International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

IMPACT ASSESSMENT OF SMOULDERING FOR WASTE TREATMENT

Ishaq Muhammad Jauro

University of Strathclyde

ABSTRACT

Global population growth has resulted in an increase in wastewater sewage sludge production, which has subsequently propelled the rise of various sludge treatment technologies. However, the increase in global CO2eq emissions and the measures taken to reduce this challenge have necessitated a demand for sustainable and innovative sludge treatment methods. Smouldering, a self-sustaining combustion process, has emerged as a viable alternative to conventional waste management methods owing to its capacity to substantially reduce waste volume and generate heat. This research assesses the efficacy of the smouldering technique as a viable option for waste treatment, focussing on its environmental impact and operational efficiency.

An assessment on a sewage sludge smouldering combustion process was conducted, scrutinizing the energy inputs and CO2 emissions of the technique. The results were further compared with the other sludge treatment approaches, which include incineration, pyrolysis, dewatering and landfill, and dewatering and land application. Evaluating the effects of these waste treatment methods, will help in establishing a sustainable process strategy. The study found that during sludge smouldering, moisture content, sludge to sand ratio, and sludge composition all have an impact on both energy consumption and greenhouse gas emissions. High moisture content and high sludge-to-sand ratios typically require higher energy inputs, but in some cases, lower moisture content and lower sludge-to-sand ratios can still require high energy requirements. Additionally, the research found that an increase in the sludge-to-sand ratio leads to an increase in GHG emissions.

The study went on to compare the energy requirements and GHG emissions of smouldering combustion with other sludge treatment techniques. The study revealed that the smouldering process uses less energy during operation compared to incineration, pyrolysis, dewatering and landfill, as well as dewatering and land application. Additionally, research revealed that self-sustaining smouldering combustion emits less CO2 than incineration, dewatering and landfills, but more than pyrolysis, and land application.

Introduction

Globally, the problem of waste management has become a major concern. It entails a variety of strategies and processes, including reducing, reusing, recycling, thermal treatment, and landfilling, all of which aim to minimise the environmental impact of waste and promote sustainability. In waste management, various techniques were used, including incineration, pyrolysis, anaerobic digestion, dewatering and landfilling, dewatering and land application, and smoldering. These techniques have been applied in various waste categories to effectively manage waste to a lesser extent and reduce its environmental impact. Although these processes have been sound and effective in managing waste, they have their own unique environmental impact, particularly when it comes to energy requirements and greenhouse gas emissions (GHGs).

In recent times, the smouldering combustion technique has been an effective process for managing waste. A process that is characterised by slow, low-temperature, and flameless burning has been put into practice in numerous disciplines, including environmenaatal science, fire safety, and waste management (Huang & Rein, 2016; Switzer *et al*., 2009; Torero *et al*., 2020). The process nearly eliminates all (up to 99.9%) of organic matter, including pollutants that were previously present in a material under a certain time of heating between 500 and 1000 oC, depending on the operation's scale (Switzer *et al.,* 2015). Engineered smouldering applications aim to create self-sustaining conditions that consume fuel without requiring additional energy input beyond ignition, underscoring the significance of efficient combustion processes (Zanoni *et al.*, 2020). Its capacity for self-sufficiency and its potential for treating waste make it a subject of interest for researchers looking for novel and sustainable solutions (Switzer *et al.,* 2009; Yermán, 2016). Research has demonstrated the energy efficiency of this process; when the reaction produces heat, the nearby fuel absorbs it, leading to self-sustaining combustion (Solinger *et al.,* 2020). The self-sustaining and energy-efficient are the main features that differentiate smouldering from other techniques of waste treatment, i.e., thermal treatment and incineration (Grant *et al.,* 2016).

Ebrahimzadeh *et al.* (2017) conducted studies that suggest the potential use of smouldering combustion in waste treatment and environmental remediation due to its intricate dynamics and mechanisms. Smouldering combustion is a distinct method of combustion that is different from standard flaming combustion because of its slow and persistent nature. Consequently, a wide range of environmental and waste treatment applications can utilise this method. (Huang & Rein, 2016). Especially for materials with a high moisture content, smouldering combustion has shown promise as a method for waste management and soil remediation (Switzer *et al.,* 2009; Wyn *et al.,* 2021). This approach to combustion shows its potential in a variety of biological and engineering applications by providing a self-sustaining burning process.

The ability of smouldering combustion to benefit co-waste management, including land restoration, hazardous liquid management, and decentralised sanitation, demonstrates its potential benefits in solving environmental challenges (Rashwan *et al*., 2023; Switzer *et al.,* 2015). Waste water treatment (sludge treatment) is one notable sector in waste management that uses the smouldering technique. Rashwan *et al.* (2016) conducted a study on the use of self-sustaining smouldering combustion for the destruction of wastewater biosolids. Their results showed that smouldering combustion is an effective way to get rid of waste and clean up the environment. Additionally, studies have indicated the potential of self-sustained smouldering combustion in waste management by treating moist faeces under certain circumstances (Onabanjo *et al.,* 2016).

