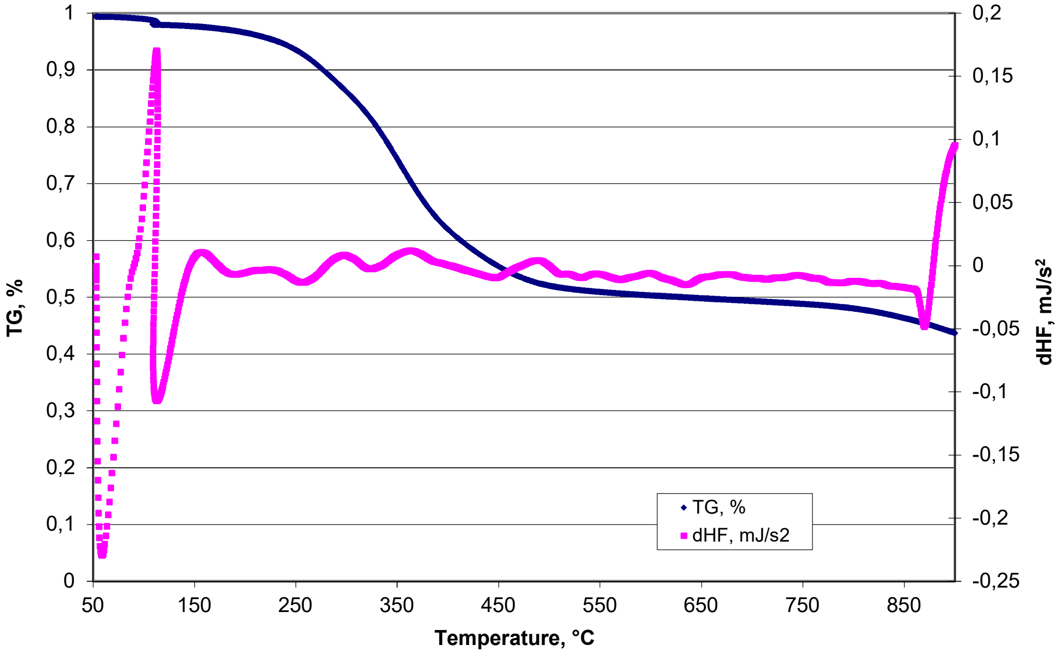
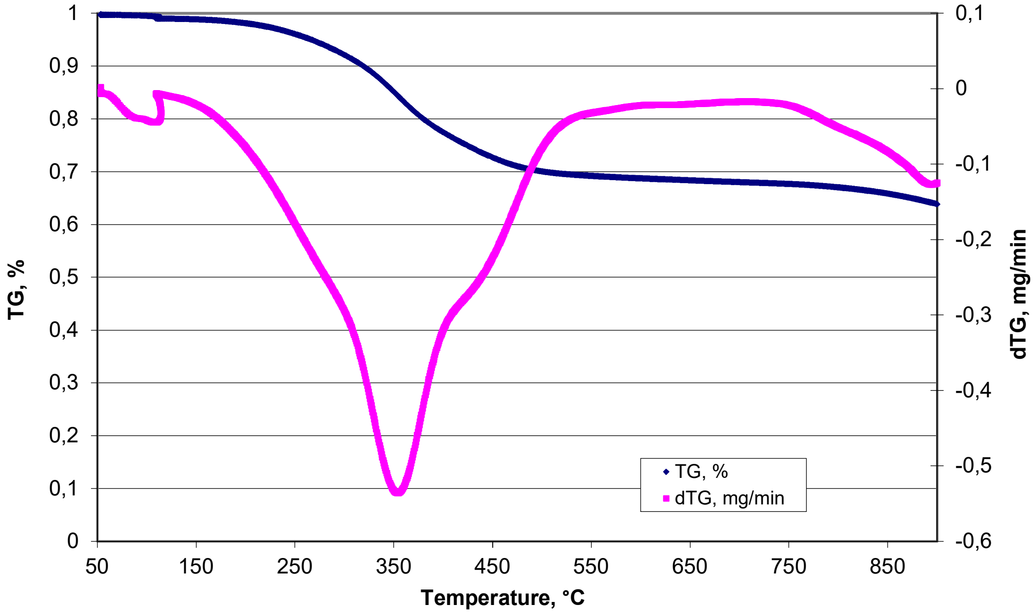


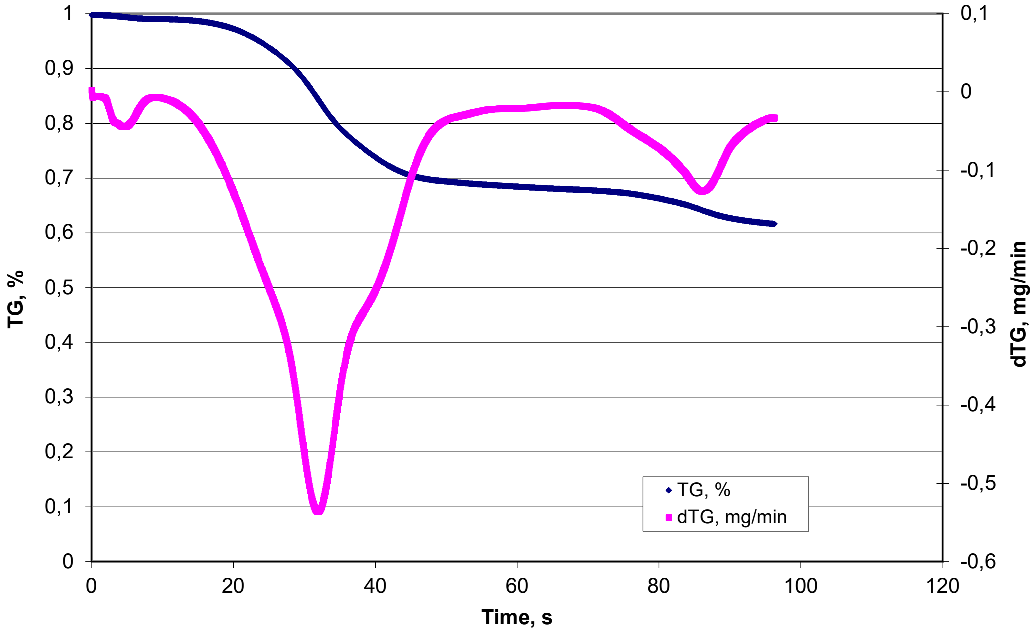
(d)

Figure 3.1.9 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen**)** of HTC of Secondary SS at 200 ^{0} C plus 5-minute residence time (a), (b), (c), (d).

4. HTC of Secondary sewage sludge (SS) at 200º C plus one hour residence time



(a)



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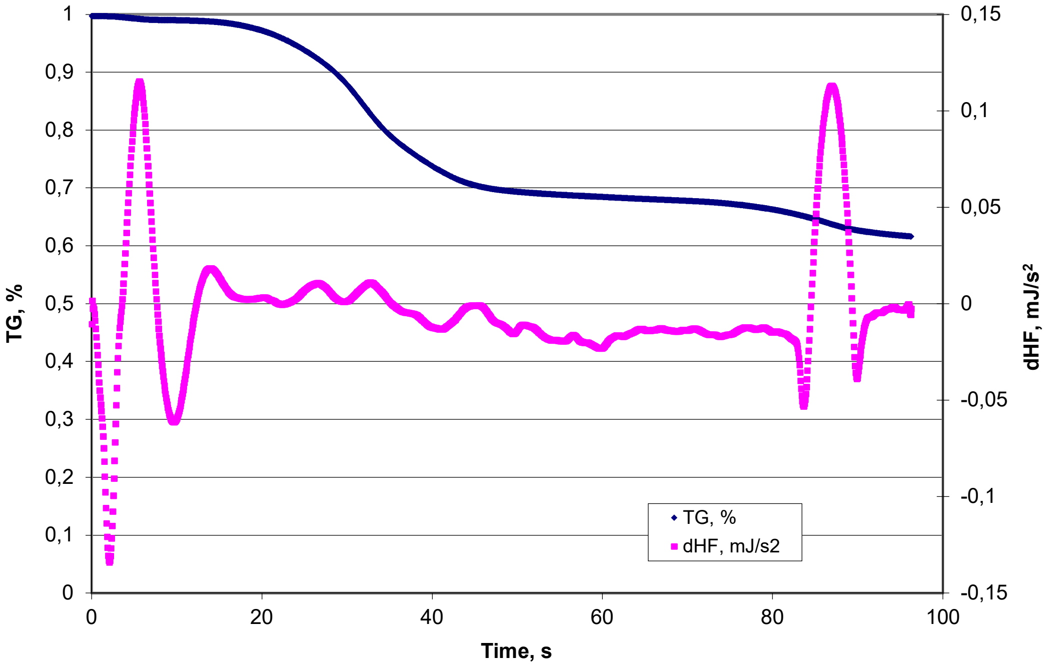

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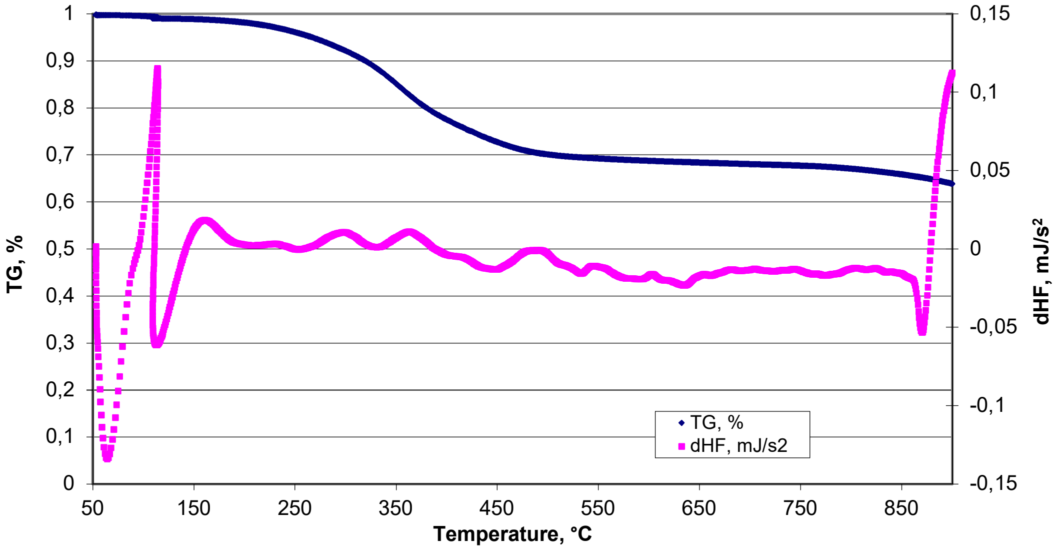
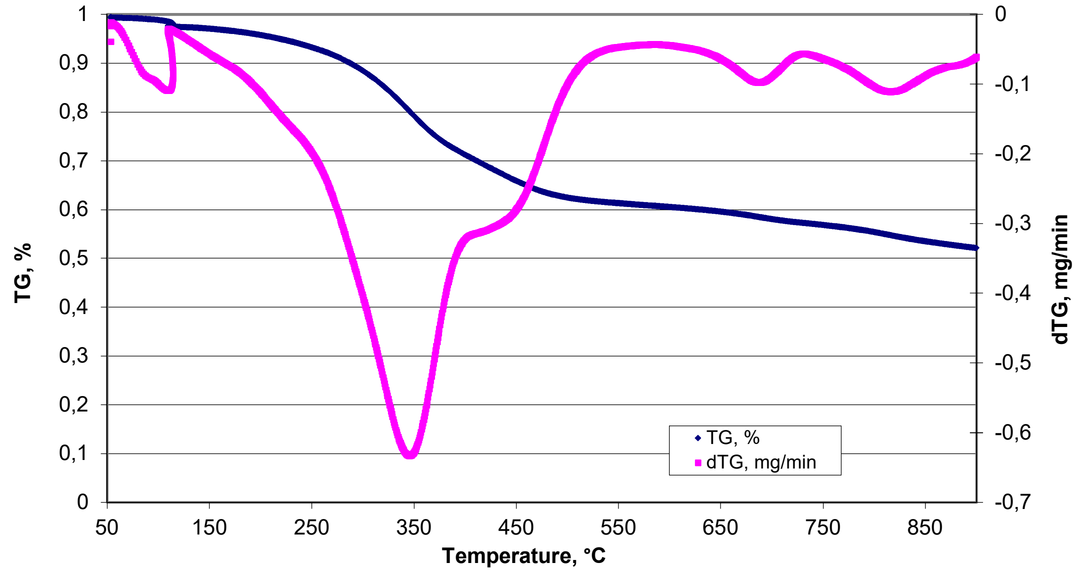


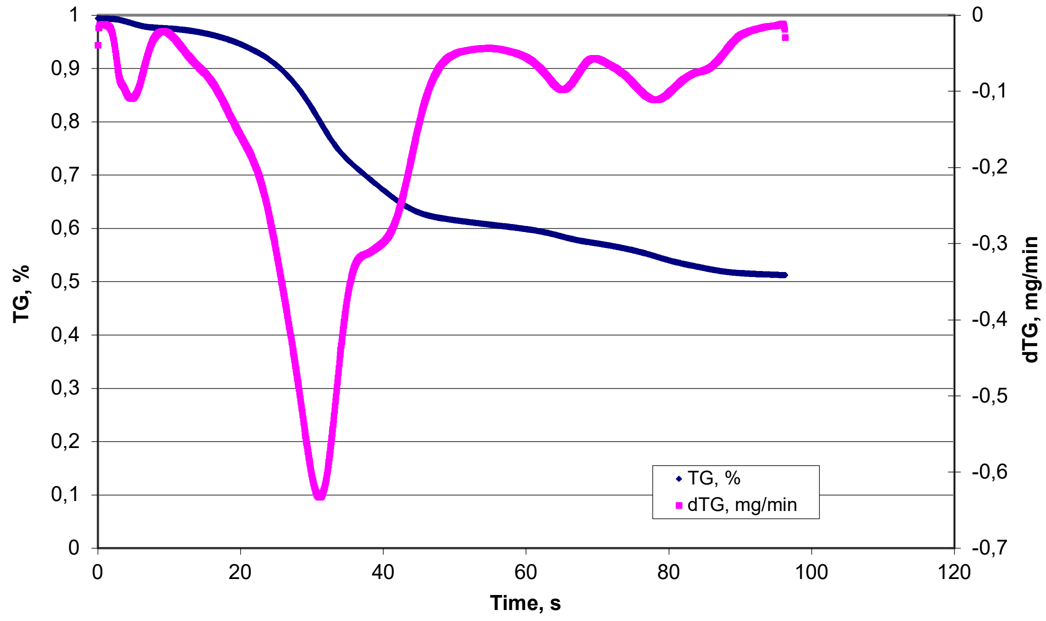
(d)

Figure 3.1.10 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen) of HTC of Secondary SS at 200° C plus one hour residence time (a), (b), (c), (d).

