An Evaluation of Sludge-to-Energy Recovery Methods

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Abstract

Due to rapidly population growth, the increasing volume of sewage sludge from wastewater treatment facilities is becoming a prominent concern globally. The disposal of this sludge is particularly challenging due to the high content of organic, toxic and heavy metal pollutants in its constituents which poses severe environmental hazard. The use of this waste as a valuable energy resource represents an innovative stride in the achievement of a circular low carbon economy. However, the deterring properties of sewage sludge as a fuel is its high moisture and ash content which differentiates it from other solid fuels and complicates its thermal conversion. This study presents a simple analysis of four sewage to energy recovery routes (anaerobic digestion, combustion, pyrolysis and gasification) with emphasis on recent developments in research, benefits and limitations of the technology and future research considerations to ensure cost and environmentally viable sewage to energy pathway. Further research in conventional and microwave assisted pyrolysis and gasification of sewage sludge is required for promoting their economic viability and competitiveness in the future.

Keywords: Sewage sludge, sludge-to-energy, anaerobic digestion, combustion, pyrolysis, gasification.

1.0 Introduction

The increasing population and growth in urbanization has not only resulted in higher demands on finite resources such as land space, water, food and energy, it has also led to an increase in environmental challenges which includes but not limited to pollution and waste management challenges. These issues are quite detrimental to the global goal of sustainable development. Hence, they have ignited a global interest in sustainable strategies for energy production, utilization and waste management. A direct and an easily overlooked consequence of the increasing waste globally is the escalating volume of urban wastewater, especially sewage sludge. Sewage sludge can be described as any solid, semi-solid or liquid waste generated from a wastewater treatment facility. This wastewater can be sourced from municipal, commercial or industrial processes. Recently, the annual sewage sludge production has been estimated at 10 million tons (dry matter), 20 million tons and 49 trillion litres in Europe, China and United States respectively, and further increase has been projected due to economic and population growth [1, 2].

The energy content of sewage sludge reported in past literature varies between 11.10 – 22.10MJ/Kg which indicates comparable and/or higher calorific values in comparison to lignite and various biomass samples [2]. Unfortunately, the appropriate treatment and disposal of sewage sludge has only been adopted in developed countries while smaller and less developed countries still result into disposing a large portion of such generated waste into water bodies, leading to ecological degradation. The use of disposal techniques like landfills or storage are declining due to shortage of land and rising environmental and health concerns. Aside from disposal, the efforts on sustainability have also increased focus on the recovery and reuse of such sludge after purification treatment which requires further processing and sewage sludge management dynamics[3]. Until recently, the most predominant usage of such recovered sludge was for agricultural use such as fertilizers but due to the increasingly restrictive environmental standards because of its high organic and heavy metals contents. As a result, the requirements for biological routes such as anaerobic digestions, as well as thermal reactors such as incinerators for pre-treatments and processing of such wastes before re-use has increased [1]. Such thermal processing aids the recovery and usage of sludge derived products such as raw rare metals, phosphorus, ash and organic fuels. However, most of the well-established processes (mostly storage routes) remain quite limited in their capacities and capabilities to appropriately and economically meet all legal and environmental safety standards. This creates an engineering and design challenge associated with sewage sludge recycling technologies with focus on energy recovery from such wastes. Aside from the anaerobic digestion, thermochemical conversion of sludge is the most promising energy conversion route. However, the differences in the physical and chemical properties of sludge compared to other solid fuels such as coal and biomass that have relatively lower moisture, heavy metals and nitrogen contents necessitates the need for further research into the viability and effectiveness of such thermochemical conversion technologies for sewage sludge. This is particularly necessary to avoid technical challenges and ensure commercialisation potential. This review work provides a detailed assessment of energy recovery routes (biological and thermochemical processes) for extracting high-value products (heat, power and synthesis gas) from municipal sludge based on recent developments in the field. The content specifies various technologies, their suitability, effectiveness and limitations when used for processing sludge based on past studies and a comparative analysis. This would also include an in-depth discussion on the properties of using sludge as feedstock individually or co-utilised with other solid fuels and the importance of pre-processing such as drying on the thermochemical processing yield.

2.0 Materials and Scope

This study focusses on the review and analysis of various conversion processes and technologies used for energy recovery from sewage sludge. It assesses the benefits and drawbacks of different approaches. The literatures used in this review paper is globally sourced and it includes some insights on scientific and technological developments useful in obtaining an effective, economically viable and environmentally safe energy recovery technique for sewage sludge processing. Anaerobic digestion, combustion, pyrolysis and gasification are the main technologies analysed with detailed evaluation of their technological, social, environmental and financial implications. In addition, the identification of influencing factors and some barriers to the sustainable development of these technologies for sludge-to-energy was highlighted.

3.0 Sludge-to-Energy Recovery Methods

The importance of energy recovery in contemporary waste management practices remains assured due to its sustainability impact on global waste minimization, resource optimization and alternative energy generation. As a result, the presently relevant conversion technologies have been highlighted in Figure 1.