Smouldering combustion has also shown promise in turning lignocellulosic wastes into useful products like biochar and bio-oil, which indicates that it has the potential to recover resources (Wyn *et al.,* 2023). Fournie *et al.,* (2022) research on the use of smouldering combustion for phosphorus recovery from sewage sludge ash emphasises the technique's potential for resource recovery and environmentally friendly waste management techniques. Researchers have conducted studies on the scalability and energy recovery potential of smouldering as a sewage sludge treatment technology (Rashwan *et al.,* 2021a). By optimizing smouldering processes, innovative waste management technologies can effectively transform sewage sludge into energy while minimizing environmental consequences.

Waste Water (Sewage Sludge) Treatment

Efficient waste management is crucial for ensuring environmental sustainability and safeguarding public health. Among the various waste types, waste water, particularly sewage sludge, is a challenging waste form because of its large volume, complex composition, and potential environmental dangers if not appropriately managed. Conventional wastewater treatment techniques, such as incineration, pyrolysis, dewatering and landfilling, and dewatering with application, typically have high energy consumption, are expensive, and can emit a higher amount of greenhouse gases (GHGs), thereby worsening the environmental impact they are intended to mitigate.

Recently, smouldering combustion has become a viable alternative in waste water treatment with several promising benefits. These advantages include lower energy consumption and the ability to simultaneously destroy organic pollutants while producing energy. Rashwan *et al.,* (2023) listed smouldering combustion as one of the most sustainable techniques for managing wastewater because of its self-sustenance.

However, the process, which is exothermic in nature, converts carbon compounds and an oxidant into carbon dioxide, carbon monoxide, methane, and volatile organic compounds (VOCs) (Chen, 2023; Grant *et al.,* 2016). These emitted molecules are considered among the major greenhouse gases. According to Torero *et al*. (2022), non-uniform reactions, composition, and sludge type lead to a high fraction of CO2 and CO during sludge smouldering. Some studies have documented the energy usage and direct greenhouse gas emissions during the smouldering process of sewage sludge (Feng *et al.,* 2021; Rashwan *et al.,* 2021). These studies, however, have not quantified the energy requirements and carbon footprint of this process.

As a result, this research will aim to fill this knowledge gap by assessing the impact of smouldering as a waste treatment technique for wastewater (sewage sludge). The study will critically evaluate the operational and embodied carbon associated with sewage sludge treatment using the smouldering method and compare it with the other sludge treatment techniques. The purpose of this is to evaluate the potential of smouldering to improve waste management methods, minimise environmental effects, and present a more sustainable approach to wastewater (sludge) treatment. The findings of this research have the potential to make a substantial contribution to the advancement of more efficient and enduring waste treatment methods, in line with international environmental objectives and regulatory standards.

Research Aims, Objectives, and Structure

This study aims to assess the impact of the smouldering technique by calculating the process's carbon footprint. The study will focus on its application in waste-water treatment (sewage sludge) and examine its potential as a sustainable technique by evaluating the associated carbon emissions.

The following objectives will assist in achieving the research's goal:

1. Identify the sources of operational and embodied carbon of the smouldering process.
2. To ascertain the operational carbon associated with all the stages of the smouldering process, such as energy requirements, mixing requirements, and additional emissions output.
3. To assess the embodied carbon associated with all the materials involved in the smouldering process, such as sand, and filtration process.
4. To compare the carbon footprint of smouldering with other technologies of waste water (sewage sludge) treatment.

2. Methodology

This chapter will detail the methods used to achieve the objectives of this study. It described the source of data used in calculating energy requirement, as well as the operational and embodied carbon.

2.1 Conceptual boundaries of the carbon balance

In smouldering combustion, the major sources of carbon emissions fall into the operational and embodied carbon categories. The operational carbon emissions can further be subdivided into combustion emissions and energy requirements during the smouldering process. Combustion emissions are direct emissions that are released during the smouldering process as a result of combustion of organic material, which includes carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), and volatile organic compounds (VOCs). Energy inputs during the smoulding process can contribute to the operational carbon emission. These energy requirements can include ignition energy, energy input for air injection, mixing energy requirements, and separation energy (Feng *et al.,* 2021). In the context of embodied carbon emissions, in sewage sludge smouldering, these emissions come from material production, equipment, sand, input material mixing, post-treatment testing, and hardware energy requirements from the filtering process.

This study will mainly focus on direct smouldering carbon emissions, energy input requirements, carbon emissions associated with sand, and filtration energy input. Therefore, it will not assess the entire life cycle of smouldering processes. Figure 3.1 illustrate the conceptual model of smouldering operation. This research utalises a smouldering data from sewage sludge treatment process in access the smouldering impacts. The data was sourced from a study by Rashwan *et al., (*2021a) on scaling up self-sustained smouldering of sewage sludge for waste-to-energy.