5. HTC of AD digestive sewage sludge (SS) at 200ºC plus 5-minute residence time



(a)



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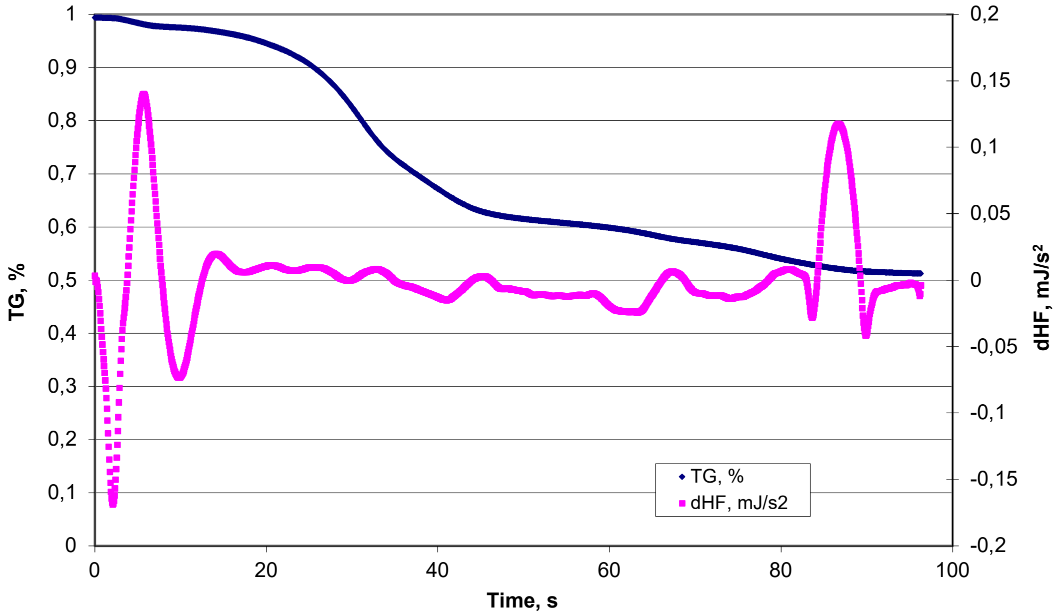

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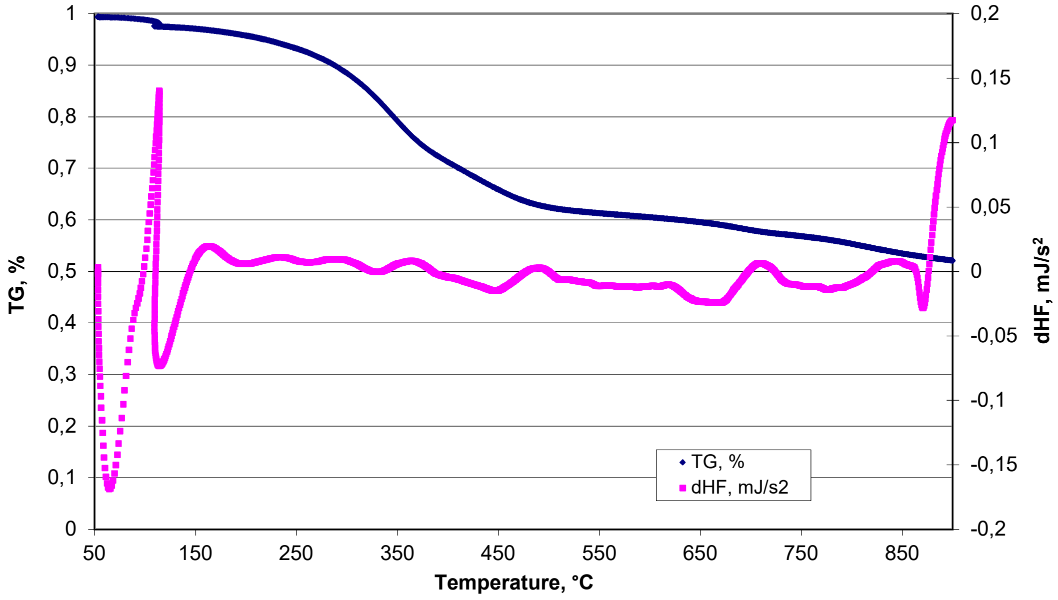
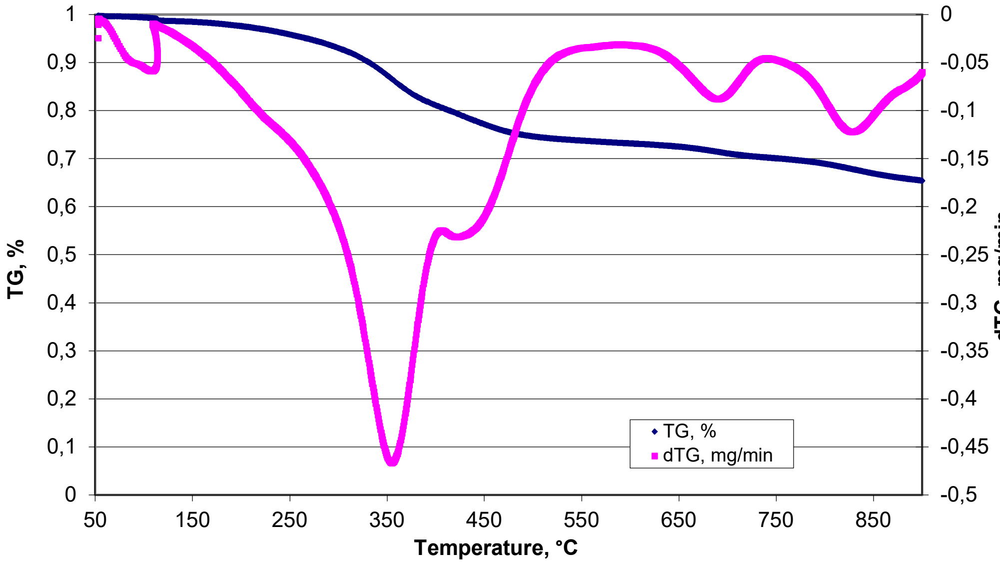


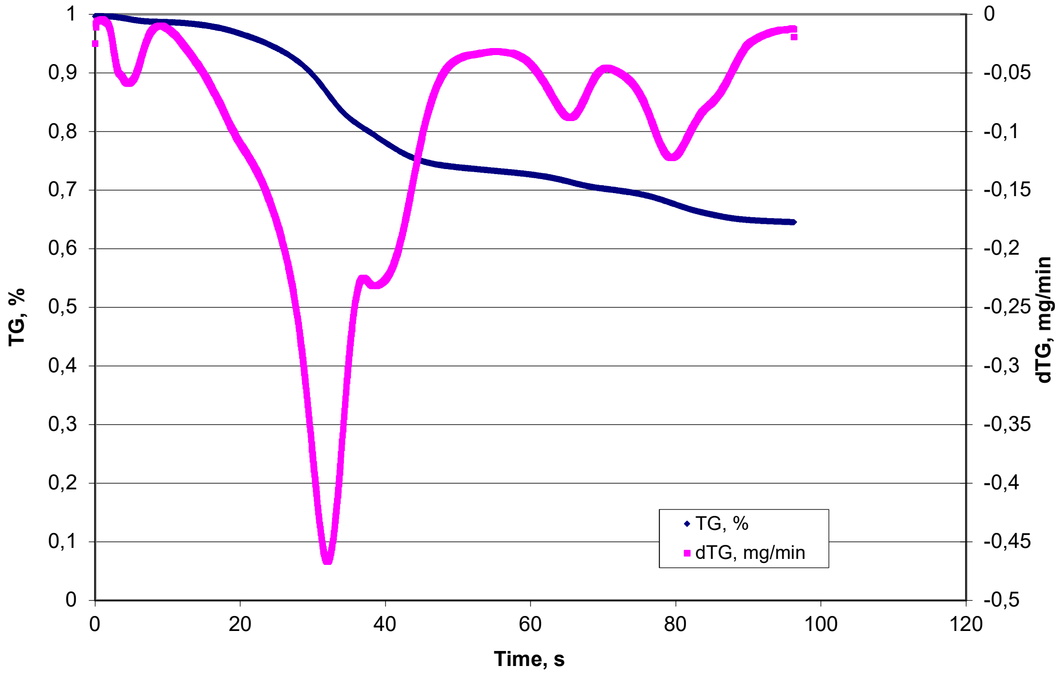
(d)

Figure 3.1.11 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen) of HTC of AD digestive SS at 200^0 C plus 5-minute residence time (a), (b), (c), (d).

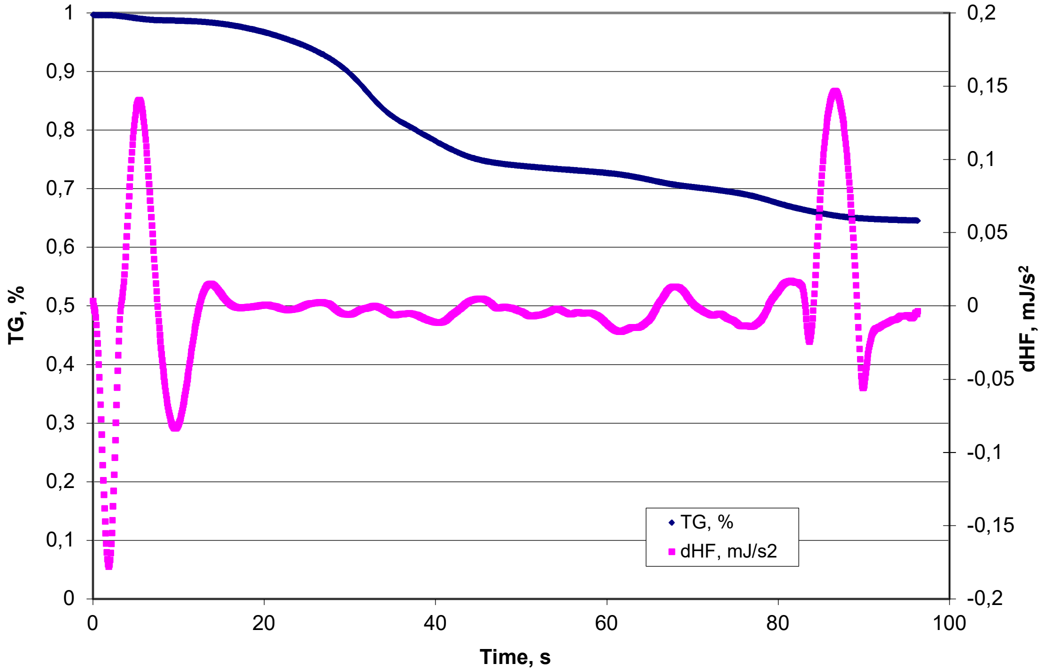
6. HTC of AD digestive SS at 200º C Plus one hour residence time.



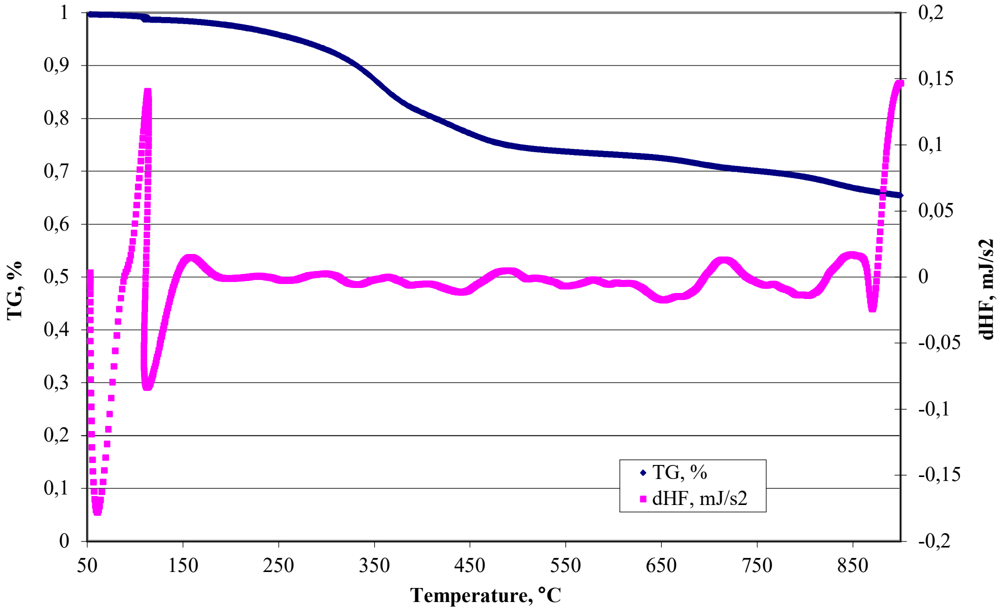
(a)



(b)



(c)



(d)

Figure 3.1.12 Graphical representation of Thermogravimetric Analysis (TGA with Nitrogen**)** of HTC AD digestive SS at 200^0 C Plus one hour residence time (a), (b),(c), (d).

Higher values suggest a better potential for energy generation. In Table 3.1.4 The calorific value is a measure of the energy content of a fuel or waste material.

The sample with the highest calorific value, primary sewage sludge (17.87 MJ/Kg), suggests that it contains a larger quantity of organic materials that may be easily transformed into energy.

Sewage Sludge Secondary (17.08 MJ/Kg): Although it has a somewhat lower calorific value than the primary sludge, it is nevertheless a substantial source of energy. The treatment procedures it goes through could be the cause of the variation in energy content.

AD Sewage Sludge for Digesting (12.72 MJ/Kg): This has a significantly lower calorific value, which may be related to the anaerobic digestion process it goes through, which can lessen the amount of organic content that can be used to produce energy.

Janowek Sewage Sludge (15.70 MJ/Kg): Its reasonable amount of organic material makes it appropriate for energy recovery, as indicated by its intermediate calorific value.

All things considered, these results suggest that sewage sludge, especially the primary and secondary kinds, can be a useful source of energy. The nature of the sludge and the various treatment methods are probably to blame for the variances in calorific value. Particularly when considering sustainable and renewable energy sources, this knowledge is essential for waste management and energy recovery methods.

Table 3.1.4 Calorific value of sewage sludge

S.no.	Sample Description	Calorific Value (MJ/Kg)
01	Primary Sewage Sludge	17.87
02	Secondary Sewage Sludge	17.08
03	AD digestive Sewage Sludge	12.72
04	Janowek Sewage Sludge	15.70

An essential idea in the study of chemical processes is activation energy, especially when kinetics is involved. It stands for the bare minimum of energy required for reactant molecules to engage in a chemical reaction. Finding the activation energy in the context of sewage sludge following hydrothermal carbonization (HTC) sheds light on the kinetics of the procedure.