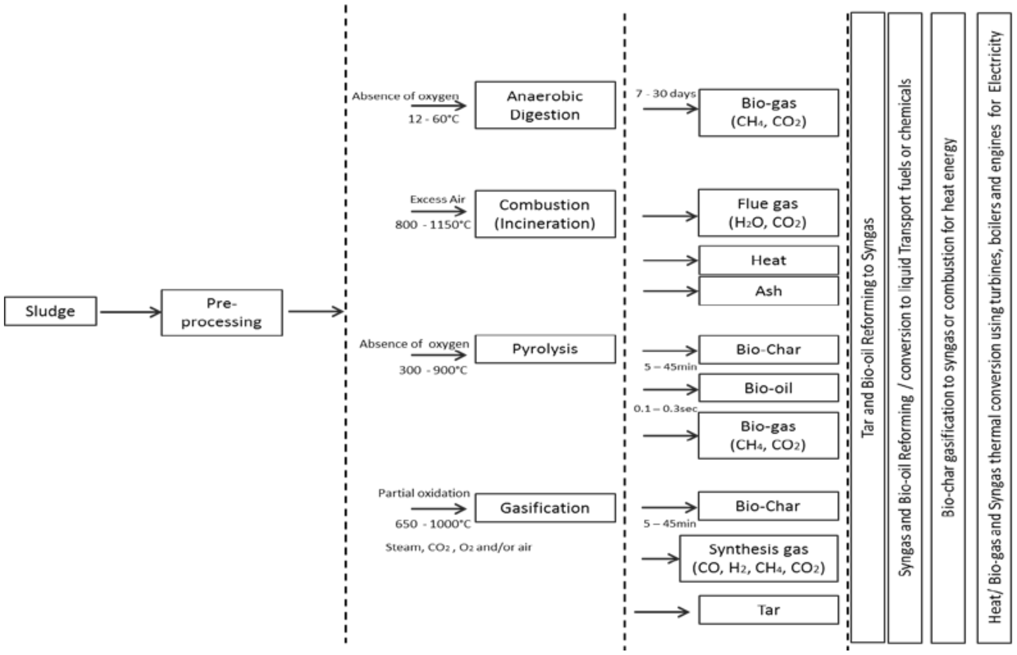


Figure 1: Potential Sewage-to-Energy Recovery routes

3.1 Pre-processing of Sludge

The constituents of sludge are made of organic matters such as carbohydrates, proteins, fats and oil, a range of microorganisms (both living and dead), and inorganic elements which are characterized with high-energy content. Nevertheless, the properties of sewage sludge are highly variable and dependent on its origins, wastewater treatment system, seasonal variations and production processes such that pre-usage processing such as drying can easily improve its organic contents percentile and their calorific value significantly. This makes the variability of their chemical composition more extreme in comparison with traditional biomass and coal samples. In addition to this, sludge has been identified for its high water content, toxic inorganics such as silver, cadmium, zinc, cobalt, chromium, copper, nickel, lead, mercury, and arsenic, organic pollutants, pathogens and microbiological pollutants [4-6]. These heavy metals are mostly pollutants from physiochemical and biological processes such as industrial waste water, corrosion in pipelines, food, medicine, textile materials and cosmetics.

The proximate analyses of sludge is such that the volatile matter of biomass>sludge>coal; the fixed carbon of coal>biomass>sludge; while the ash content (mostly aluminium, calcium, iron, magnesium, sodium, phosphorus, silicon and titanium) of sludge is higher than that of biomass and coal due to its extremely high inorganic content [7]. Similarly, the ultimate analyses of sludge reveal higher nitrogen (from protein and peptides), higher hydrogen and comparable carbon contents to lignite and biomass. The sulphur and oxygen content remain higher than biomass but comparable to that of lignite. Wet sludge has approximately 98% moisture content and with the application of mechanical dewatering processes, about 73 – 84% of the water content remains while only free water and some of the interstitial water can be removed as they are not influenced by the solid particles. Irrespective of this dewatering process, the remnant moisture (mostly vicinal water) requires the application of thermal energy for eliminating them. The use of heat can reduce the moisture to very small content ~5.6% which is mostly chemically bonded water from inorganics such as calcium or aluminium hydroxides [7, 8]. The drying of fuels for vaporising their moisture content before further thermal processing has been well established for biomass and low rank coals such that the thermal process is designed to use up waste heat energy from the fuel thermal processing for the initial drying of the fuels. However, the drying process involves additional energy and operating costs [9, 10]. The importance of drying for energy recovery from sludge is for the physical transformation of the waste material from wet matter into granular feedstock that can be easily handled and further use in most thermal processes.

3.2 Anaerobic Digestion

Anaerobic digestion is a biological process that occurs in an inert environment for the conversion of organic compounds into biogas by the use of microorganisms. The use of naturally occurring bacteria for biodegradation involves a series of biochemical stages including hydrolysis, acidogenesis (fermentation), acetogenesis and methanogenesis[11]. Hence, each stage affects the performance of the digester. This technique is adopted globally as the technologically mature and cost effective process used for stabilizing sludge before final disposal. Alternatively, sludge remnant after this digestion process has high nutritional contents (phosphorus, potassium and nitrogen) which can be used as compost and/or fertilizers for agricultural and soil reclamation purposes.

The biogas produced is made up of 60 – 70% methane, 30 – 40% carbon dioxide and trace elements of other gases with total calorific value of 13 – 21MJ/kg^3. This biogas can be recovered for heat and electricity production via numerous energy recovery routes. The potential of using such waste derived energy in the waste water treatment plan has the potential of offsetting about 50% of the operational energy used in such facilities [10, 12]. Alternatively, the energy can be used at other sources or sold to the grid. The utilization of this biogas contributes to the reduction of greenhouse gases emissions that occurred previously from the flaring or non-utilisation of the derived biogas (in landfill situations) as traditionally adapted because methane has 25 times more global warming potential in comparison to carbon dioxide. Nonetheless, this method of processing has a huge limitation with the long reaction time required and the need for suitable reaction conditions for the microorganism development which makes the profitability of this technology limited to large waste water treatment plants. Other limitations are depicted in Figure 2. The enhancement of the biogas yield and quality (methane to CO_2 fraction), reduction of reaction time and implementation of better control strategies are the main factors being investigated by researchers. Still, temperature remains one of the most decisive considerations that influence the quality and quantity of the biogas and its reaction time (digestion rate).

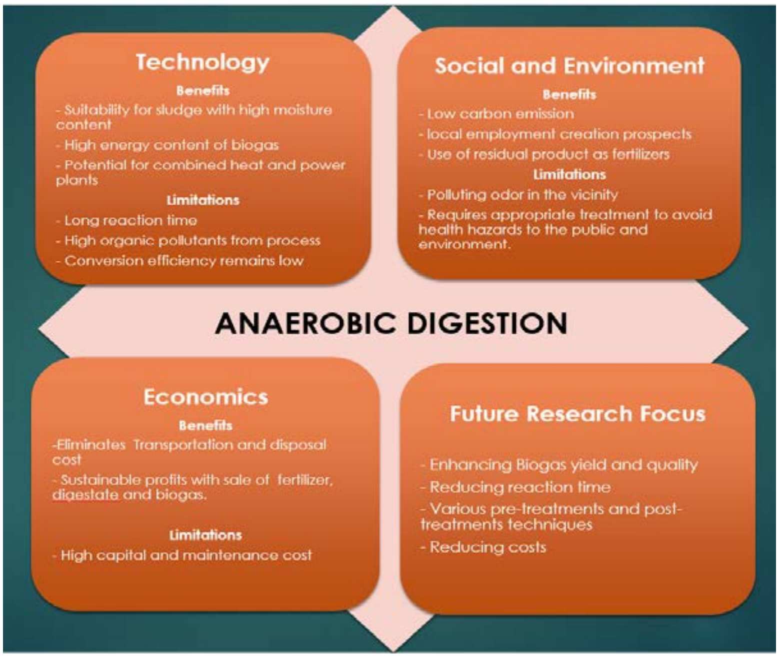


Figure 2: Technological, socio-environmental and economical assessment of anaerobic digestion for sewage processing