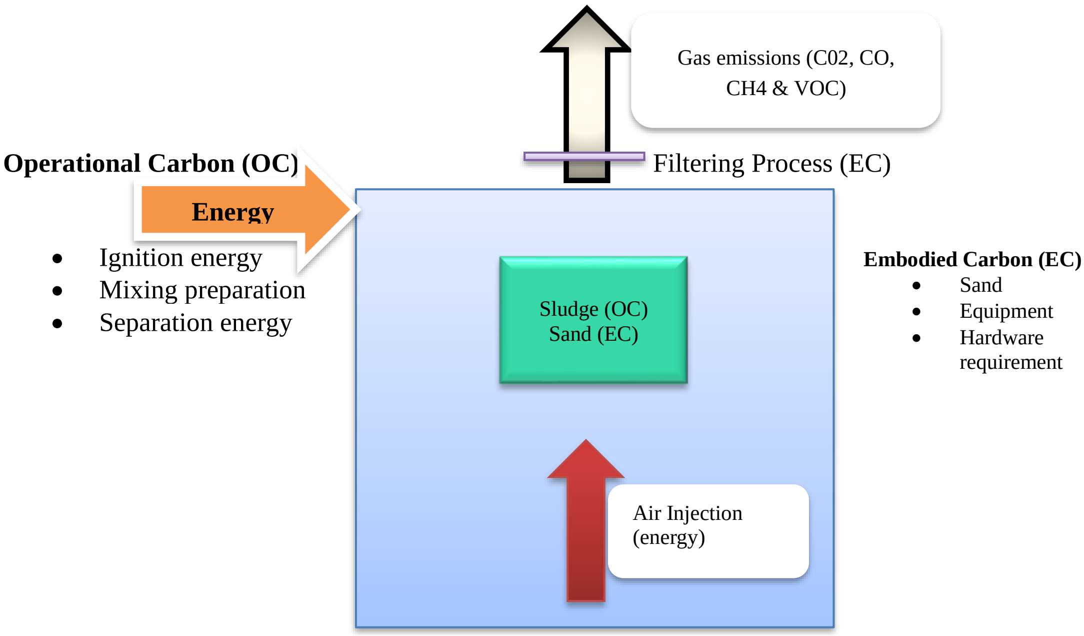

Figure 3.1- Sewage Sludge Smouldering Operational Model

3.2.1. Smouldering Parameter

Rashwan *et al.,* (2021a) provided data from 20 self-sustaining smouldering combustion experiments on sewage sludge (Table 4.1). The mass mixture of sludge and sand in kg was determined using the mass, volume, and density relationship (Bissenov *et al.,* 2020).

$$Mass\ mixture = V \times \rho_{sand}^{bulk} \qquad (2-1)$$

and,

$$V = height(m) \times cross\ sectional\ area\ (m^2) \qquad (2-2)$$

Assuming the bulk density of sand to be 1602 kg/m3 (Certified Material Testing Products, 2024). Then, the amounts of sand and sludge was determined using the sludge to sand mass ratio.

2.2.1. Operational Carbon

This study determined the distribution of carbon across CO2 and CO based on their respective molecular weights and mass fractions (Tchobanoglous, Burton, and Stensel, 2003). Initially, the dry weight of the sludge and ash weight were determined by considering their moisture content and ash content, respectively. The ash weight was subtracted from the dry weight of the sludge to obtain the organic matter weight. To estimate the carbon content in dry solids, the organic matter weight was multiplied with the given mean fraction value of CO (Rashwan *et al.*, 2021a). The dry weight of carbon in the dry sludge was used to find the total mass of carbon in the wet sludge. This is done by multiplying the mass of sludge with the percent carbon in sludge. The amounts of CO2 and CO (relative ratios) are calculated from the mean fraction of CO given in the data (Rashwan *et al.*, 2021a). The individual CO2 kg (CO2eq), CO kg (CO2eq), and the total kg CO2e are calculated. This was obtained by multiplying the masses of CO2 and CO with their respective Global Warming Potential (GWP) factors (IPCC, 2009).

Also, the energy required to ignite the smouldering process (Qin) was calculated in MJ using,

$$Qin = Mss \times LHVss \qquad (2-3)$$

where, Qin is an energy input in MJ, Mss is a mass of sewage sludge in kg, and $LHVss$ is the lower heating value of the sewage sludge in MJ/kg (Sapmaz and Kılıçaslan 2023).