A thermochemical conversion process called hydrothermal carbonization involves treating biomass—like sewage sludge—in a water medium at high temperatures and pressures. The organic matter in the sludge is broken down and converted by this process into hydrochar, a solid product that is high in carbon. It's critical to comprehend this process' activation energy for several reasons:

Process Optimization: By understanding the activation energy, the hydrothermal carbonization process may be made more efficient. Researchers can modify temperature, pressure, and residence time to attain desired reaction rates and product yields by knowing the energy needs for the processes involved.
Economic Viability: Analyzing the activation energy helps determine whether hydrothermal carbonization is a cost-effective way to remediate waste. It facilitates cost comparisons with various treatment approaches and aids in estimating the energy input needed for the process.
Scale-Up Considerations: Hydrothermal carbonization must be scaled up on an industrial scale, and this requires an understanding of the activation energy. It guarantees effective operation across a range of operating situations and aids in the prediction of greater reactor performance.
Environmental Impact: Determining the activation energy helps to comprehend how hydrothermal carbonization affects the environment. Energy consumption can be lowered by process parameter optimization, which lowers greenhouse gas emissions and the environmental impact overall.

The Activation Energy of HTC of AD digestive sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time is low as compared to others it means the minimum energy required for reactant molecules to engage in a chemical reaction for this sample as compared to others. In conclusion, determining the activation energy of sewage sludge following hydrothermal carbonization is critical to process optimization, economic viability analysis, ease of scale-up, and environmental effect reduction. It offers insightful information that can help with decision-making during the creation and application of this waste treatment system.

When calculating activation energy from a graph, the Arrhenius equation—which links temperature and a reaction's rate constant—is usually utilized. The following is the Arrhenius equation:

$$k= Ae^{-E_a}/RT \tag{9}$$

Where
k is the rate constant
A is the pre- exponential factor
E_a is the Activation Energy
R is the Gas Constant (8.314J/mol K)
T is the absolute Temperature (in Kelvin)

By taking logarithm of both side of equation (9)

$$\ln(k) = \ln(A) - E_a/RT \tag{10}$$

This equation represents a linear relation between ln(k) and 1/T, Where the slope of the line is - E_a/R

Use these procedures to determine activation energy from a graph:

- Measure the reaction's rate constant at each temperature while experimenting with changing temperatures.
- Plot a graph of ln(k) versus 1/T, where k is the rate constant, and T is the absolute temperature in Kelvin.
- Determine the slope of the line from the graph.
- Use the Slope value to calculate the activation energy using the equation.

$$E_a = - \text{Slope} \times R \tag{11}$$

To get the activation energy, substitute the gas constant (R) and the slope value from the graph into the equation.

It is significant to remember that the linearity of the graph and the quality of the experimental data determine how accurate the activation energy calculation is. For precise computations, make sure the temperature is also stated in Kelvin.

In Figure 3.1.14 Slope is 10177 and R is 8.314, according to equation (11) E_a is equal to -84.6 KJ.

Table 3.1.5 Activation Energy of Sewage Sludge

S.no.	Sample Description	Slope	Activation Energy (KJ)
01	HTC of Primary sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time	10177	84.6
02	HTC of Primary sewage sludge (SS) at 200 ^{0}C plus one hour of residence time	9714.2	80.7
03	HTC of Secondary sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time	4080.9	33.9
04	HTC of Secondary sewage sludge (SS) at 200 ^{0}C plus one hour of residence time	3558.2	29.5
05	HTC of AD digestive sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time	3315.5	27.5
06	HTC of AD digestive SS at 200 ^{0}C Plus one hour residence time	3861.1	32.1

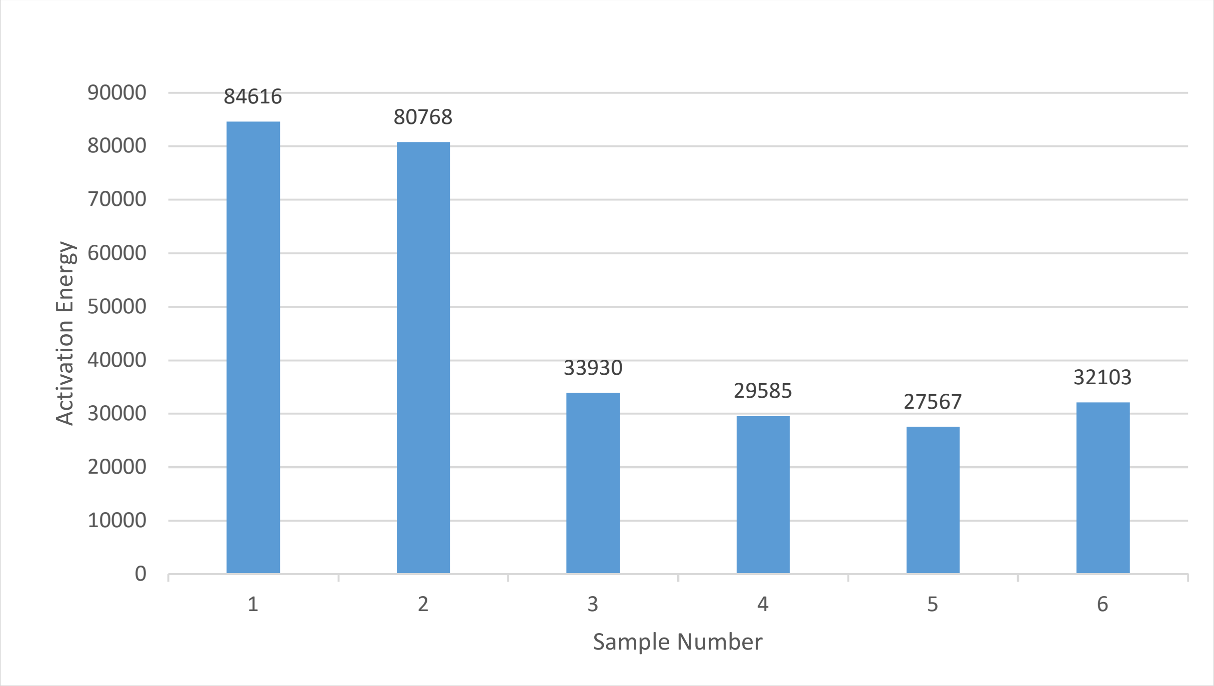


Figure 3.1.13 A Bar Diagram of Comparison of Activation Energy of Sewage Sludge

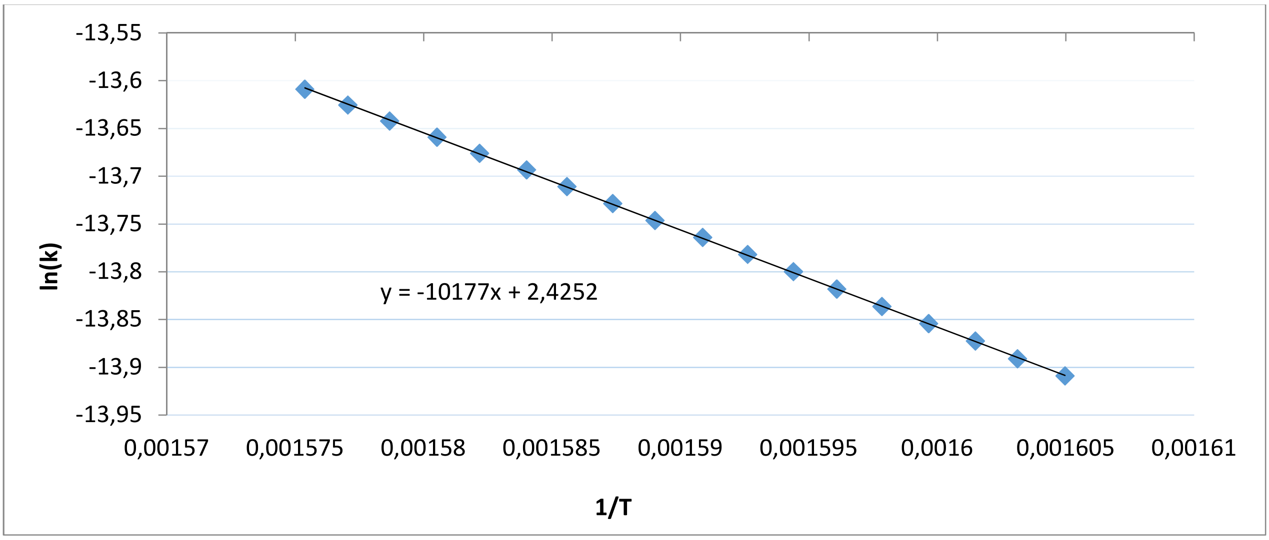


Figure 3.1.14 Graphical representation equation whose Activation Energy calculated of the HTC of Primary sewage sludge (SS) at 200 ^{0} C plus 5-minute residence time

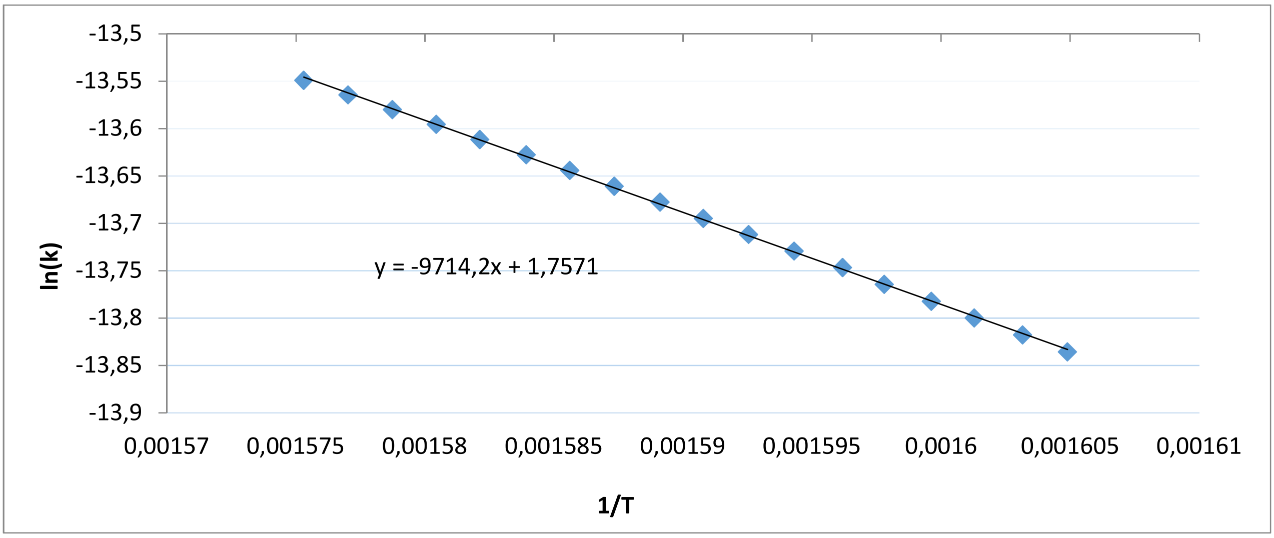


Figure 3.1.15 Graphical representation of the equation whose Activation Energy calculated of HTC of Primary sewage sludge (SS) at 200 ^{0} C plus one hour of residence time

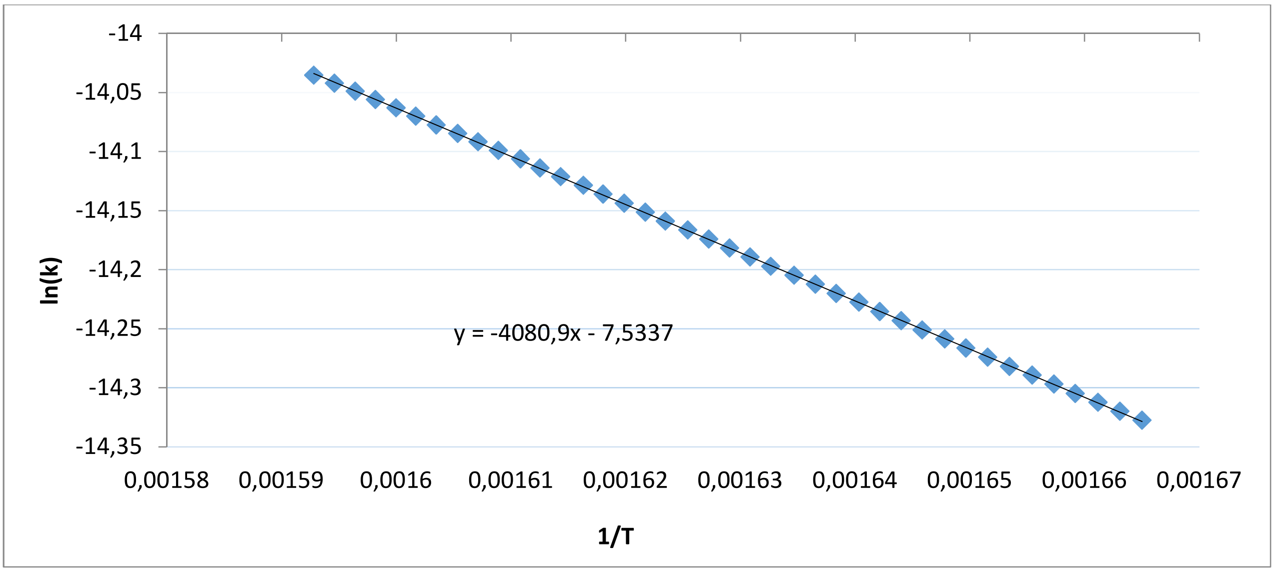


Figure 3.1.15 Graphical representation of the equation whose Activation Energy calculated of HTC of Secondary sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time

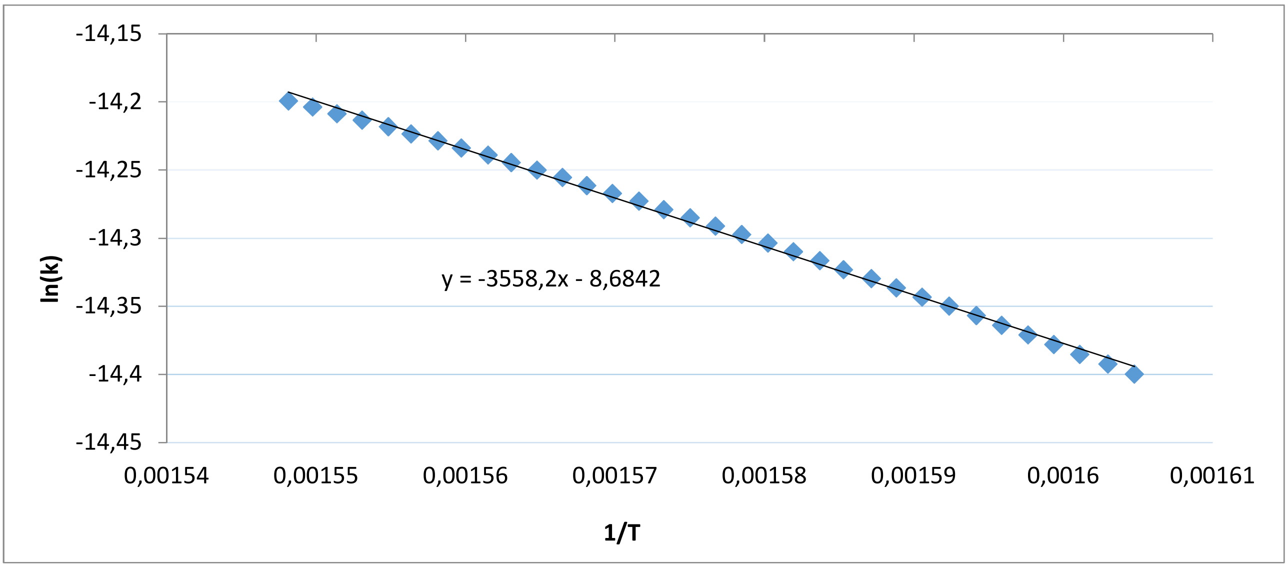


Figure 3.1.16 Graphical representation of the equation whose Activation Energy calculated of HTC of Secondary sewage sludge (SS) at 200^0 C plus one hour residence time