The use of chemical, mechanical and thermal pre-treatments to enhance the anaerobic conversion of volatile solid sludge for improving anaerobic digestion has been widely adopted recently as summarised in Table 1. Chemical pre-treatments mainly involve the use of strong reagents such as acid and alkali and oxidants for adjusting the pH of the sludge such that the yield of biogas is maximised by increasing the soluble organic fraction. Mechanical pre-treatments involve the use of mechanical vibration such as ultra-sonication for the disruption of the organic solid in the sewage sludge. Physiochemical pre-treatment such as microwave radiation which quickens biological, chemical and physical processes due to heat and extensive collisions from the vibration of molecules and ion movement. Thermal hydrolysis involves the use of heat and/or pressure treatment for improving sludge digestibility. Some studies revealed negligible change in methane yield with increase in biogas produced while others have contrasting views on the improvement in the solubility of the organic contents in the sludge as extensively reviewed [13] . In summary, there is need for a systematic comparison profile of individual pre-treatments methods and combined treatment routes as utilized in recent researches such as thermal plus chemical pre-treatments. Unfortunately, most of these researches do not consider the energy, life cycle, environmental and economic costs and benefits of these pre-treatment methods which must be well accounted for a sustainable process. This is because the additional cost, energy and/or chemical inputs required by these pre-treatment techniques to maximize biogas yield may not necessarily be energy, environment or cost efficient and their impacts must be analysed before such techniques can be implemented in practice.

Table 1: Summary of key research on Anaerobic digestion and pre-treatment methods

Author(s)	Fuel types Investigated	Reactor type used	Pre-treatment	Observations
[14]	Thickened waste activated sludge and inoculum sludge (15 - 20 days old)	Full scale, semi-continuous (12 days) anaerobic digester at 15 days hydraulic retention time (HRT) at 35°C	Acid pre-treatment - HCl for attaining pH 6 - 1 (chemical)	Optimal acid dosing for attaining pH of 2 obtained same biogas yield in 13 digestion days versus 21days required for untreated sludge. 14.3% increase in methane yield.
[15]	Pulp and Paper sludge	Batch reactor at 42 days HRT at 37°C	Alkali pre-treatment - 4g / 8g/16g NaOH/100g total solid sludge (chemical)	54 - 88% increase in methane production with 8g NaOH being the optimal amount of pre-treatment chemical. Alkaline pre-treatment can be more suitable for soluble chemical oxygen demands (COD) degradation (83 - 93%)
[16]	Sewage Sludge (7 days old)	Batch reactor at 30 days HRT at 33°C	Ozonation at 10 - 50 mg O3/l gas for up to 3 hrs 38 mins to get 0.05g / 0.1g / 0.2g O3 / g COD	Partial oxidation was promoted by the ozonation reaction which increased methane production by a factor of 1.8. Digestion rate accelerated by a factor of 2.2. Optimal ozone dose of 0.1g O3/g COD.
[17]	Waste activated sludge	Continuous reactor at 20 days HRT at 35°C	Thermo-chemical pre-treatment -130°C and 170°C for 30 - 60 mins, pH 10 - 12 (KOH)	21.3% increase in soluble COD at 130C, further 32% increase in SCOD at 170°C at pH 10. SCOD reaches 83% for pH12 sludge at 170°C . 72 - 78% increase in biogas yield, 36.4% increase in COD removal was achieved.
[18]	Waste activated sludge and inoculum sludge	2 batch reactors for 20 days solid retention time (SRT) at 55°C (thermophilic) and 35°C (mesophilic)	Mechanical pre- and inter-stage treatment using sonication at 24KHz, 400W at 5 - 30mins	Total methane production increased by 42%, volatile solid removal by 13% and SCOD elimination was increased by 22%.
[19]	Sewage Sludge	batch reactor at 35°C for 10 days	Mechanical pre-treatment using sonication at 150W at 0 - 60mins	38 - 91% soluble COD fraction. 64 - 95% increase in methane yield with optimal enhancement at 45 minutes sonication.
[20]	Thickened sludge (500g)	Semi-continuous reactor at 20 days HRT for 67days at 37°C	physiochemical pre-treatment using microwave radiation at 800W at 2.45GHz for 1 minute	117% increase in soluble COD fraction. 45% increase in Sludge removal. 20% increase in biogas yield
[21]	dewatered sludge (high solid sludge)	batch reactor at 28 days SRT at 37°C	Thermal pre-treatment using low temperature hydrolysis at 60 - 90°C , for 1 - 72hrs	557 - 1678% increase in SCOD, negligible change in biogas yield. Optimal SRT of 18 - 20 days
[21]	dewatered sludge (high solid sludge)	batch reactor at 28 days SRT at 37°C	Thermal pre-treatment using high temperature hydrolysis at 120 - 180°C , for 15 - 180 mins	582 - 1087% increase in SCOD, 6.3 - 16.5% increase in biogas yield. SRT reduction to 12 - 14 days