The LHVss is defined in a way that accounts for water loss as,

$$LHV_{ss} = HHV(1-M) - ML_v \qquad (2-4)$$

where, HHV is the higher heating value of sludge in MJ/kg, M is a moisture content of the sludge in percentage, and L_v is the latent heat of veporisation of water (2.447 MJ/kg at 25 °C) (Boundy *et al.*, 2011; Rashwan *et al.*, 2016). Assuming the HHV of sewage sludge at an initial moisture content of 72–80% and an ash content of 19–23% is 18 MJ/kg *(*Rashwan *et al., 2016).*

Also, energy inputs from air injection, mixing preparation, and separation were determined. Assuming energy inputs from air injection, mixing preparation, and separation for sewage sludge smouldering were 0.0073 kWh, 6.0861 kWh, and 0.0145 kWh per tonne of sludge, respectively (Feng *et al.*, 2021). The study directly related the energy input results to the mass of the sludge, thereby determining their respective energy inputs.

2.2.2. Embodied Carbon

As previously discussed in chapters 2 and 3, these emissions are linked to the production, processing, transportation, and disposal of a product or material. In the sludge smouldering aspect, embodied carbon will account for sludge transportation and sand extraction.

Carbon associated with sand extraction is among the major sources of embodied carbon in sewage sludge smouldering. Studies that specifically estimate the embodied carbon of sand associated with sewage sludge smouldering are rare. However, various life cycle assessment (LCA) studies have estimated the embodied carbon of a sand quarry. According to Vinci and Rapa (2019) research, a sand quarry has a lower embodied carbon of around 0.0121 kg CO2eq per kg sand. This value can vary depending on factors such as the sand's source and the specific processes involved in its extraction, processing, and transportation. However, this study assumes that 1.01 kg of sand extraction and transportation produce 0.0121 kg of CO2eq (Vinci and Rapa 2019).

2.3 Summary of Key Findings

The methodology described a comprehensive approach for estimating the energy inputs and assessing the carbon emissions of the sewage sludge smouldering. It utilised established equations and data from relevant studies, ensuring a standardized and systematic analysis of the energy requirement and carbon impacts of the smouldering process. The next chapter will present the results and discuss based on these calculations, providing insights into the carbon footprint and the energy demand of sewage sludge smouldering technique.

3. Results and Discussion

This section includes a discussion on the various external energy inputs involved in the smouldering process of sewage sludge. Additionally, the section will include a discussion on the smouldering emissions. The chapter will further compare the external energy input requirements and the GHG emissions for smouldering sludge with other sewage sludge treatment techniques.

Various approaches are used in estimating carbon footprints. Including, Life-cycle Assessment, Input-Output Analysis (IOA), Hybrid method and GHGs Protocol. This study also evaluated the direct and indirect emissions of sludge treatment, as well as its energy requirements. However, the offset emissions were not estimated. The study analyses 20 forward smouldering experiments and estimate their energy requirement, and carbon emission (Table 3.1).

Table 3. 1: Smouldering energy requirement in kWh per kg and CO2e in kg per tonne of wet and dried Sewage Sludge across RUM and LAB Experiments (Rashwan *et al.*, 2021a).

Experiment	MC %	Ash %	sludge/Sand [g/kg]	Qin	Qair. inj.	Qmix	Qsep.	CO2	CO	CO2e	Total Energy
DRUMS 1	73	22	222	0.04287	4E-05	0.03351	8E-05	344.344	71.344	415.688	0.07649
DRUMS 2	75		222	0.03692	4E-05	0.03351	8E-05	-	-	-	0.07055
DRUMS 3	75		222	0.03692	4E-05	0.03351	8E-05	441.467	91.4667	532.933	0.07055
DRUMS 4	3.2	28	41.7	0.04855	0.00018	0.15283	0.00036	-	-	-	0.20193
DRUMS 5	40	24	60	0.23169	0.00013	0.10754	0.00026	294.272	51.072	345.344	0.33961
DRUMS 6	72	23	153	0.06276	5.5E-05	0.04587	0.00011	416.724	116.424	533.148	0.1088
DRUMS 7	72	27	153	0.06276	5.5E-05	0.04587	0.00011	377.678	98.4527	476.13	0.1088
DRUMS 8	74	22	153	0.05462	5.5E-05	0.04587	0.00011	422.136	117.936	540.072	0.10065
DRUMS 9	73	24	222	0.04287	4E-05	0.03351	8E-05	355.3	79.8	435.1	0.07649
DRUMS 10	74	25	222	0.0399	4E-05	0.03351	8E-05	350.625	78.75	429.375	0.07352
LABS4	3.4	28	40	0.0499	0.00019	0.15857	0.00038	406.296	121.296	527.592	0.20903
LABS5(1)	40	24	60	0.27017	0.00015	0.1254	0.0003	-	-	-	0.39601
LABS5(2)	71	24	153	0.06683	5.5E-05	0.04587	0.00011	374.528	90.7947	465.323	0.11287
LABS6	72	23	153	0.06276	5.5E-05	0.04587	0.00011	451.733	143.733	595.467	0.1088
LABS7	72	27	153	0.06276	5.5E-05	0.04587	0.00011	428.267	136.267	564.533	0.1088
LABS8	74	22	153	0aaaa.05462	5.5E-05	0.04587	0.00011	-	-	-	0.10065
LABS11 (1)	37	28	63	0.21741	0.00012	0.10271	0.00024	406.296	121.296	527.592	0.32048
LABS11 (2)	3.2	28	42	0.04909	0.00018	0.15455	0.00037	437.976	148.176	586.152	0.2042
LABS12 (1)	3.2	29	44	0.04588	0.00017	0.14443	0.00034	431.893	146.118	578.011	0.19082
LABS12 (2)	3.2	29	44	0.03819	0.00014	0.12021	0.01527	384.252	107.352	491.604	0.17381