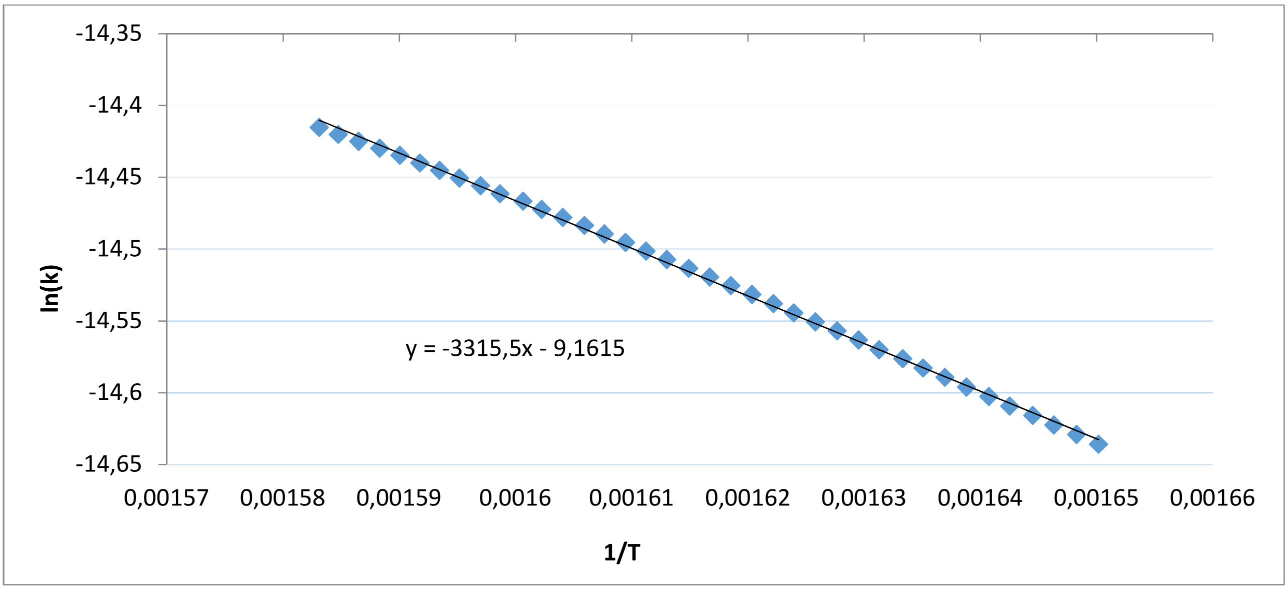


Figure 3.1.17 Graphical representation of the equation whose Activation Energy calculated of HTC of AD digestive sewage sludge (SS) at 200 ^{0}C plus 5-minute residence time

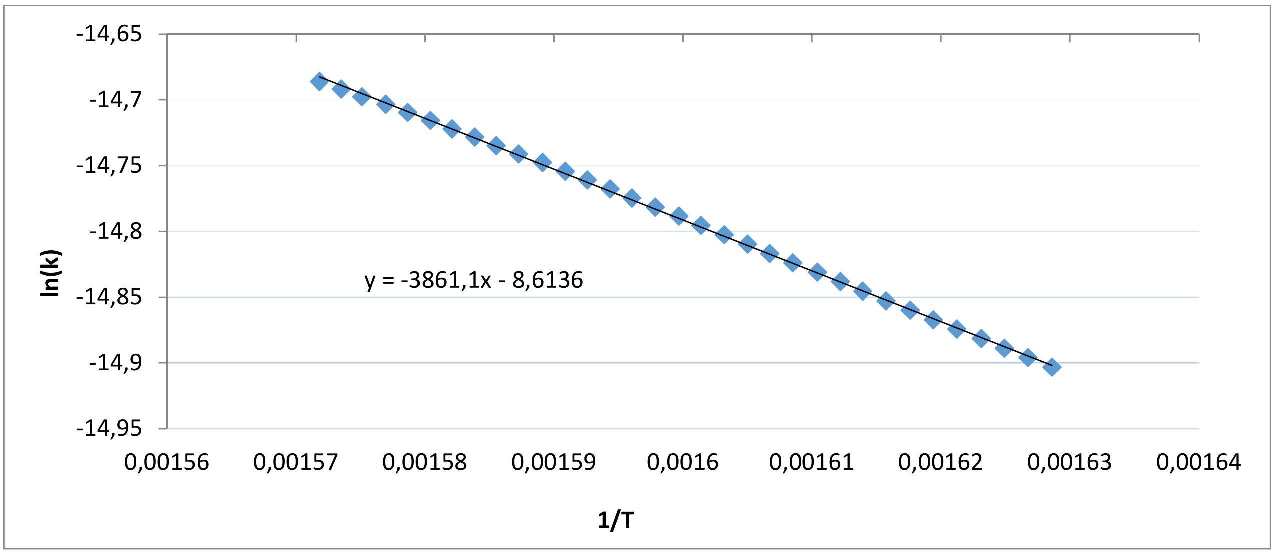


Figure 3.1.18 Graphical representation of the equation whose Activation Energy calculated of HTC of AD digestive SS at 200 ^{0} C Plus one hour residence time.

3.2 Dewatering after Hydrothermal Carbonization

Sewage sludge that has been dewatered usually goes through additional treatment or disposal. The outcomes are contingent upon the sludge's properties and the dewatering technique employed. But these are some typical results-

1. Dewatering sewage sludge removes a large amount of its water content, which turns it into a more solid substance with a lower moisture content. This facilitates the handling and transportation of the sludge.
2. Increased Solid Content- Depending on how well the dewatering procedure works, the sludge's solid content will rise after it has been dewatered. Dewatered sludge usually has a larger percentage of inorganic and organic solids.
3. Better Management Features- Compared to wet sludge, dewatered sludge is frequently simpler to handle and control. It might be more cake-like or granular in consistency, which would allow for more processing or disposal.
4. Reduced Volume- One of the main goals of dewatering is to get rid of as much sludge as possible because doing so can save a lot of money on disposal and transportation. Depending on the technique employed, dewatering can reduce volume by 70% to 90%.
5. Pathogen Reduction: Dewatering may also result in a decrease in the concentration of pathogens in the sludge, enhancing handling and disposal safety depending on the technique used and the ensuing treatment procedures.

6. Possibility of Resource Recovery: Organic matter, nutrients (phosphorus, nitrogen, etc.), and energy are among the valuable resources that dewatered sludge may include. These resources can be recovered using techniques like composting, anaerobic digestion, or incineration with energy recovery, depending on local laws and the technology available.

After dewatering, sewage sludge usually yields a more manageable, less bulky, and possibly safer substance that can be treated further or disposed of in compliance with environmental laws and best practices.

Typically, there are three categories for the moisture content of sludge: 1. Gravitational water, which is water removed using gravity. 2. Capillary water- water in the capillary gaps and surrounding soil particles that are cohesively retained in a film. 3. Hygroscopic water- water that sticks firmly to solids and can only be evaporated [84]. In Figure 3.2.1 the dewatered from sewage sludge is almost 170 grams out of 200 grams.

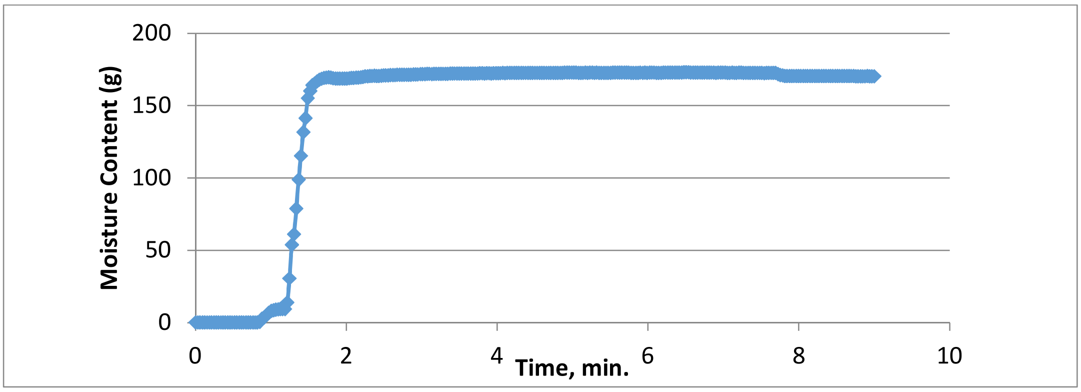


Figure 3.2.1 Dewatering graph of Primary Sewage Sludge at 200 ° C plus five-minute residence time

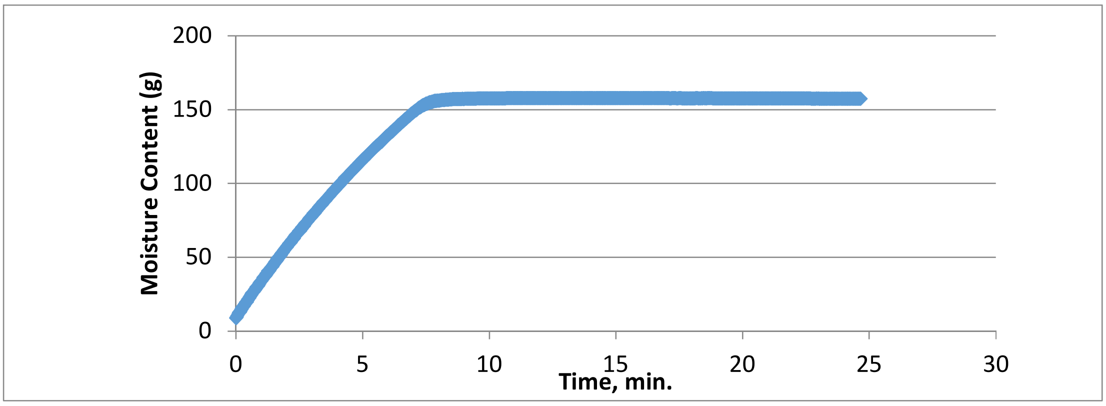


Figure 3.2.2 Dewatering graph of Secondary Sewage Sludge at 200 ° C plus one hour residence time

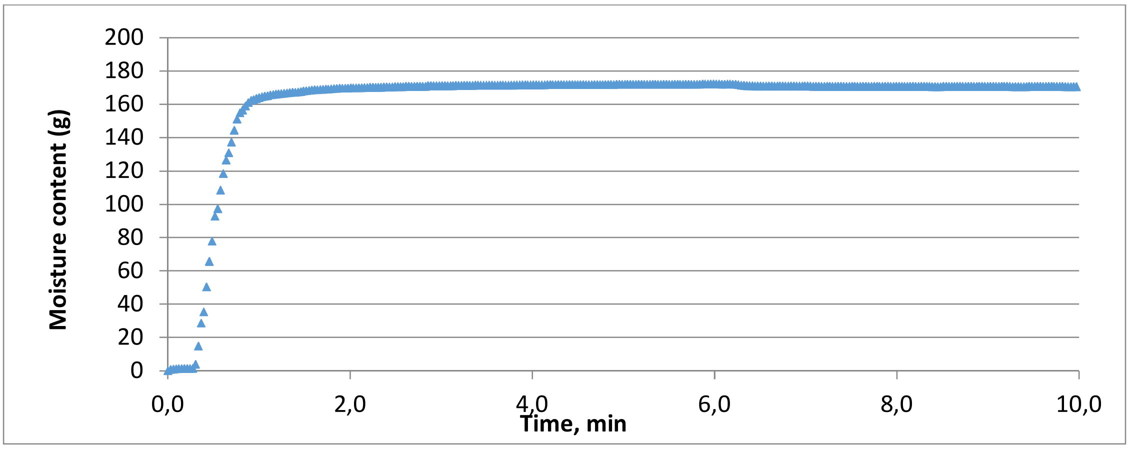


Figure 3.2.3 Dewatering graph of primary Sewage Sludge at 180 ° C plus five-minute residence time

3.3 Plasma Gasification of Sewage Sludge

In this procedure, temperature is important. The gas's hydrogen content was larger than in Striugas et al.'s work [63]. In all cases, the starting time was less than 60 seconds. Following initiation, there was a period of early stabilization during which the gasifier was not yet in equilibrium and conditions were progressively shifting, causing the gas's heating value to fluctuate in cycles. These cycles can be explained by changes in the gas's C_xH_y composition brought on by the reactor's bottom-falling, comparatively heavy sewage sludge being pyrolyzed. The char particles from the sewage sludge then grew lighter and were entrained after devolatilization. Given that the longest test lasted 14 minutes, it is reasonable to assume that the unit can operate steadily for an extended period if fuel quality fluctuation is low. An appealing and environmentally responsible solution for treating sewage sludge and using it as energy is plasma gasification. This work illustrates the potential for energy usage in the treatment of sewage sludge through an integrated process that includes plasma gasification. The percentage of Hydrogen production is rich in the composition of syngas in Primary and AD Digestive sewage sludge at 200 ^{0}C under one hour and five minutes of residence time. The hydrogen % in LHV of Janowek sewage sludge is higher as compared to other sewage sludge in different temperatures and different residence times but in some cases, Primary and AD digestive is better in certain temperatures and residence times. The LHV of Primary sewage sludge is 10.10 MJ/m^{3} and the value of LHV in Primary sewage sludge case is improved, only in the case of 250 ^{0}C under one hour of residence time is decreased. The Primary sewage sludge at 180 ^{o}C HTC plus one hour residence time has 18.69 MJ/m^{3} which is higher than Janowek sewage sludge.