3.3 Combustion

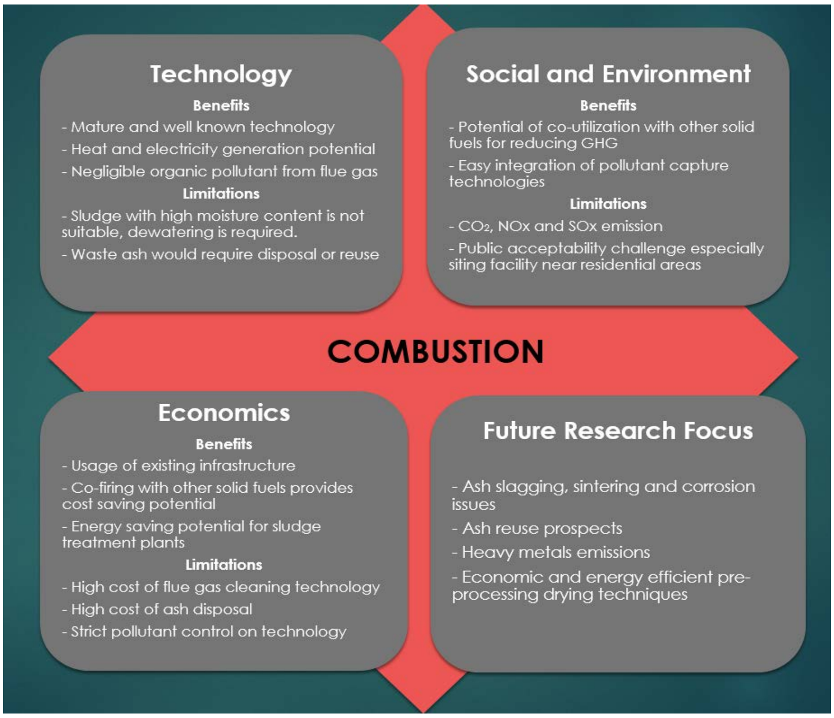
The combustion of all solid fuels is similar to that of sewage sludge. It involves the high temperature oxidation of fuels to obtain heat, carbon dioxide, water vapour and other trace gases. However, the use of combustion technology for waste materials such as sludge can be used for primarily generating heat (conventional combustion) or for reducing the volume of the waste materials (incineration). The conventional use of the heat generated from combustion technology is for electric power generation via heat engines whereas incineration systems may or may not utilise the heat generated from combustion as their main purpose is for burning off harmful elements from waste before final disposal or re-use of residual ash in the construction industry. The use of incinerators is famous for clinical and municipal solid wastes and it has gained more attention recently due to the need of reducing the use of cultivable land for waste disposal [2]. Hence, the burning off of all the organics and the melting and agglomeration of ash is required for the decrease in sludge volume is required for incineration while the drying, devolatilization and burning of volatiles is more crucial for the conventional combustion system for heat generation[22]. This indicates the considerations required for combustion and incineration efficiency of sewage sludge combustion. Such systems need to be equipped with flue gas cleaning facilities to minimise emissions, fly ash or hazardous gas emissions.

There are various combustion reactors such as multiple hearth, rotary kiln, cyclone and fluidised bed furnace which have different fuel feeding, operating mode and benefits. However, the fluidised bed furnace has gaining more popularity for wet (35 – 59% moisture) and dried sludge due to its simplicity, inexpensive cost, uniform heating, low pollutants in flue gas (≤50% CO and NOx pollution, ≤40% CO_2), lower residence time and high combustion efficiency as influenced by process parameters [23-25]. Recent studies on sewage sludge combustions have been summarised in Table 3. The main challenge with combustion of sewage sludge is mostly the high moisture and ash content, which influences the thermal characteristics of the fuel and the design requirements of the combustor. High moisture content is not only deterrent for increasing the bulk density of the fuel, lowering the energy content and causing incomplete oxidation, it also requires additional time, oxidants and energy required for drying the sludge and has potential for forming erosive sulphuric compounds [26]. Additionally, sludge with >80% moisture content requires auxiliary fuels for sustaining the reaction and results in lower heating values [27]. Apart from moisture, it is essential to understand the transformation of these inorganic compounds and their behaviours during combustion due to its importance in the operation and maintenance of the reactors. The slagging and agglomeration concerns in sewage sludge combustion is related to both alkali-induced and silicate melt induced deposition of ash on reactor surfaces. This would lead to reduction in thermal efficiency of the process and raise operational cost. Furthermore, the high chlorine content associated with sludge, mostly from iron chloride used in water treatment plants, poses high corrosion risk. The final concern associated with sewage sludge ash is heavy metals emission which has adverse effect on health and environment. Comprehensive explanations of ash related concerns in sewage sludge combustion has been reviewed by others [2, 28] and the necessity of flue gas cleaning and particulate control measures integration was established. Furthermore, the use of the subsequent ash or slags for other applications must also be reflected upon, particularly those that can be used for agricultural reclamation or in construction industry. Benefits and limitations of this technology for sewage sludge processing is highlighted in Figure 3.

More recently, the co-use of sludge with other fuels such as coal, biomass, other solid waste, or oil shale has been investigated as a means of avoiding the high cost associated with dedicated reactors, an avenue for reducing net carbon emissions from coal power plants, increasing calorific value and/or to improve energy efficiency of the system [29-33]. In these cases, the technical and economic viability of co-utilisation for heat, electric power or cogeneration of both must be studied critically with attention paid to consideration relating to the influence of co-combustion on operational efficiency, pollutants formation, flue gas emissions, and ash related issues in order to meet the acceptable standards for energy, environment and financial profitability throughout its processing stages.

Table 3: Summary of key research on combustion of sewage sludge

Author(s)	Fuel types Investigated	Reactor type used	Observations
[27]	Thermally dried (TD) and bio-dried (BD) sewage sludge (50 - 450µm)	Horizontal tube furnace for isothermal combustion at 600 - 1000°C (air, 10 mins)	Removal of ~26% more moisture in BDSS resulted in higher LHV (37.9%), higher combustion index and prevents incomplete combustion. ~20% and 15.7% less nitrogenous gas and CO emission in the flue gas. Up to 26.5% less NO but increase in SO_2 emitted in BDSS in comparison to TDSS.
[33]	Rice husk and sewage sludge	Muffle furnace at 600 & 750°C for sewage sludge and rice husk/sewage sludge ash	High Fe and heavy metals in sewage sludge ash. In the rice husk/sewage sludge blend, heavy metals were stabilized, reducing emission and retention in ash. Mechanical properties of the ash derived from co-combustion has potential use as cement material substitute.
[29]	Sewage sludge; brown and hard coal; pine and straw (as pellets)	Bench reactor at 800 - 900°C in air	Optimisation of reactor temperature and air flow velocity for different particle size such that at 7.5mm, sludge requires 800 – 800°C and 2.8m/s to minimise ignition time and surface temperature of fuel while ensuring burnout. This could be used to match fuels that can be co-blended together i.e brown coal or willow with 800 – 850°C and 2.8m/s optimal condition.
[25]	Dewatered sewage sludge	Pilot scale Rotary dryer (128 - 354°C) with Moving bed combustor at 700 – 800°C (Inlet); 950 - 1150°C (post combustion)	CO emission was reduced by controlling and optimizing the oxygen content (from exhaust gas) and temperature of the dryer. The NOx emissions remained below standard limits by optimising excess air, air/fuel feed rate and maintaining low reaction temperature. The high temperature in the post combustion chamber aided decomposition of PAH in flue gas.
[34]	Activated sewage sludge and dewatered oil shale blends at 10, 30, 50, 70, 90wt% sludge (< 178µm)	Thermogravimetric analyzer (TGA) at 1000°C, 10 - 30°C/min (80ml/min air)	Blending with sewage sludge resulted in easier ignition properties due to its higher volatile content. Ash content increased due to higher ash of oil shale. Blends with 10wt% sludge resulted in combustion promotion by reducing activation energy.
[35]	Sewage sludge and water hyacinth blends at 10, 20, 30 and 40wt% water hyacinth	TGA at 1000°C, 10 - 40°C/min (50ml/min CO_2/O_2)	Drying and combustion reaction zone of sewage sludge was improved by blending with water hyacinth, enhancing reactivity.
[32]	Sewage sludge and bituminous coal blends at 5 - 50wt% (< 75µm).	TGA at 900°C, 20°C/min (80ml/min N_2/O_2). 5% catalyst (CaO, CeO_2, MnO_2 and Fe_2O_3)	The blending of sewage sludge with coal at high fractions (>10wt%) deteriorated the combustion characteristics of the blends in comparison to coal. The use of catalysts, particularly Ce- and Fe- based, drastically improved the ignition and combustion properties of the blends.
[36]	Sewage sludge blended with lignite, hard coal and willow at 50:50wt% (as pellets)	Bench reactor at 800 - 900°C in air	Volatiles / Char combustion time – Sludge + lignite (24; 73%); Sludge + hard coal (13/84%); sludge + willow (28; 67%) of reaction time. Blending with sludge reduces ignition time especially in coal samples, extends the reaction time for biomass blend and maximum surface temperature.
[37]	Sewage sludge and wheat straw blends at 20 – 80wt% biomass (< 200µm)	TGA at 1000°C, 20°C/min (100ml/min N_2/O_2).	The addition of wheat straw to sewage sludge improves the char combustion reactivity and heat released due to changes in physiochemical properties such as higher surface area and pore volume of the pyrolytic char.