3.1 External Energy Inputs

The major external energy inputs in the treatment of sewage sludge are: starting energy (ignition energy), which is the energy required to begin the process; energy from air injection; mixing preparation energy; and separation energy. The process has a total energy requirement of around 0.39601 to 0.07055 kWh/kg under various moisture content conditions that range from 75% to 3.2%, across both the DRUM and LAB experiments. The total energy input was calculated as,

$$Q_T = Qin + Qsep + Qair + Qmix \qquad (3-1)$$

where, Q_T is the total energy input, Qin is the ignition energy, $Qmix$ is the mechanical mixing energy, $Qair$ is the energy from air injection, and $Qsep$ is the separation energy input. Figure 3.1 highlights the energy variations across the experiments. The reason for the energy variation might be due to wide ranges in the sludge moisture content and differences in the sludge to sand ratio.

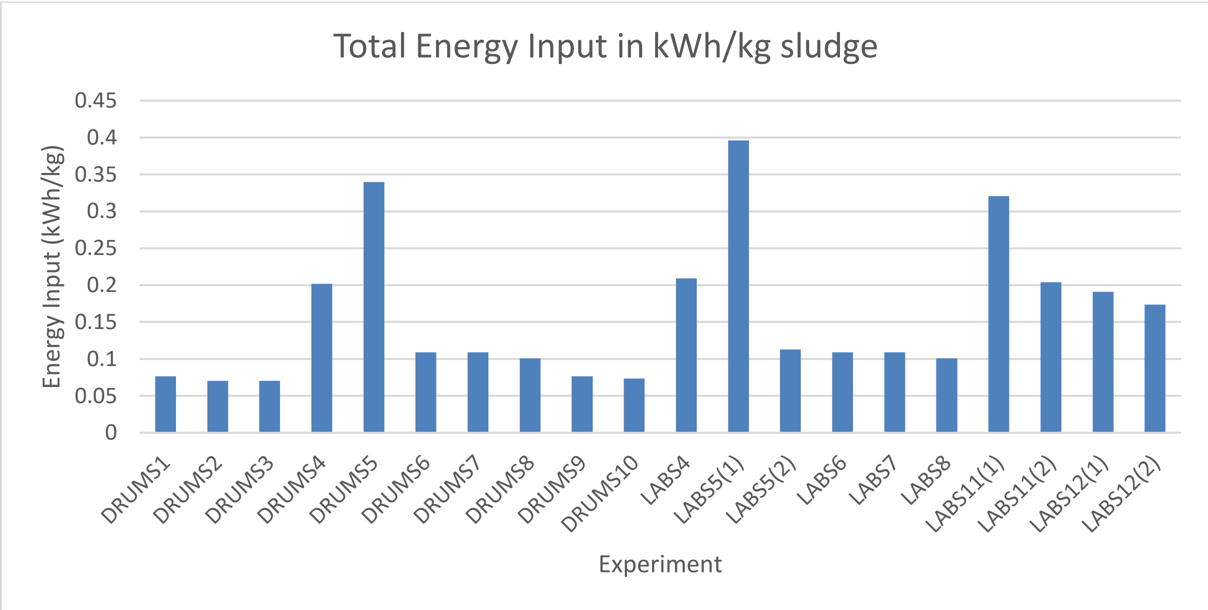

Figure 3.1- Sewage Sludge Smouldering Energy Input

3.1.4. Other Sewage Sludge Technologies

In comparison to other techniques for sewage sludge treatment, such as incineration, pyrolysis for fuel production, dewatering and landfilling, and dewatering and land application, the smouldering process was found to have a less energy requirement. Table 4.2 highlight the techniques energy requirement from lowest to the highest.