Table 3.3.1 Lower Heating Value (LHV) of sewage sludge after plasma gasification

S. no.	Sample Description	LHV MJ/m^3
1	HTC of primary SS at 200 degrees plus 5 min residence	10.10
2	HTC of Primary SS at 200 degrees plus 1-hour residence	8.29
3	HTC of secondary SS at 200 degrees plus 5 min residence	7.81
4	HTC of secondary SS at 200 degrees plus 1-hour residence	6.98
5	HTC of AD digestive SS at 200 degrees plus 5 min residence	11.84
6	HTC of AD digestive SS at 200 degrees plus 1 hour residence time	6.38
7	HTC of Primary SS at 250 degrees plus 5 min residence	9.05
8	HTC of primary SS at 250 degrees plus 1-hour residence	7.96
9	HTC of secondary SS at 250 degrees plus 5 min residence	5.64
10	HTC of secondary SS at 250 degrees plus 1-hour residence	8.80
11	HTC of AD digestive SS at 250 degrees plus 5 min residence	15.62
12	HTC of AD digestive SS at 250 degrees plus 1-hour residence	10.75
13	HTC of primary SS at 180 degrees plus 5 min residence	9.35
14	HTC of secondary SS at 180 degrees plus 5 min residence	5.53
15	HTC of Primary SS at 180 degrees plus 1-hour residence	18.69
16	HTC of secondary SS at 180 degrees plus 1-hour residence	10.03
17	HTC of AD digestive SS at 180 degrees plus 1-hour residence	5.03
18	HTC of primary SS at 300 degrees plus 5 min residence	12.53
19	HTC of secondary SS at 300 degrees plus 5 min residence	7.01
20	HTC of AD digestive SS at 300 degrees plus 5 min residence	7.04
21	HTC of primary SS at 300 degrees plus 1-hour residence	9.26
22	HTC of secondary SS at 300 degrees plus 1 hour residence time	7.83
23	HTC of AD digestive SS at 300 degrees plus 1-hour residence	4.77

Table 3.3.2 Lower Heating Value (LHV) of Janowek sewage sludge after plasma gasification

S.no.	Sample Description	LHV MJ/m^3
24	HTC of Janowek Sewage Sludge at 200 degrees plus 4-hour residence time	10.48
25	HTC of Janowek Sewage Sludge at 200 degrees plus 4-hour residence time	11.51
26	HTC of Janowek Sewage Sludge at 200 degrees plus 4-hour residence time	14.10

Graphical Presentation of Plasma assisted gasification of sewage sludge

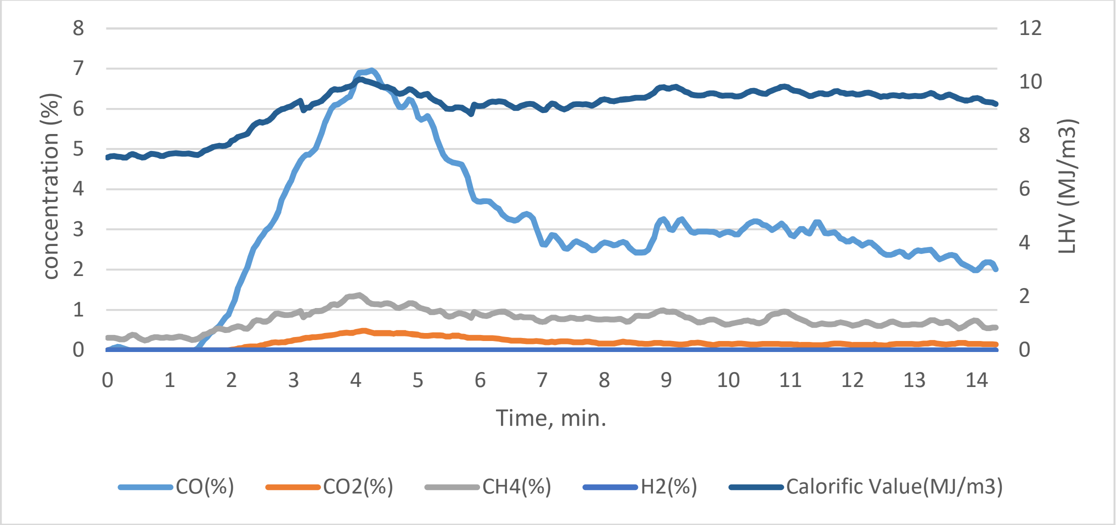


Figure 3.3.1 Graph of Plasma Gasification of HTC of primary ss at 200 ºC plus five min. residence time

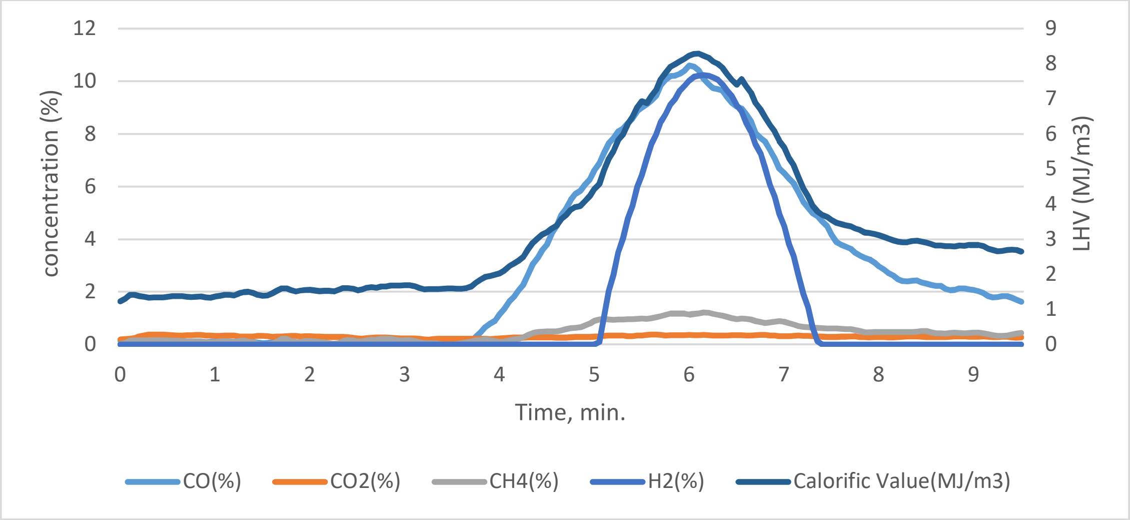


Figure 3.3.2 Graph of Plasma gasification of htc of primary ss at 200 º C plus one hour residence time (Again experiment)

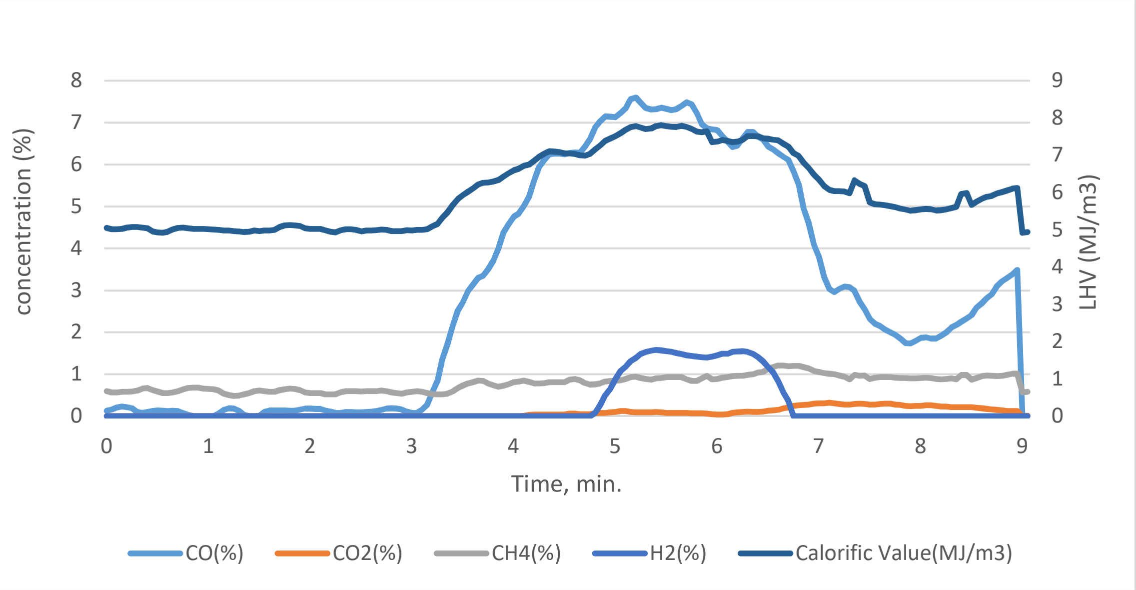


Figure 3.3.3 Graph of Plasma Gasification of HTC of secondary SS at 200 ºC plus five-minute residence

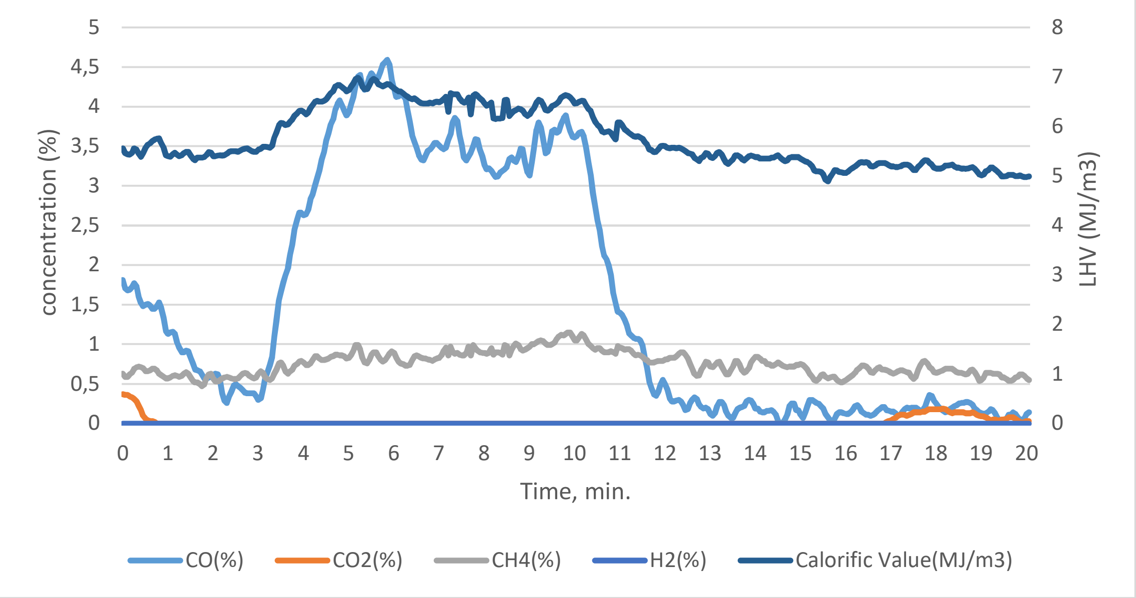


Figure 3.3.4 Graph of Plasma Gasification of HTC of secondary SS at 200 ºC plus one-hour residence

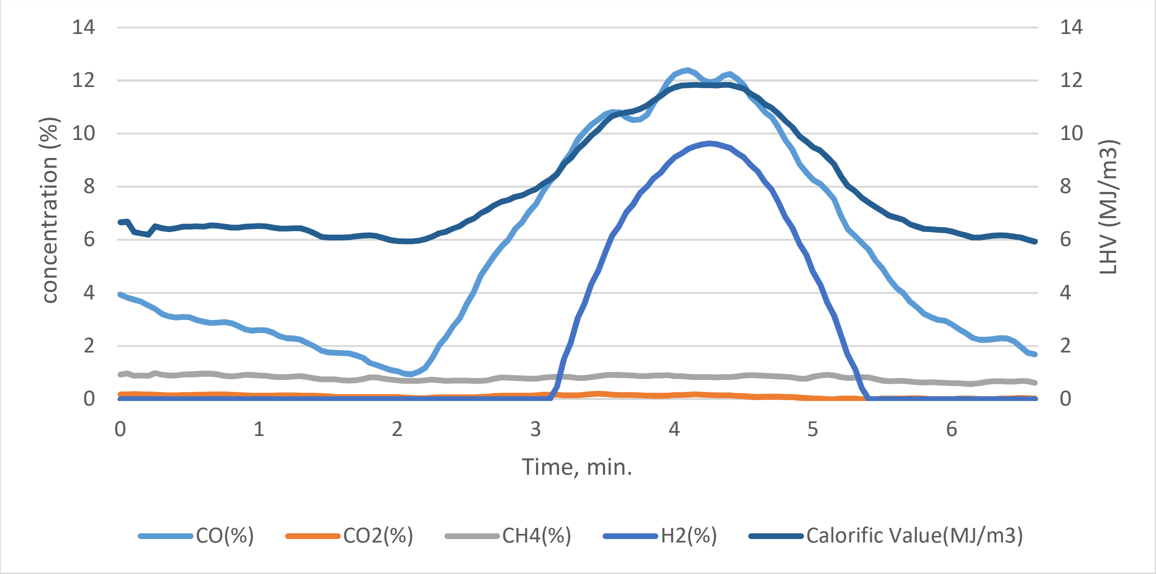


Figure 3.3.5 Graph of Plasma Gasification of HTC of AD digestive SS at 200 ºC plus five min. residence time

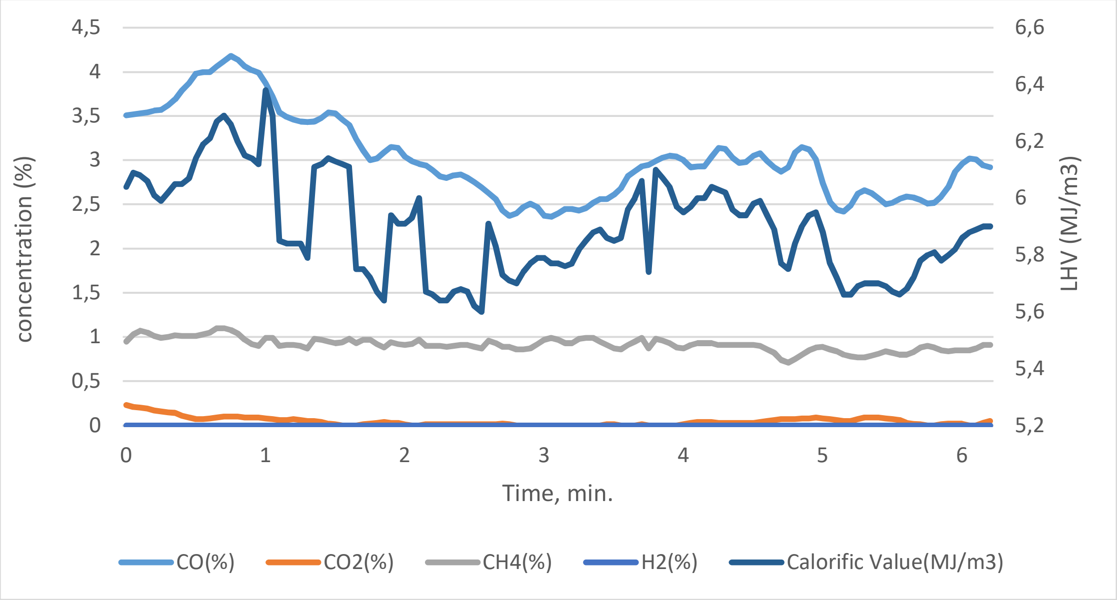


Figure 3.3.6 Graph of Plasma Gasification of HTC of AD digestive SS at 200 ºC plus one hour residence time