Technology

Benefits

- Mature and well known technology
- Heat and electricity generation potential
- Negligible organic pollutant from flue gas

Limitations

- Sludge with high moisture content is not suitable, dewatering is required.
- Waste ash would require disposal or reuse

Social and Environment

Benefits

- Potential of co-utilization with other solid fuels for reducing GHG
- Easy integration of pollutant capture technologies

Limitations

- CO_2, NOx and SOx emission
- Public acceptability challenge especially siting facility near residential areas

COMBUSTION

Economics

Benefits

- Usage of existing infrastructure
- Co-firing with other solid fuels provides cost saving potential
- Energy saving potential for sludge treatment plants

Limitations

- High cost of flue gas cleaning technology
- High cost of ash disposal
- Strict pollutant control on technology

Future Research Focus

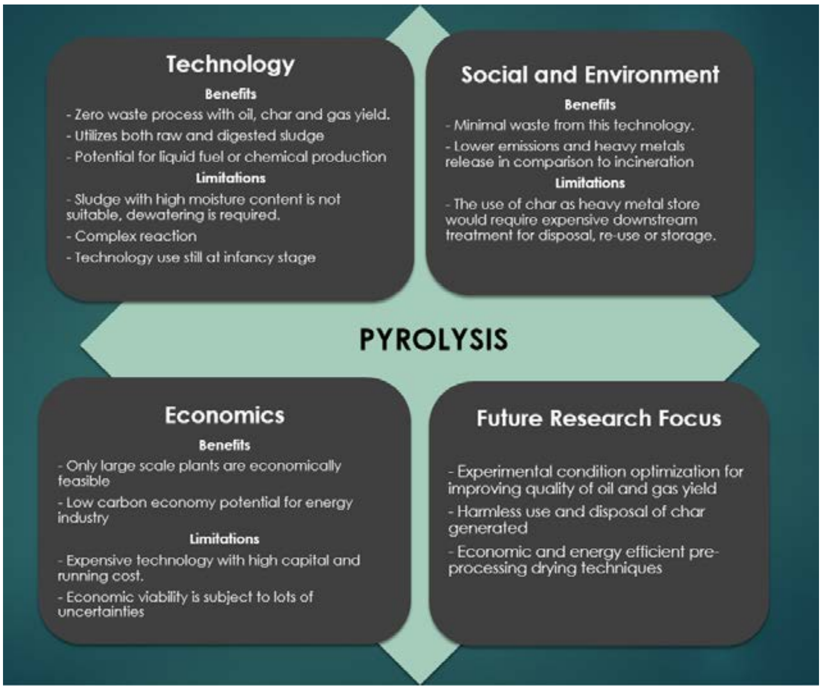
- Ash slagging, sintering and corrosion issues
- Ash reuse prospects
- Heavy metals emissions
- Economic and energy efficient pre-processing drying techniques

Figure 3: Technological, socio-environmental and economical assessment of combustion for sewage processing

3.4 Pyrolysis

Pyrolysis is the thermal decomposition or degradation of fuel in an inert (non-reactive) environment; it is for producing bio-oil, solid char and gaseous fuel. It is also referred to as incomplete gasification [38]. It involves the conversion of sewage sludge without air at moderate operating temperature (350 - 900°C) [39, 40]. Previous studies with the TGA have established that the decomposition of sewage sludge occurs in various stages due to the heterogeneous nature of the waste such that after the drying at ≤ 200°C, the minor decomposition of decomposable organic matter, dead organisms and lipids follows at 200 - 300°C[41, 42]. This is followed by the decomposition of proteins, organic polymers and cellulosic constituents at temperatures ≤700°C. Further secondary reactions are aided at temperatures around 600°C such that the unstable primary products go through further pyrolysis to form secondary tar and gases. Other reaction progressions may result into the polymerization of some tars to produce coke. The difference in product distribution and yield characteristics mainly results from fuel characteristics (chemical compositions and particle size), reactor type and operating conditions (temperature, turbulence, residence time, pressure, feed rate and catalyst) [2]. These considerations, along with the intricate reaction chemistry, phase transitions and transport phenomena further complicates this energy recovery method. The condensation of the gaseous vapours into bio-oil with an organic fraction of ~33MJ/kg heating value occurs after cool down [43, 44].