Incineration

In the context of the incineration technique, the energy input value is a crucial factor to take into account while incinerating sludge in order to implement effective and sustainable waste management techniques. Numerous studies have discussed the energy consumption and generation aspects of sludge incineration. He *et al.*, (2023) determined the energy used in the sludge dewatering and incineration procedures. The amount of energy required for the incineration of sewage sludge varies based on a number of variables, including the sludge's moisture content, the kind of incineration technology employed, and the process's efficiency. According to Sapmaz and Kılıçaslan (2023), the net energy needed for sludge incineration might range from 555 to 1068 kWh per tonne of dry sludge. The necessity to dry the sludge, which typically has a high moisture content (up to 80%) before incineration, is the reason for the high energy demands for the technique (Sapmaz and Kılıçaslan 2023).

Sewage sludge treatment using incineration requires a significant amount of energy for air injection due to the necessity of maintaining optimal combustion conditions and ensuring complete burning of the sludge. The process, which is aerobic in nature, involves the combustion of organic substances in the presence of sufficient oxygen (air). Suez's (n.d.) research reveals that a fluidised bed incinerator, a common sludge type, typically requires an energy injection (air injection) ranging from 200 to 300 kWh per tonne of sludge. This energy is used to maintain the fluidised state of the sand bed and ensure thorough mixing and combustion of the sludge. However, after incineration, the process requires less energy to mix sludge and separate the ash and residues. According to a study by He *et al.* (2023), the energy requirements for mixing sludge and separation after incineration range from 5 to 20 kWh and 10 to 30 kWh per tonne of sludge, respectively.

Pyrolysis

In the realm of pyrolysis, the energy input value can vary widely based on several factors, such as the type of sludge, the moisture content, and operational conditions. Generally, the energy requirement for pyrolysis processes is significant because the sludge must be heated to high temperatures. Typically, the input energy requirement for sewage sludge pyrolysis is in the range of 200 to 600 kWh per tonne (kWh/t) of sludge, depending on the specific conditions and technology used (Lu *et al.*, 2009). Compared to starting energy for pyrolysis, mixing sludge to ensure homogeneity before pyrolysis typically requires low energy. According to research by Xie *et al.* (2023), the energy consumption for mechanical mixing of the sludge was estimated to be approximately 1–5 kWh per tonne (kWh/t) of sludge. The post-pyrolysis separation procedures, which involve separating the gas, liquid (bio-oil), and char phases, also require energy. However, the separation process necessitates a higher energy input compared to the mixing process. The energy requirement for the separation was estimated to be around 10–20 kWh/t of sludge. Research by Wang *et al*., (2012) divided the energy consumption associated with the pyrolysis process into three stages. The first stage is moisture evaporation, followed by heating and drying, and the third stage is reaction (endothermic or exothermic). He estimated the total energy requirement to be between 250 and 400 kWh/t of sludge, depending on the differences in moisture content of the sludge.

Dewatering and Land Filling/Application

Numerous studies clarify the energy requirement for the dewatering and landfilling processes. According to Lu *et al.*, (2011) and (Pinasseau *et al*., 2010), the energy consumption for sludge dewatering and landfilling is approximately 120–131 kWh per tonne of sludge. The amount of energy required to mix sludge during the dewatering and landfilling processes varies depending on the type of machinery used and how well the mixing goes. Mixing is a crucial step in ensuring consistent sludge properties and enhancing the effectiveness of stabilisation and dewatering procedures. Typically, mixing sludge during dewatering and landfilling requires 3 to 20 kWh of energy per tonne of sludge (Pinasseau *et al.,* 2010). This range takes into account variations in the equipment type, the specific treatment and stabilisation techniques used, and the mixing process.

Table 4.2- Energy Input Requirement for the Various Sewage Sludge Treatment Techniques in kWh per tonne Sludge

Method	**Energy Input (kWh/t)**	**Refeermce**
Smouldering	110	
Dewatering and Landfill/ Land Application	120–131	Lu *et al.,* (2011); (Pinasseau *et al.,* 2010
Pyrolysis	200 - 600	Wang *et al.*, (2012); (Lu *et al.*, 2009).
Incineration	555 - 1068	Sapmaz and Kılıçaslan (2023),

4.2. Smouldering Emission

Smouldering of sewage sludge produces various emissions, including pollutants and greenhouse gases. In the context of greenhouse gases, the smouldering of sewage sludge emits CO2, CO, CH4, and volatile organic compounds (VOCs) (Tang *et al.*, 2023). Rashwan *et al.*, (2021a) estimated that CO2 carries the highest emission ratio among the GHGs emitted, particularly in self-sustained smouldering combustion. According to Surawski *et al.* (2015), CO2 emissions tend to increase during smouldering combustion, while CO emissions also increase, but to a lesser extent.

Notably, the biomass content in the sludge must be carefully taken into account when evaluating GHG emissions from sewage sludge treatment. When assessing CO2 emissions from sewage sludge, different nations use different techniques. For instance, some countries attribute all CO2 emissions to biomass (Kang *et al.,* 2017). This emphasises how important it is to have standardised techniques in place in order to accurately measure the greenhouse gas emissions from the sewage sludge treatment process. This study identified two major carbon-containing gas species: carbon dioxide (CO2) and carbon monoxide (CO). Because all of the experiments were self-sustaining, CO2 was identified as the primary source of carbon emissions. Also, CO was observed, which is the second principal substance released during any biomass combustion process (Manisalidis *et al.,* 2020).