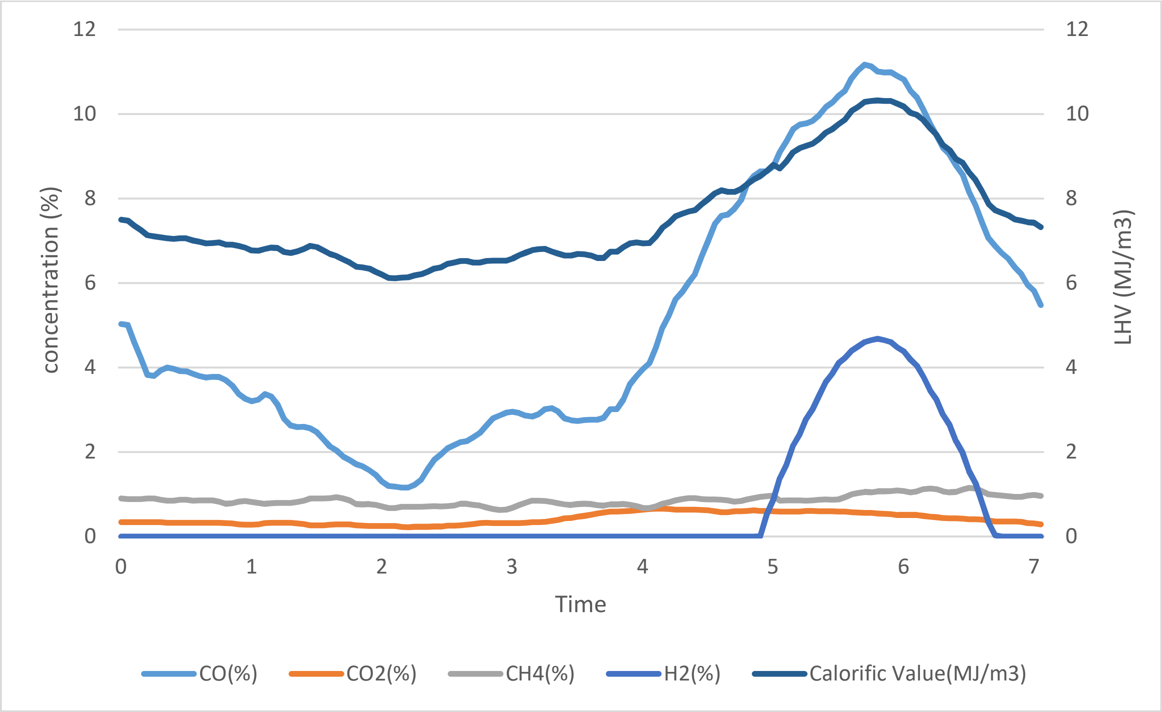


Figure 3.3.7 Graph of Plasma gasification of Janowek sewage sludge

3.4 Elemental Analysis of Ash and Discussion

In general, it is observed that the mixed trends of variations of the percentage of Titanium, Iron, Potassium, magnesium, Manganese, aluminum, and sodium were observed after plasma gasification. However, there are many episodes of increased Iron percentage at various residence times and temperatures after plasma gasification. The knowledge of these metals has a significant role in deciding the future of plasma ash. It is evident that most of the time the iron has increased hence making it suitable for applications in the field of ceramics, so tiles were made out of it. In Table 3.4.1 The percentage of Fe in secondary sewage sludge increases when the HTC temperature increases. Increasing the temperature does not affect the percentage of Fe in the rest of the two sewage sludge. The sewage sludge in which Fe % is high after plasma gasification is suitable for tiles making However it can also be most effective for corrosion according to the percentage of elements through testing. AD digestive sewage sludge Fe % increases with higher temperature within five min. residence time. It means The AD digestive sewage sludge can be useful for tiles making under five min. residence time. According to Table 3.4.1 all analysis is based on sewage sludge before Plasma gasification. But according to Table 3.4.2 one very interesting thing is that the percentage of Fe in sewage sludge increases after Plasma gasification in secondary sewage sludge cases at almost every temperature. The percentage Fe in Janowek sewage is very low as compared to secondary sewage at 300 ^{0}C HTC It means secondary sewage sludge is more suitable than Janowek sewage sludge after Plasma Gasification for tiles making.

Tabel 3.4.1 Microwave Plasma atomic emission spectroscopy (MP AES) Before Plasma Gasification of sewage sludge

S.no.	Sample Description	Ti %	Fe %	K %	Mg %	Mn %	Al %	Na %
01	HTC of Primary SS in 200 degree C plus 5 min. residence time	0.07	15.95	1.07	1.28	0.14	1.71	2.544
02	HTC of Primary SS in 200 degrees C plus 1 hour residence time	0.08	15.53	1.34	1.31	0.14	1.84	3.12
03	HTC of Secondary SS in 200 degree C plus 5 min. residence time	0.14	26.33	2.80	3.31	0.25	3.46	2.83
04	HTC of Secondary SS in 200 degree C plus 1 hour residence time	0.14	25.82	2.67	3.32	0.25	3.53	3.40
05	HTC of AD digestive SS at 200 degrees C plus 5 min. residence time	0.20	19.76	3.82	3.32	0.34	4.60	------
06	HTC of AD digestive SS at 200 degrees C plus 1 hour residence time	0.24	20.42	2.11	3.56	0.36	5.08	2.76
07	HTC of Primary SS in 250 degree C plus 5 min. residence time	0.13	18.74	0.89	1.59	0.16	2.53	1.78
08	HTC of Primary SS in 250 degree C plus 1 hour residence time	0.09	17.25	1.12	1.60	0.14	2.32	2.76
09	HTC of Secondary SS in 250 degree C plus 5 min. residence time	0.18	32.44	5.86	3.69	0.28	4.79	-------
10	HTC of Secondary SS in 250 degree C plus 1 hour residence time	0.24	39.75	3.69	4.15	0.40	6.80	-------
11	HTC of AD Digestive SS in 250 degree C plus 5 min. residence time	0.30	33.19	2.98	3.70	0.48	6.88	-------
12	HTC of AD Digestive SS in 250 degree C plus 1 hour residence time	0.15	27.91	1.83	2.75	0.22	3.33	3.26
13	HTC of Primary SS in 180 degree C plus 5 min. residence time	0.05	12.46	0.77	1.05	0.12	1.24	1.96
14	HTC of Secondary SS in 180 degree C plus 5 min. residence time	0.04	14.80	1.63	1.62	0.07	0.77	2.37
15	HTC of Primary SS in 180 degree C plus 1 hour residence time	0.07	15.98	1.22	1.34	0.16	1.84	3.19
16	HTC of Secondary SS in 180 degree C plus 1 hour residence time	0.16	32.16	3.18	3.58	0.30	4.23	-------
17	HTC of AD digestive SS in 180 degree C plus 1 hour residence time	0.09	21.00	1.98	2.13	0.17	1.92	3.39
18	HTC of Primary SS in 300 degree C plus 5 min. residence time	0.12	28.71	1.04	2.32	0.28	4.12	2.34
19	HTC of Secondary SS in 300 degree C plus 5 min. residence time	0.23	36.86	4.47	4.24	0.44	7.68	-------
20	HTC of AD digestive SS in 300 degrees C plus 5 min. residence time	0.25	30.68	3.06	3.93	0.51	6.79	------
21	HTC of Primary SS in 300 degree C plus 1 hour residence time	0.14	35.20	1.37	2.90	0.28	4.70	3.17
22	HTC of Secondary SS in 300 degree C plus 1 hour residence time	0.26	34.91	5.40	4.62	0.37	6.66	-------
23	HTC of AD digestive SS in 300 degrees C plus 1 hour residence time	0.12	28.92	1.80	2.78	0.21	3.17	3.28

Tabel 3.4.2 Microwave Plasma atomic emission spectroscopy (MP AES) after Plasma Gasification of sewage sludge

S.no.	Sample Description	Ti %	Fe %	K %	Mg %	Mn %	Al %	Na %
01	HTC of Primary SS in 200 degree C plus 5 min. residence time	0.10	14.83	0.76	1.29	0.14	2.27	1.66
02	HTC of Primary SS in 200 degrees C plus 1 hour residence time	0.43	12.47	1.03	1.41	0.14	4.42	1.58
03	HTC of Secondary SS in 200 degree C plus 5 min. residence time	0.51	22.45	4.66	4.41	0.45	8.82	-
04	HTC of Secondary SS in 200 degree C plus 1 hour residence time	0.33	24.63	3.38	4.36	0.39	7.16	2.92
05	HTC of AD digestive SS at 200 degrees C plus 5 min. residence time	0.42	22.07	4.94	4.44	0.48	8.54	-
06	HTC of AD digestive SS at 200 degrees C plus 1 hour residence time	0.36	11.92	3.34	4.55	0.62	10.72	-
07	HTC of Primary SS in 250 degree C plus 5 min. residence time	0.14	11.85	1.01	1.85	0.19	3.05	2.02
08	HTC of Primary SS in 250 degree C plus 1 hour residence time	0.32	19.84	2.72	3.68	0.41	10.52	-
09	HTC of Secondary SS in 250 degree C plus 5 min. residence time	0.79	22.10	9.02	5.31	0.54	10.66	-
10	HTC of Secondary SS in 250 degree C plus 1 hour residence time	0.36	23.34	5.74	5.42	0.63	10.87	-
11	HTC of AD Digestive SS in 250 degree C plus 5 min. residence time	0.42	31.95	4.11	5.11	0.66	12.50	-
12	HTC of AD Digestive SS in 250 degree C plus 1 hour residence time	0.10	26.95	1.23	3.02	0.21	3.08	1.84
13	HTC of Primary SS in 180 degree C plus 5 min. residence time	0.12	20.45	1.34	2.38	0.21	3.36	2.47
14	HTC of Secondary SS in 180 degree C plus 5 min. residence time	0.38	16.51	2.89	3.60	0.21	4.62	-
15	HTC of Primary SS in 180 degree C plus 1 hour residence time	0.80	15.77	2.45	3.18	0.38	11.36	3.37
16	HTC of Secondary SS in 180 degree C plus 1 hour residence time	0.23	28.32	4.58	5.72	0.55	8.78	-
17	HTC of AD digestive SS in 180 degree C plus 1 hour residence time	0.28	21.48	3.23	4.17	0.30	5.63	-
18	HTC of Primary SS in 300 degree C plus 5 min. residence time	0.14	26.9	1.28	3.66	0.29	6.60	1.68
19	HTC of Secondary SS in 300 degree C plus 5 min. residence time	0.18	42.96	3.37	5.32	0.38	6.45	-
20	HTC of AD digestive SS in 300 degrees C plus 5 min. residence time	0.21	31.04	2.65	5.07	0.43	6.57	3.27
21	HTC of Primary SS in 300 degree C plus 1 hour residence time	0.14	41.00	1.28	4.02	0.37	6.65	2.38
22	HTC of Secondary SS in 300 degree C plus 1 hour residence time	0.75	36.21	6.64	5.81	0.50	10.37	-
23	HTC of AD digestive SS in 300 degrees C plus 1 hour residence time	0.22	44.24	2.68	4.79	0.41	7.34	3.07
24	HTC of Janowek SS at 200 degrees plus 4-hour residence time	0.08	30.16	1.99	3.17	0.25	4.10	2.76

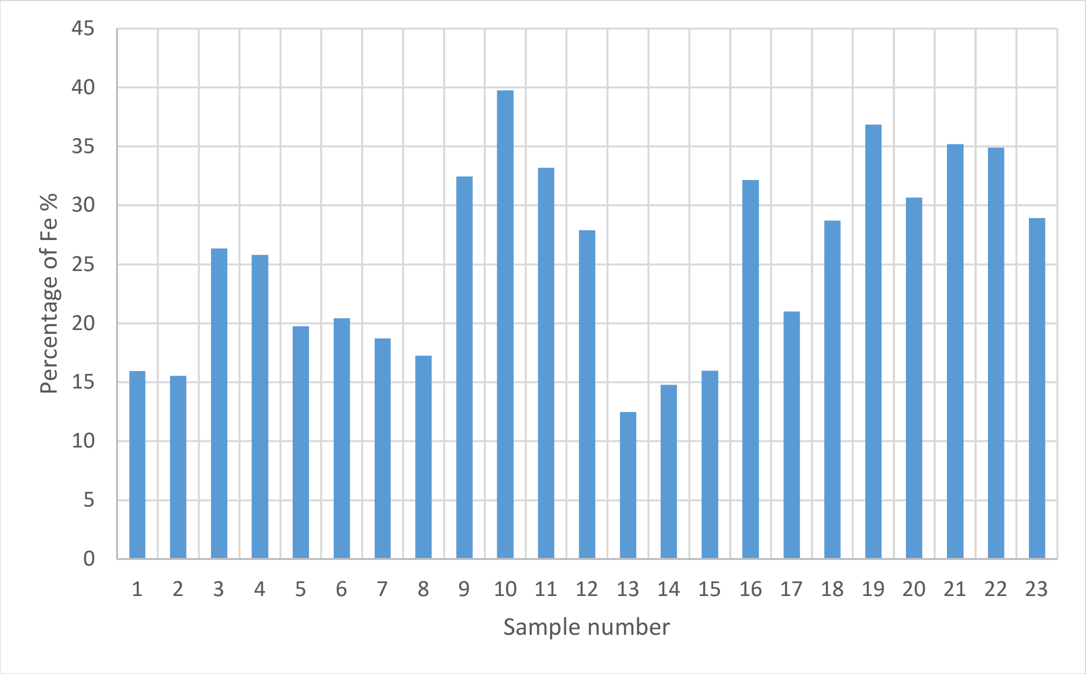


Figure 3.4.1 Graphical presentation of Comparison of Fe % in the sample of sewage sludge before Plasma Gasification