The maximization of the bio-oil yield is the common aim of sewage sludge pyrolysis as the heating value is slightly higher than bio-oil from biomass. However, the bio-oil generated from sewage sludge has >23% moisture content which diminishes the fuel quality by reducing energy density, flame temperature and causing deterrent combustion properties when used in engines in comparison to biomass-derived bio-oil [45, 46]. In addition, the high fraction (~33%) of O-containing compounds in the oil significantly limits its thermal output and causes intrinsic instability of the bio-oils which prevents its use as commercial replacement for fuel oil [45]. According to literature [47-49], liquid yield is maximised between 450 – 550°C such that lower temperatures would be inadequate for optimal breakdown while higher temperatures favour increase in gas yield due to thermal cracking of tar. Hence, minimisation of residence time has been adopted as an approach to prevent secondary reaction [48, 50]. This technology is not suitable for wet sludge sample and requires drying because of the influence of moisture on the reactor operating conditions (steam-rich atmosphere), oil quality and increase in non-condensable gases [51]. Interestingly, the use of microwave powered reactors has been studied to enhance the use of high moisture sludge with limited influence on product distribution with or without catalysts [52]. The bio-oil yield from sewage sludge pyrolysis ranges from 14 – 57.5% as seen in Table 4, which summarises results from past studies. As a result, the use of various heating rates, catalysts and reaction temperatures on sewage sludge has been adopted for maximizing liquid products as investigated by various researchers who determined that char and gas yield decreases and increases respectively with increasing reaction temperature [53-55]. Their results shows that the bio-oil yield is optimal between 500 – 600 °C [52, 56, 57]. The change in operating temperature, however influences the composition of the bio-oil in terms of the water, aromatic and aliphatic compounds. Regardless of the operating condition, char remains the highest product due the contribution of char and ash (~50wt%) offering advantages such as negligible pollutant emission in comparison to incineration because of its low operating temperature and inert atmosphere [56]. As a result, heavy metal emissions and their adverse impact is minimized. The contributions of the high inorganic compounds in sewage sludge pyrolysis includes the increase in solid residue due to prevention of organic matter decomposition by some metal oxides (CaO, ZnO) and promotion of secondary cracking reactions by catalytic species [58]. Therefore, char and gaseous yield are likely to increase with high ash contents. This establishes the need of pre-treatment for removing some inorganic matters via leaching or the rapid removal of char from the pyrolysis chamber. The solid char can be used further as an economic alternative of a catalyst, for heat generation via combustion, and/or as heavy metal or organic contaminant store (by adsorption). All of which requires further consideration on more attractive, harmless application and disposal methods of this char because it retains the heavy metals in sludge [59]. Although the exhaust stream from this reaction requires less emissions / pollutant clean-up facilities, pyrolysis is a complex process and its economic viability remains dependent on ability to maximize efficiency and produce high valued oil, gas and char that can be furthered processed for heat, chemical and liquid fuels production. The use of pyrolysis for sewage sludge processing is not well established and requires further research on treatments, operating conditions optimization and further minimization of heavy metal in products as depicted in Figure 4.



Technology
Benefits
- Zero waste process with oil, char and gas yield.
- Utilizes both raw and digested sludge
- Potential for liquid fuel or chemical production
Limitations
- Sludge with high moisture content is not suitable, dewatering is required.
- Complex reaction
- Technology use still at infancy stage

Social and Environment
Benefits
- Minimal waste from this technology.
- Lower emissions and heavy metals release in comparison to incineration
Limitations
- The use of char as heavy metal store would require expensive downstream treatment for disposal, re-use or storage.

PYROLYSIS

Economics
Benefits
- Only large scale plants are economically feasible
- Low carbon economy potential for energy industry
Limitations
- Expensive technology with high capital and running cost.
- Economic viability is subject to lots of uncertainties

Future Research Focus
- Experimental condition optimization for improving quality of oil and gas yield
- Harmless use and disposal of char generated
- Economic and energy efficient pre-processing drying techniques

Figure 4: Technological, socio-environmental and economical assessment of pyrolysis for sewage processing

Table 4: Summary of key research on pyrolysis of sewage sludge

Author(s)	Fuel types Investigated	Reactor type used	Observations
[45]	Sewage sludge (0.5 – 3mm) (Anaerobic digested and thermally dried before use)	Conical spouted bed reactor at 450, 500 and 600°C with <100ms residence time (fast pyrolysis)	Bio-oil yields was 44.8, 48.5 and 45.4wt% at 450, 500 and 600°C. Liquid yield was maximised at 500°C due to low volatile residence time and lack of secondary cracking reactions. Char and gas were highest at 450°C and 600°C respectively. The fuel properties differ from hydrocarbon and biomass derived oils, hence more suitable for chemical production.
[54]	Dried sewage sludge	Horizontal tubular furnace reactor (2L/min N_2 at 450 - 650°C. slow and fast pyrolysis at 8 and 100°C/min)	Fast Pyrolysis - Char yield reduced from 47.07 to 29.96% with increasing temperature. Tar yield increased to maximum (46.14%) at 550°C and then decreased with further increase in temperature. Gas yield increases with increase in temperature. Slow Pyrolysis – Decrease in char (33.24 - 53.6%) and tar (32.18 - 38.28%) and increase in gases (14.24 – 28.64%) due to secondary cracking reactions.
[53]	Wet sludge (84.9 ±1.2 wt% water)	Multimode microwave reactor (900W, 200mL/min N_2 , 400 - 800°C for 30mins)	Gas phase: 15 – 29%; Liquid phase: 14 – 20%; and Solid fraction: 57 – 69%. The maximum yield and heating value (HV) of bio-oil was obtained at 600°C and the HV 2.7 times of the dried sludge cake. Microwave processing is promising for sludge.
[60]	Digested and dried sewage sludge	Fluidized bed reactor (3kW, 200mL/min N_2 , 446 - 720°C for 30mins)	Maximum of 54wt% of bio-oil was obtained with HV of about 2 times that of the dried sewage sludge HV of gas and char ranged from 5 – 30 and 5- 10MJ/Kg. The bio-oil has negligible hazardous metals but has very high N content.
[61]	Thickened excess activated , dewatered digested and dried excessive activated sludge	Semi-continuous lab scale flash pyrolysis reactor at 500°C	Bio-oil yields varies between 39.2 – 57.5%. The water content of bio-oil varies between 10.3 – 17% based on the sludge type. HV ranged between 23.9 – 29.0MJ/kg for bio-oil and 5.2 – 10.6MJ/kg for char.
[62]	Primary sewage sludge, thickened waste activated sludge and digested sludge bio-solids	Cylindrical batch pyrolysis reactor at 250 - 500°C with zeolite as catalyst and acid pre-treatment.	Calorific value of 32 – 42MJ/kg and 7 – 23MJ/kg for bio-oil and char respectively. Oil yield ranges between 4 – 42% with maximum at 500°C for primary sludge. Other types of sludge generated maximum oil at ~400°C. Char yield varies between 33 – 87% with maximum at 250°C. The use of zeolite reduces char yield but does not impact the oil yield considerably. Pre-treatment did not enhance the bio-oil yield. Most economically viable option is the use of primary sludge at 500°C.
[57]	Sewage sludge (78% water content)	Benchtop batch and continuous microwave reactor (1000W and 2.45GHz at 450 - 600°C) with HZSM-5 catalyst	Bio-oil yield ranges from 16.47 – 39wt% with maximum at 550°C. Char yield decreased from 62.26 – 32.98wt% with increasing temperature. The continuous reactor increased bio-oil yields by ~16%. The use of HZSM-5 decreased the bio-oil generated in both reactors.
[52]	Sewage sludge	Microwave oven of 750W at 2.45GHz with HZSM-5 catalyst	Maximum yield of bio-oil was achieved at 550°C. The oil and gas yield are maximum without the use of catalyst while char yield increased with catalyst loading. However, the quality of bio-oil

Author(s)	Fuel types Investigated	Reactor type used	Observations
		from 450 - 600°C	(lowest oxygen- and nitrogen- containing compounds) was improved at catalyst to feed ratio of 2:1.