The sum of all the GHGs released during smouldering results in the total CO2e of the process. Table 4.1 presents the total CO2e in this study, which ranges from 345.34 to 595.47 kg per tonne of sludge. It was calculated as,

$$total\ CO2e = \sum(CO2 + CO)\ kg\ CO2e \qquad (4-2)$$

where, CO2 is the carbon sssssdioxide, and CO is the carbon monoxide emitted during the smouldering process.

4.2.3. Total Green House Gases (CO2 Equivalent)

As mentioned earlier in this chapter, these experiments determined only the CO2 and CO emissions, which are believed to be among the major greenhouse gases that contribute to global warming (Wu *et al.,* 2021). Figure 4.2 displays the CO2e from the study, which ranges from 345.34 to 595.47 kg per tonne of sludge, representing the lowest and highest values, respectively. The highest CO2e was observed in LAB S6; this might be due to the high organic content in the sludge, which aids in the combustion of the sludge, producing excess CO2 during the process. Concurrent to this, DRUM S5, with the lowest organic matter content, released the lowest CO2e (345.34 kg per tonne of sludge). Research by Werther and Ogada (1999) explains how the organic content of sewage sludge impacts its combustibility and the resultant emissions.

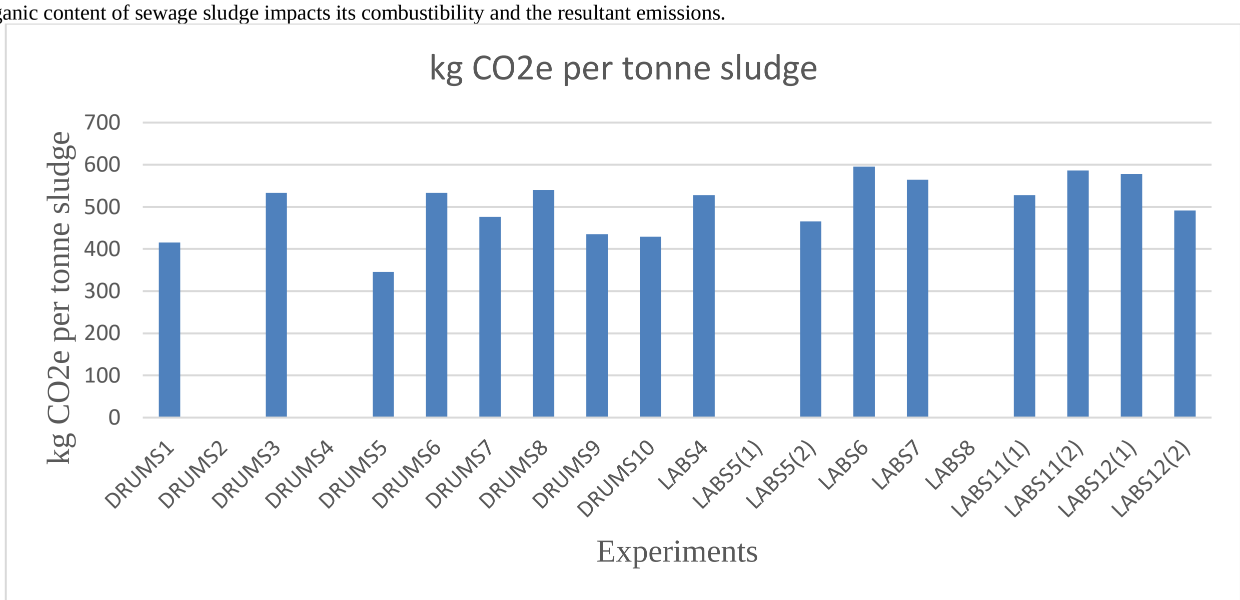

Figure. 4.2- Sewage sludge smouldering experiments across DRUM and LAB, and their kg CO2eq per tonne of sludge.

Compared to other sludge treatment techniques, sewage sludge smouldering has demonstrated a lower energy requirement and moderate CO2 emission. Looking into tables 4.1 and 4.2, we will find that DRUM S10 has a moderate energy requirement and CO2eq emission, respectively. Figure 3.3 displays the energy input distribution and GH emission in DRUM S