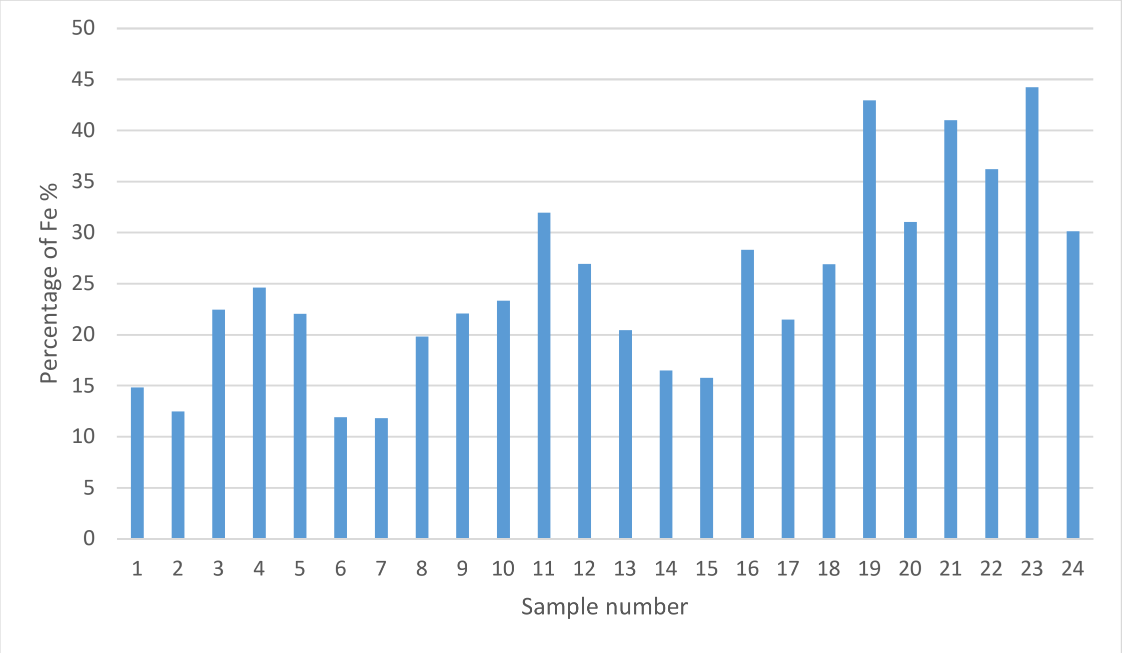


Figure 3.4.2 Graphical presentation of Comparison of Fe % in the sample of sewage sludge after Plasma Gasification

3.5 Scanning Electron Microscopy and Energy Dispersive X-ray of Sewage Sludge after hydrothermal Carbonization

1. HTC of primary SS at 200 degrees plus 5 min residence

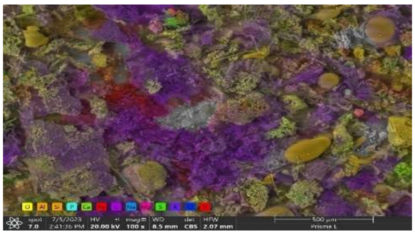


Figure 3.5.1 100 X magnification

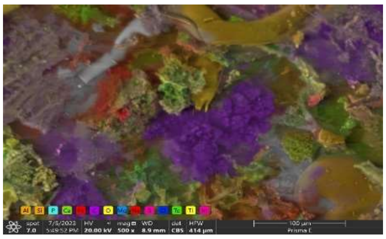


Figure 3.5.2 500 X magnification

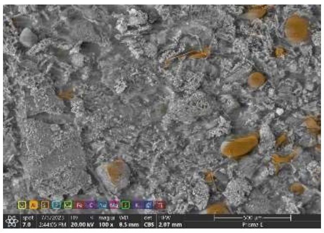


Figure 3.5.3 Al

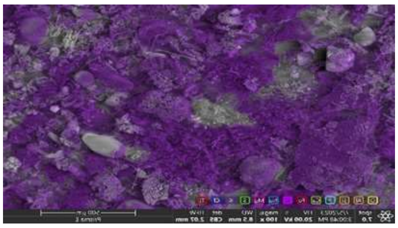


Figure 3.5.4 C

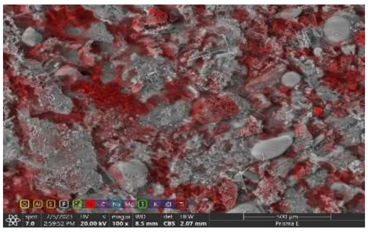


Figure 3.5.5 Fe

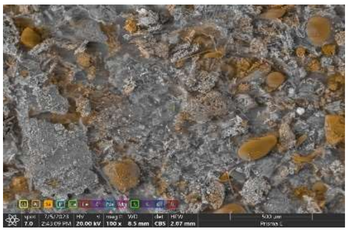


Figure 3.5.6 Si

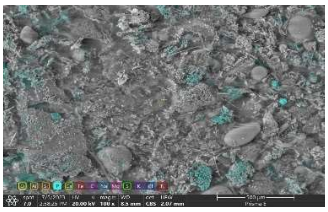


Figure 3.5.7 P

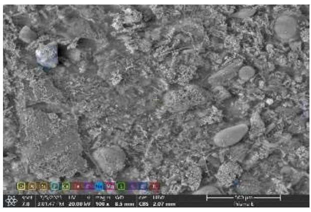


Figure 3.5.8 Na


Figure 3.5.9 S

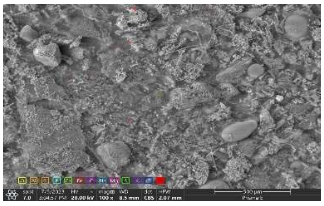


Figure 3.5.10 Ti

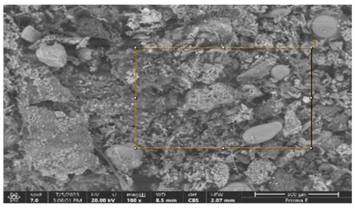


Figure 3.5.11 EDX

The two images offered are colorized scanning electron microscopy (SEM) images that suggest primary sewage sludge (SS) hydrothermally carbonized (HTC) after five minutes of treatment at 200 degrees Celsius. When used in conjunction with an energy-dispersive X-ray spectroscopy (EDS) instrument, SEM images enable us to analyze the surface topography and composition at the microscale and provide information about the elemental composition.

(500x Higher Magnification)

As the scale bar for 100 micrometers (µm) indicates, the magnification is 500 times (500x). Elements Detected: Al (aluminum), Si (silicon), P (phosphorus), Ca (calcium), Fe (iron), C (carbon), O (oxygen), Mg (magnesium), Na (sodium), S (sulfur), Cl (chlorine), Te (tellurium), Ti (titanium), and In (indium).

Observations: We can discern finer textures and details at this higher magnification. Particle-by-particle interactions become increasingly apparent. The surface morphology and any possible agglomerations or formations brought about by the HTC process are easier to see.

(100x Lower Magnification)

Magnification: one hundred times (100x), with a 500 micrometer (µm) scale bar.

Elements Found: Elements such as Al, Si, P, Ca, Fe, C, O, Mg, Na, S, K, Cl, and Ti were found, similar to those found in the first image.

Observations: By displaying the distribution of elements and bigger structures or patterns in the sample, this reduced magnification offers a more comprehensive picture of the sample.

Comparative Analysis and Discussion

Elemental Distribution: A complex composition of sewage sludge is shown by the presence of many elements in both photos. The distribution of these elements is probably represented by the colorization in both photos, but the greater magnification image makes the true spatial distribution easier to see.

Surface Morphology: We can observe more minute surface morphological characteristics in the higher magnification image that are not as apparent in the lower magnification image. The surface exhibits heterogeneity with different particle sizes and shapes, which may be indicative of the sludge's organic and inorganic components.

Drying Coefficient Implications: The physical properties seen in the SEM pictures, like porosity and particle size, can directly affect how the sludge behaves after it dries. For example, a more porous construction that lets water escape more easily could speed up drying.

Analytical Value: While the lower magnification image offers information on the general distribution and overall uniformity of the sample, the higher magnification image is more useful for studying particular characteristics or particles.

It's crucial to keep in mind that the field of view decreases significantly with increasing magnification when comparing SEM photos taken at various magnifications. As a result, the image at higher magnification could not accurately depict the characteristics of the full sample but rather provide a close-up view of a smaller region. The image with less detail and at a lower magnification, on the other hand, provides a better overall sense of the material.

Both images should be examined in tandem for a thorough examination in order to comprehend the sample's macroscopic and microscopic characteristics, which can then guide how the material is handled and treated.

Energy dispersive X-ray (EDX)

In Figure 3.5.11

Total Number of Counts: 890330

Total Acquisition Time: 58 seconds

Average Count Rate: 15351 cps

Acceleration Voltage: 20 kV

Table 3.5.1 EDX of HTC of primary SS at 200 degrees plus 5 min residence

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	63.5	0.2	48.4	0.2
O	24.7	0.4	25.1	0.4
Na	0.3	3.0	0.4	3.0
Mg	0.4	1.1	0.6	1.1
Al	1.8	0.4	3.1	0.4
Si	3.5	0.3	6.3	0.3
P	1.0	0.5	2.0	0.5
S	0.3	0.2	0.7	0.2
K	0.1	1.3	0.4	1.3
Ca	2.2	0.3	5.5	0.3
Ti	0.1	2.9	0.3	2.9
Fe	2.0	0.3	7.1	0.3

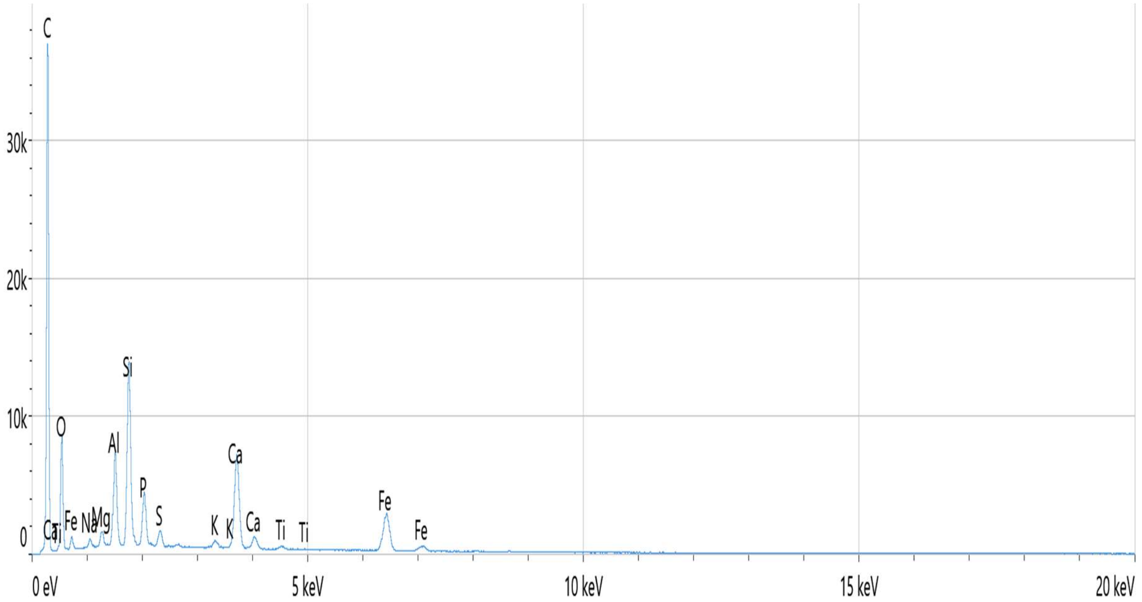


Figure 3.5.1 EDX graph of HTC of primary SS at 200 degrees plus 5 min residence

2. HTC of Primary SS at 200 degrees plus 1-hour residence

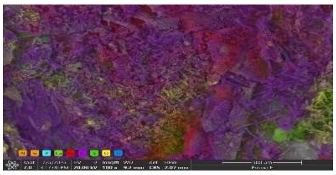


Figure 3.5.12 100 X magnification

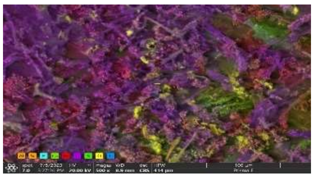


Figure 3.5.13 500 X

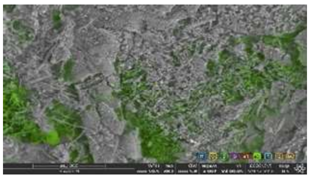


Figure3.5.14 Ca

Figure 3.5.15 C

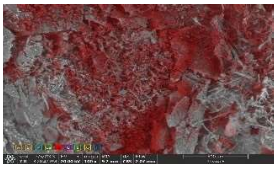


Figure 3.5.16 Fe

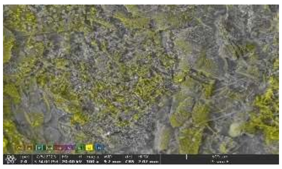


Figure 3.5.17 O

Figure 3.5.18 Si

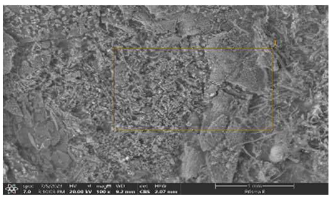


Figure 3.5.19 EDX

These two photos are colorized scanning electron microscopy (SEM) images of primary sewage sludge (SS) hydrothermally carbonized (HTC) at 200 degrees Celsius for one hour. The sample is shown in the pictures at two distinct magnifications, enabling a close inspection of the morphology and elemental makeup of the substance.

Initial Picture (Magnification of 100x)

100 times the magnification (100x).

Scale: 500 micrometres are shown by the scale bar.

The elements that have been identified include titanium (Ti), aluminum (Al), silicon (Si), phosphorus (P), calcium (Ca), iron (Fe), carbon (C), sulfur (S), and oxygen (O).

Observations: A general picture of the surface morphology and elemental distribution of the sample is discernible at this reduced magnification. The image's varied color scheme suggests a complicated dispersion of different elements.

Second Picture (Magnification of 500x)

500 times the magnification (500x).

Scale: One hundred micrometers is shown by the scale bar.

Elements Recognized: Elements that are similar to those in the first image are recognized.

Observations: The sample can be examined more closely thanks to the increased magnification, which also makes it possible to see more accurate positions for the elemental composition and finer features of the surface structure.

Comparative Analysis and Discussion

Detail vs. Overview: The first image provides a broad overview of the sample, whereas the second image displays greater detail because of its higher magnification. Understanding the sample's microstructural characteristics, which are not visible in the image at lower magnification, may depend on this.

Elemental Distribution: The existence and distribution of different elements are highlighted in both photos by the use of color labelling. Understanding the micro-environment within the sludge is aided by being able to pinpoint these constituents' precise locations in the higher magnification image.

Morphological aspects: Particle size, porosity, and the degree of aggregation are morphological aspects that may be seen in the higher magnification image. These properties have a significant impact on the drying process and the drying coefficient.

Implications for the HTC Process: The higher magnification image's detailed view can shed light on the modifications made to the sewage sludge by the HTC process.

such as the production of a porous structure that could speed up the drying process or change how inorganic and organic materials combine.

Homogeneity and Variability: The homogeneity of the treatment effect throughout the sample can be evaluated by comparing the two photographs. A consistent distribution of particular traits or elements across both magnifications could suggest a consistent treatment procedure.

The photos offer useful information that can be utilized to correlate the treated sludge's physical and chemical properties with how it behaves throughout further processing stages, such drying. The heterogeneous character seen at both magnifications points to intricate interactions between the inorganic and organic components, which can have a big impact on the characteristics of the material.