3.5 Gasification

The thermochemical conversion of sewage sludge's organic content into high value gases such as H_2 and CO known as synthesis gas, as well as CO_2, CH_4 and other hydrocarbons is the main basis for gasification. This reaction occurs in a partially oxidized reaction atmosphere at high temperature (800 - 1000°C) [63-65]. Gasification can be done using air, carbon dioxide, oxygen, steam, or mixtures of such gases. Past studies have identified that the gasifying agent has an impact on the calorific value of the syngas obtained which ranges from 4 - 12MJ/m^3 with gases of higher heating value extracted from the oxy-gasification [66, 67]. The product gas can be used directly for heating or electricity generation via heat engine or can be further processed for chemicals or liquid fuel synthesis. Gasification is divided into four sub-stages which are drying of sample (70 - 200°C), devolatilsation (350 - 600°C), oxidation of volatiles and char gasification. Hence, it can also be termed as an incomplete combustion or extended pyrolysis reaction in which gas-solid, gas-gas and liquid cracking reactions are required in order to maximize the gaseous product yield. After the drying stage, the pyrolysis of the samples is done for generating volatiles and char that can be fully oxidized to drive the other reaction stages. Therefore the oxidation stage (with temperatures up to 1200°C) produces heat to run the gasification, pyrolysis and drying stage. Finally, the high temperature reduction of the char produced from pyrolysis is for producing light hydrocarbon gases. The position of these sub-stages in the gasifier immensely affects the flow of gasifying agent, reaction process and operating efficiency, thereby becoming a deciding factor in choice of reactors. There are three main types of gasifiers – fixed bed downdraft, fixed bed updraft and fluidized bed gasifier and detailed comparison can be found elsewhere [39, 68]. In summary, the fixed bed alignment involves a flow of gasifying agent and heat up or down the reactor chambers to activate the drying, pyrolysis and gasifying stages consecutively. This leads to efficiency reduction and shorter residence time (particularly for char oxidation which is the rate-limiting step) in comparison to the fluidized bed that allows instantaneous occurrence of all sub-stages which allows completion of the gasification process [69].

Table 5 summarises past studies on sewage sludge gasification with emphasis on different gasifying agents, reaction conditions, and catalyst use. Their results emphasizes the dependence of the end product on the sludge properties and the experimental conditions such as equivalence ratio (ER), gas residence time, catalytic influences and operating temperature. The optimization of these factors are required for maximizing gas yield, enhancing gas quality, minimizing tar yield and reaction efficiency. The reaction of sewage sludge with low (<0.2) or high (>0.5) equivalence ratio results in low gasification efficiency due to incomplete gasification and enhanced combustion respectively [70-72]. This has been reported by others and their findings justified optimal ER between 0.2 – 0.4 for maximizing the production of CO, H_2, CH_4 and other light hydrocarbons and increasing efficiency [73-75]. The impact of residence time is crucial in ensuring complete gasification, hence a longer residence time of the gas would allow more char conversion to take place in the reactor [76]. This would also enhance cracking of tar, heavier volatiles and steam reforming which improves the quality and quantity of produced syngas. Similarly, the adoption of various catalysts (nickel, dolomite, zeolite, olivine and alumina) have been studied for improving gasification of sewage sludge, particularly for reducing tar content [63, 77, 78]. It was observed that dolomite was quite effective in eliminating tar yield and the combination of dolomite with activated carbon as bed material maximized H_2 yield also [77, 79]. The use of nickel based catalyst have indicated high tar reduction and lower NOx formation, however the deactivation of such catalyst at high temperatures from coke deposition remains a challenge [78, 80]. Finally, the influence of the bed temperature on the distribution of yields, gas quality and process efficiency has been studied by various works such that lower temperatures favour tar and char production while higher temperatures favour gas yield and overall efficiency of process [71, 78, 81]. This temperature must not only increase the quantity but also the quality of syngas generated while ensuring that the tar removal process would not be more complicated as a result of tar reduction at higher temperatures process [82]. In addition, this high temperature must be well considered to avoid clinker formation.

Table 5: Summary of key research on gasification of sewage sludge

Author(s)	Fuel types Investigated	Reactor type used	Observations
[83]	Digested sewage sludge	Three stage gasifier (auger (650°C), fluidized bed (815°C) and tar cracking (815°C) reactors connected serially), gasifying agent - pre-heated air, Catalyst - activated carbon , ER – 0.3	The use of activated carbon increase syngas yield by 12%, while reducing tar, hydrogen sulphide and ammonia content in the syngas. In addition, the carbon conversion and tar removal efficiency increased by 10 and 26% respectively. The use of Fe- and Ni- impregnated activated carbon reduced the hydrogen sulphide and ammonia respectively. Increasing the gasification time (~8hrs) effectively removed tar in output.
[63]	Dried Sludge	Laboratory scale fluidized bed gasifier (800°C), gasifying agent – air + steam, ER – 0.3, Catalyst – dolomite, feedrate – 110 – 322 kg/hr m^2	Different feed rate influenced the quality and composition of the tar generated. Higher feed rate decreased syngas yield while increasing tar content while lower feed rate maximized H_2 and CO in product. The use of dolomite enhanced tar removal efficiency to ~71%. 20 – 36% increase in H_2 yield with dolomite.
[84]	Solar dried sewage sludge	Laboratory scale fixed bed gasifier (700 - 1000°C), gasifying agent –steam (3g/min)	Char gasification, H_2 and CO content of the producer gas increased with increasing temperature. Energy conversion efficiency was maximum at 1000°C.
[85]	Digested sewage sludge	Laboratory scale fluidized bed gasifier (750 - 850°C), gasifying agent – air, ER – 0.25 – 0.35, alumina bed	The heating value and cold gas efficiency increased with increasing temperature, attributed to steam reforming and cracking of tar. The gas yield increased with increasing ER. H_2 content of syngas increases with the alumina bed.
[86]	Sewage sludge	Laboratory scale fixed bed gasifier (650 - 850°C), gasifying agent – steam (0.2g/min), Catalyst – calcium oxide(CaO), Ni- and Fe- impregnated CaO	Without the CaO sorbents, hydrogen fraction and overall syngas yield increases with increase temperature. The use of CaO at lower temperatures increased the H_2 fraction by enhancing tar cracking, however CaO with higher temperatures, the H_2 fraction reduced while CO_2 increased. Though carbon conversion efficiency and cold gas efficiency increased with CaO use, it had negligible influence on char gasification but on tar cracking. The impregnation of metals improved methane reforming and char conversion.
[87]	Dried sewage sludge	Laboratory scale gasifier (1000°C), gasifying agent – steam (2.5 - 20g/min)	Higher reaction temperature improved water gas shift reaction rates, hence CO_2 and H_2 generation rates increased at the expense of CO and CH_4 with time. Increase in steam flow rate increased the syngas generation rates at lower residence time. Carbon conversion is enhanced with higher steam flow rate.
[88]	Oven-dried sewage Sludge	Bench scale rotary Kiln gasifier, 750 - 850°C, ER 0.05 – 0.24	Producer gas of higher heating value was obtained at temperatures of 800 – 850°C and ER of 0.15 – 0.24. Maximum cold gas efficiency of 67% was obtained at 850°C with ER of 0.16

The main challenges of sewage sludge gasification are mainly ash related issues due to the high content of inorganic constituents, tar minimisation and clean up issues and sludge composition (moisture, nitrogen and sulphur) on product yield. The high content of ash and heavy metals in sewage sludge has a lot of adverse influence on gasifier operation, specifically sintering, agglomeration and clinker formation which leads to frequent shut down and maintenance of the reactor [89, 90]. In addition, the probable volatization of gas phase compounds of the inorganic elements like phosphorus and mercury at high temperatures [91-94]. The presence of tar in the product distribution reduces gaseous product and condensation of such tar leads to clogging, fouling and other inefficient downstream issues. In addition, the need for tar removal from the syngas is a necessity which must be done either inside the gasifier (experimental conditions optimisation or catalyst) and/or after the gasifier (post-reaction clean up using scrubbers) which incurs additional capital and operational costs [95, 96]. Furthermore, the impact of fuel properties such as moisture, nitrogen and sulphur content results in promotion of tar, ammonia, hydrogen cyanide and hydrogen sulphide formation. This affects the operation of the reactor, product distribution and the quality of the product gas. The evaluation summary of this technology is depicted in Figure 5.

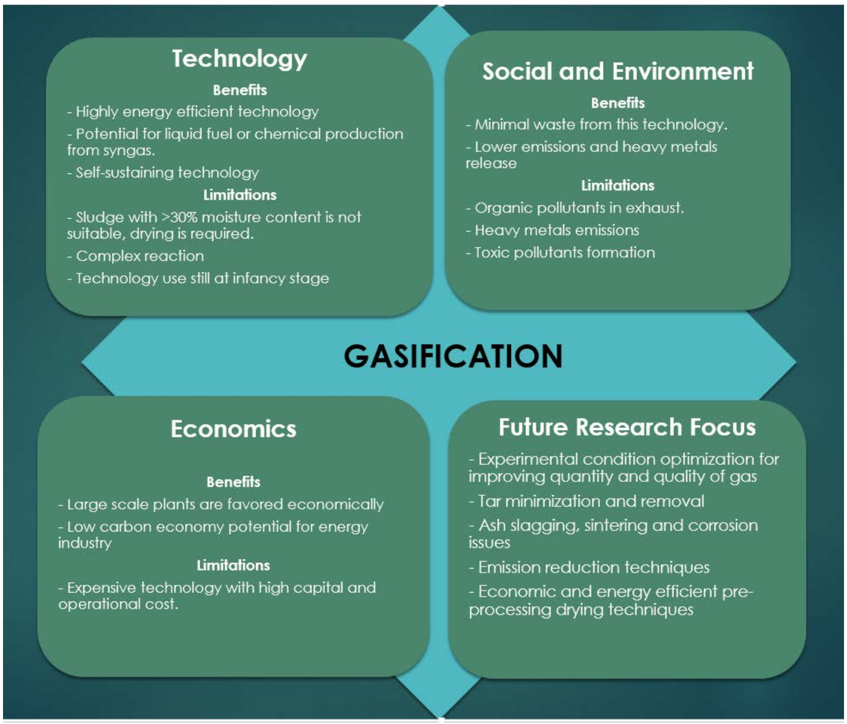


Figure 5: Technological, socio-environmental and economical assessment of gasification for sewage processing

4.0 Conclusion

With the increasing restrictions on environment regulation standards due to the imminent climate change from carbon emissions, the need for strategically deployed research into improving the effectiveness and suitability of sewage to energy technologies have become crucial. The environmental limitations of traditional sewage sludge disposal methods necessitates the need for more sustained means of utilisation of such wastes. This review work identifies the potential of municipal sludge as an energy feedstock with high potential. The limitations and barriers of all considered technologies shows the need further research into sludge characterization, co-utilization of sludge, operating condition optimization and effective technology scale-up for maximizing energy recovered while reducing cost and emissions. The unique fuel properties of sewage sludge such as high moisture and ash content remains a huge obstacle for most of these technologies. The high moisture content of sewage sludge favours the use of anaerobic digestion and gasification (<30wt% moisture). However, anaerobic digestion requires more investigation of pre-processing and control strategies for enhancing efficiency, improving yield quality and reducing reaction time. Interestingly, microwave technologies such as MW– enhanced pyrolysis has been observed to have higher efficiency in using sludge of high moisture content without substantial downside in efficiency. Similarly, the high inorganic content of sludge is a huge challenge in combustion, pyrolysis and gasification reactors due to their high operating temperature which results in ash deposition, heavy metals release, gaseous pollutants, clinker formation and sintering problems which increases the cost of operation and need for clean-up of end products. Apart from the fuel properties, the operating conditions and their optimisation is a huge area requiring further research for maximising efficiency and reducing cost of for thermochemical processes. The use of catalysts, coupling of various technologies and co-use of sludge with other fuel types are potential routes to improve the economic and environmental viability of an energy efficient sewage to energy system for commercial purposes. All these processes would require in-depth feasibility, technical, economic and life cycle assessment for determining their suitability in the low carbon future.

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