Energy Dispersive X-ray (EDX)

In Figure 3.5.19 EDX

Total Number of Counts: 980569

Total Acquisition Time: 58 seconds

Average Count Rate: 16906 cps

Acceleration Voltage: 20 kV

Table 3.5.2 EDX of HTC of Primary SS at 200 degrees plus 1-hour residence

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	79.6	0.2	58.6	0.2
O	6.4	1.2	6.3	1.2
Al	0.7	0.9	1.1	0.9
Si	4.1	0.3	7.0	0.3
P	0.8	0.5	1.6	0.5
S	0.9	0.1	1.8	0.1
Ca	1.9	0.4	4.8	0.4
Ti	0.1	2.6	0.4	2.6
Fe	5.4	0.1	18.5	0.1

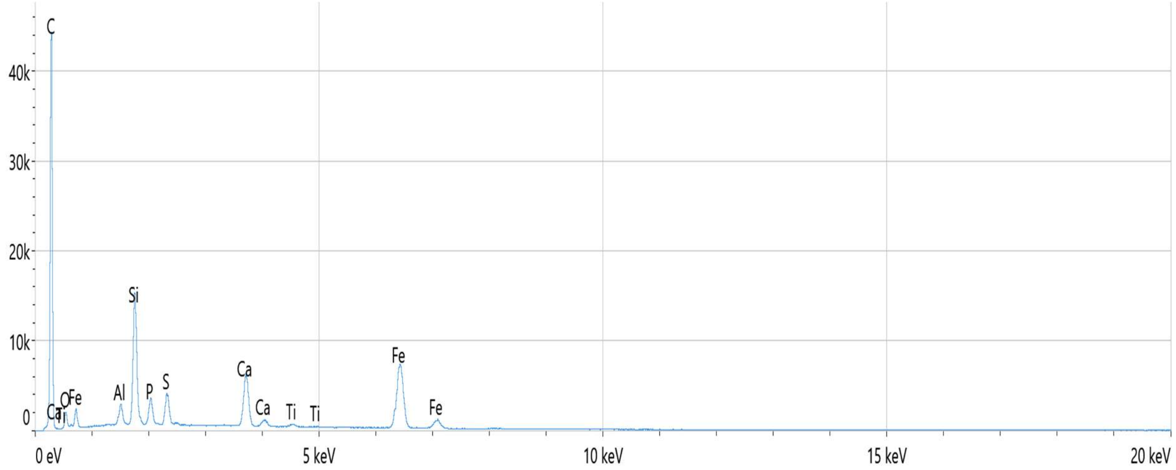


Figure 3.5.2 EDX graph of HTC of Primary SS at 200 degrees plus 1-hour residence

The current study reports the effect of HTC on the ash produced after gasification. Plasma ash is found to contain maximum carbon content. The ash produced with HTC was examined through SEM/ EDX. It was observed generally that the carbon content of HTC ASH after gasification increased. The inorganics also decreased after HTC. In this case, the dry SS before HTC is the most economical process, as it produces the highest quality fuel with the lowest cost. The highest quality of carbon is obtained from the dry SS after the HTC process. The ash obtained from the experiment with HTC ash after gasification is most suitable for tile making. This ash has a higher percentage of silica and alumina, which are the main components of ceramic tiles. The ash also has a lower percentage of impurities and ash content that is beneficial for tile making and hence can find many commercial applications in many emergent fields and it can boost the circular economy concert becoming a vital part of European countries.

The ash obtained from the experiment with HTC ASH after Plasma gasification is most suitable for tile making. This ash has a higher percentage of silica and alumina, which are the main components of ceramic tiles. The ash also has a lower percentage of impurities and ash content that is beneficial for tile making and hence can find many commercial applications in many emergent fields and it can boost the circular economy concert becoming a vital part of European counties.

Moreover, the colored SEM for various non-metals have confirmed what was observed in the elemental analysis that there are variations of their individual increase and decrease at various episodes after HTC treatment, however the substantial amount of Fe, Al, Si was observed and hence making it suitable for tile making.

3.6 Production of Tiles

When using sewage sludge to make traditional pottery, the following are the key benefits: immobilization of heavy metals, recycling of waste whose production rises daily due to the construction of new wastewater treatment plants, and lower costs for basic supplies. The values of linear contraction and the percentage of sludge don't appear to have any evident relationship in terms of the technological characteristics of the finished ceramics goods produced. However, there is a linear relationship between the increase in water absorption and the sludge percentage. In this research, the tiles are made from Janowek sewage sludge because the quantity of material for the production of tiles is sufficient, according to the elemental test the percentage of Fe after Plasma Gasification is low as compared to other sewage sludge ash. The resulting products had an average mechanical compressive strength of 28.309 N/mm2, and the water absorption rate was almost 20.8%. An innovative approach to waste management and the production of sustainable materials is to turn the ash leftover from the plasma gasification of sewage sludge into tiles. It is a shining illustration of the movement toward innovative, economic, and sustainable waste-to-material strategies. The idea's central component is a ceramic mixture consisting of 20–25% weight of ashes leftover from the plasma gasification of sewage sludge and 80–75% weight of clay. Depending on how much ash is in the finished mixture, items are made by pressing them. In Table 3.6.1 the comparison of compressive strength between different types of tiles made from different compositions.

Table 3.6.1 Comparison of main parameters and properties of tiles from sewage sludge

S.no.	Raw Material	Sludge Content %	Temperature (ºC)	Time (Min.)	Compressive Strength (MPa or N/mm^2)	Reference
01	Sewage sludge, limestone, marl, bauxite, iron ore	15	1400-1500	20	60.5	[153]
02	Sewage sludge, iron, shale, limestone, fly ash, sand	15	1450	120	60.48	[154]
03	Lime-dried sludge, iron slag limestone, clay	15	1400	60	61.8	[155]
04	Sewage sludge ash, water purification sludge ash, limestone, ferrate	16.7	1400	240	62.5	[156]
05	Marble sludge, sewage sludge, drinking water sludge, basic oxygen furnace sludge, sand, limestone, clay, iron slag	30	1000-1400	60	67.5	[157]
06	Heavy metal-contaminated sludge, surface finishing sludge, electroplating sludge, clay, limestone, ferrate	15	1400	180	-	[158]
07	Sewage Sludge ash, Gelina Clay	20	1000	120	28.309	-

The Moisture Content in this type of tile is also high, after being kept in the water for three days, the tiles are as good as in the beginning, its capacity to absorb water is also high when one experiment is done with one small tile (pills) whose starting weight was 3.02 gram and after water absorption, its weight is 3.65 grams, the percentage of water absorptions is 20.8%. This type of tile is used in the dessert side of India for local small industrial purposes as a refractory.

4 Overall conclusions and recommendations for future work

4.1 Overall Conclusion of the Thesis

The carbon content of dry sewage sludge is greatly increased by HTC treatment. The hydrogen, nitrogen, and sulphar level slightly drop. the oxygen content drops, suggesting that there may have been deoxygenation reactions during the procedure. The residence time can be 5 minutes to a day but shorter residence times—five minutes or an hour—are the focus of several investigations to develop bio-coal for energy applications. If the residence duration between 180 and 250 °C is increased, the amount of nitrogen will decrease. It is thought that the reactions become more severe with a longer residence duration.

The temperature and residence time employed in the HTC process have a substantial impact on the energy content of the syngas. For instance, the highest energy content of 18.69 MJ/m³ was created by HTC of primary SS at 180 ^{0}C and a 1-hour residence period, whereas the lowest energy content of 4.77 MJ/m³ was produced by HTC of AD digesting SS at 300 ^{0} C and a 1-hour residence. There isn't a clear pattern showing that the energy content regularly rises or falls with increasing temperature or length of stay. The findings imply that the ideal circumstances for the creation of syngas may vary depending on the kind of sludge and must be ascertained through experimentation. The elemental composition of the sewage sludge appears to be affected by HTC treatment, which tends to enrich the carbon content while diminishing the quantities of hydrogen, nitrogen, sulphur, and oxygen to variable degrees. When utilized in energy recovery procedures, this might improve the sludge's fuel qualities. The hydrochar obtained after dewatering and drying was used for plasma gasification. By Dewatering I can understand, how much water is separated and in which sewage sludge type the tendency of dewatering good as compared to others. The fixed bed Plasma gasification process is characterized by the fact that for the processing of chemically and bacteriologically contaminated organic waste (including after its hydrothermal carbonization), a non-equilibrium LF radio frequency arc plasma in the range of 50-120 kHz is used. A gasifying agent can function in multiple capacities. Depending on their applicability, gasifying agents such as CO_2, O_2, and H_2O are utilized. Figure 2.5.1 uses CO_2 as a gasifying agent because it facilitates the easy decomposition of sewage sludge carbon in plasma gasification. The intention is to create syngas, which will be utilized to power the turbine and generate a lot of CO_2, which will be used as a gasifying agent in plasma gasification. In Figure 2.5.2 H_2O is used as a gasifying agent to increase the involvement of the present Carbon of Sewage Sludge in the experiment. Dichloromethane (CH_2Cl_2) and NaOH are the cleaning system's methods for cleaning the syngas in both systems. Sulfur is reduced by using NaOH. An analyzer is used to examine each component of syngas independently. The analyzer found the percentage of CO, CO_2, CH_4, and H_2. The percentage of Hydrogen production is rich in the composition of syngas in Primary and AD Digestive sewage sludge at 200 ^{0}C under one hour and five minutes of residence time. The hydrogen % in LHV of Janowek sewage sludge is higher as compared to other sewage sludge in different temperatures and different residence times but in some cases, Primary and AD digestive is better in certain temperatures and residence times. The gas obtained in HTC had a major constituent as CO_2 along with the presence of CO, H_2, and CH_4. The syngas obtained after plasma gasification are composed of the increased percentage of Iron in plasma ash after plasma gasification making it an ideal candidate for tiles synthesis. The primary benefits of using sewage sludge in the production of traditional ceramics are the immobilization of heavy metals, The resulting products had an average mechanical compressive strength of 28.309 N/mm2, and the water absorption rate was almost 20.8%. The Moisture Content in this type of tile is also high, after being kept in the water for three days, the tiles are as good as in the beginning, its capacity to absorb water is also high.

The tiles made from the residues after Plasma gasification with gelina Clay depict a complete solution of sewage sludge by making tiles. The quality of tiles is also good and cost-effective as well as useful for different purposes of construction work. This type of tile is used in the dessert side of India for local small industrial purposes as a refractory.

4.2 Recommendations for future work

Many aspects need to be explored further rather this thesis has opened many gates for future investigation:

- The char that was produced after HTC needs further investigation to make it suitable for the adsorption process for applications in water treatment.
- More process variables should be studied like the effect of few catalysts, pressure and more over another range of temperature and residence time should be studied.
- The effect of various types of sewage sludge on the quality of Syngas can be explored.
- This thesis has given substantial evidence that Syngas produced has sufficient calorific value to be used as fuel however its conversion to methanol and then to petrochemicals and naphtha, diesel, petrol, wax, etc. Should also be studied.
- The plasma gasifier with more capacity should be studied with different types of feedstock.

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6 The list of Published/Submitted/under preparation articles/Patents/Conferences.

The following works constitute the collection of published and topically connected scientific articles, as described in Art.187 of the Law on higher education and science from 20th of July 2018 (Dz. U. 2018 poz. 1668):

Paper 1

- Vishwajeet et al “Entrained flow plasma gasification of sewage sludge-proof of-concept and the fate of inorganics”. Energies. 2022, vol. 15 No. 5, art. 1948, pp. 1-14.DOI: 10.3390/en15051948

Impact Factor of the Journal 3.2

MEiN points: 140

Citations: 18 (without self-citations)

Paper 2

Vishwajeet et al “Study of Scanning Electron Microscopy, Ultimate, Proximate Analysis of sewage sludge char and use of RET Screen software”. ZESZYTY ENERGETYCZNE,2023, status submitted.

MEiN points: 20

Paper 3

Vishwajeet et al “Influence of hydrothermal carbonization on catalytic fast pyrolysis of agricultural biomass” " Applied sciences, 2023, vol. 13, no. 7, art 4190, pp1-16.
https://doi.org/10.3390/app13074190
Impact Factor- 2.7
MEiN points: 100

Paper 4

Vishwajeet et al “Use of hydrothermal carbonization and cold atmospheric plasma for surface modification of brewer's spent grain and activated carbon". Energies. 2022, vol. 15, No. 12, art. 4396, pp. 1-11. **https://doi.org/10.3390/en15124396**
Impact Factor- 3.2
MEiN points: 140

Paper 5

Vishwajeet et al "Non-destructive diagnostic methods for fire-side corrosion risk assessment of industrial scale boilers, burning low-quality solid biofuels - a mini-review. Energies. 2021, vol. 14, no. 21, art. 7132, pp. 1-15. https://doi.org/10.3390/en14217132

Impact Factor- 3.2

MEiN points: 140

Paper 6

Vishwajeet et al "Influence of hydrothermal carbonization on high-temperature entrained flow steam gasification of sewage sludge – experimental validation of different gasification models". Status- Submitted, Applied Energy, Elsevier.

Impact Factor- 11.446

MEiN points: 200

Paper 7

Vishwajeet et al," Characterization of sewage sludge after Hydrothermal Carbonization" Status- Under Preparation, Sustainable chemistry and Pharmacy, Elsevier.

Impact factor- 6.

Patent 1

"An innovative, economical, and valuable tile product. Synthesized from sewage sludge residues after Plasma Gasification" Polish Patent File application number- P.446892, [WIPO ST 10/C PL448114], 2023.

Patent 2

"Plasma Gasification method for sewage sludge" Polish Patent File application number- P.448144, [WIPO ST 10/C PL448144], 2024.

Conference 1

15th Conference "Młodzi w Energetyce" Wroclaw University of Science and Technology, 24-26 April 2023,” SEM-EDX analysis of sewage sludge before and after hydrothermal carbonization”.

Conference 2

XXV Jubilee Congress of Thermodynamics, Gdansk, 11-14 September 2023, “Influence of HTC on dewatering of Sewage Sludge”.

Conference 3

11th edition of the "Environmental Protection & Energy Conference", on December 8, 2023, at Silesian University of Technology, Poland, on the topic of “Dewatering of sewage sludge and study of the drying coefficient”.

Conference 4

7th international conference on contemporary Problems of Thermal Engineering, Hybrid Event, Warsaw, 20-23 September, 2022, Influence of HTC on Thermal drying of Sewage Sludge digestate,URLhttps://www.sconferences.eu/cpote2022/BookOfAbstracts/Abstract/3

Conference 5

14th Conference "Młodzi w Energetyce" Wroclaw University of Science and Technology, 14-16 November 2022,” RET Screen Software- A Tool Useful in Energy Management”.

Conference 6

Elsevier Energy and Climate Transformations: 3rd International Conference on Energy Research & Social Science, Manchester,20-23 June 2022 "Fast pyrolysis of agricultural biomass – influence of HTC pretreatment and use of CaO as a catalyst”.