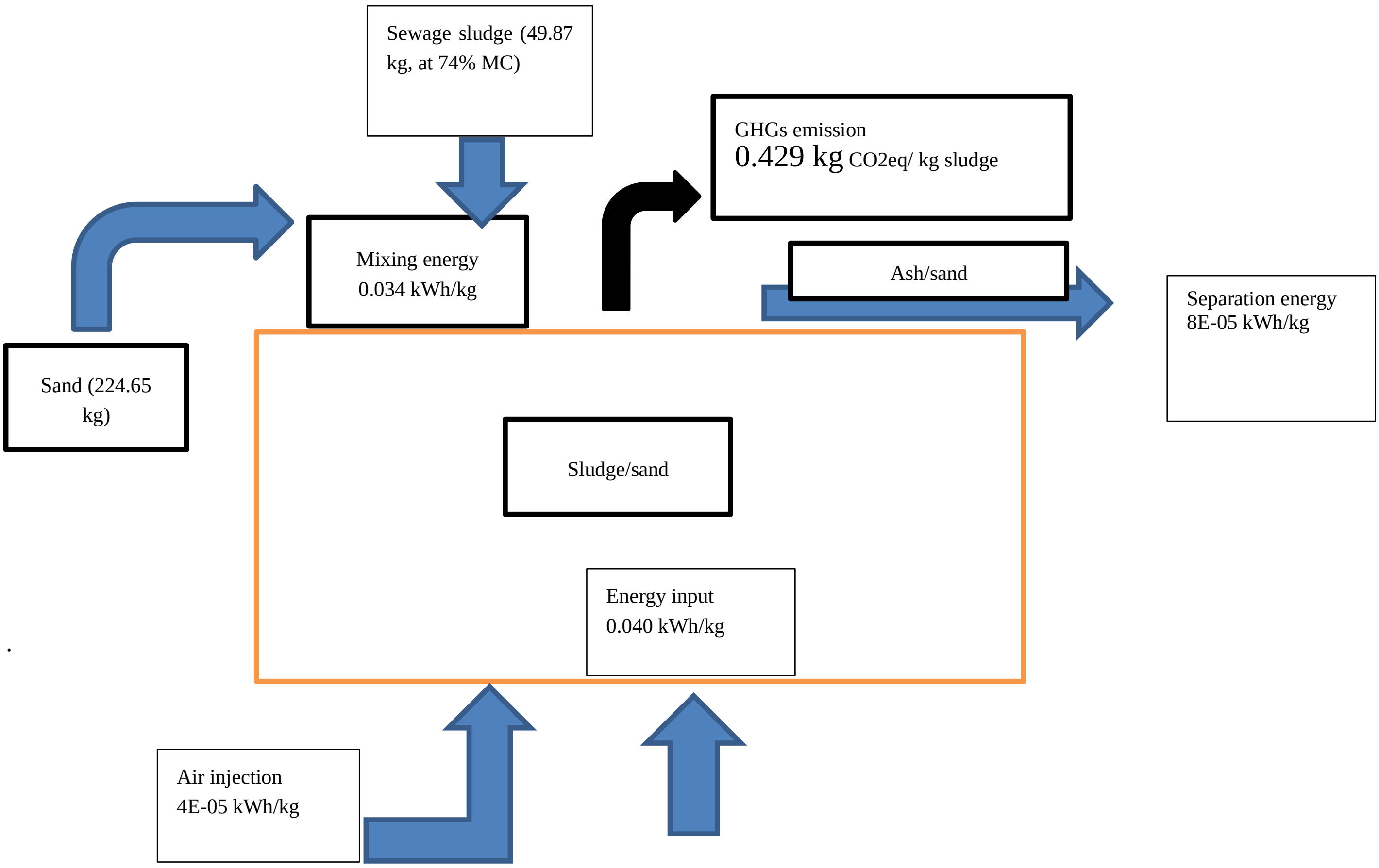

Figure 3.3- Average sludge smouldering energy inputs in kWh/kg and kg CO2eq emission per kg sludge

3.3. Other Sludge Treatment Methods (CO2 Equivalent)

In contrast to the smouldering technique, other sewage sludge treatment methods—incineration, dewatering, landfill, thermal treatment for fuel products, dewatering, and agricultural application released higher CO2. According to numerous studies, the incineration technique, which operates at a very high temperature (650–1100 °C) in the presence of a sufficient amount of air, emits CO2e of around 600–1200 kg/t of sludge (Zhao *et al.*, 2022; Hu *et al.*, 2024; Houillon and Jolliet, 2005). These emissions are primarily caused by direct and indirect emissions from transport, electricity use, and fuel use. The major GHGs released during sewage sludge incineration include nitrous oxide (N2O) and carbon dioxide (CO2) (Lee *et al.*, 2015). According to Hu *et al.*, (2024), during the sludge incineration process, CO_2 contributes to the highest overall GHGs emissions (about 897.56 kg CO_2-eq). Also, the process has a relatively high N_2O emissions of 113.10 kg CO_2-eq, this accounts to about 11.2% of total GHGs emissions. In contrast, CO and CH4 contribute to the least overall GHGs emission, releasing 7.44 and 0.47 kg CO_2-eq, respectively.

Researchers Hu *et al.* (2024), Wang *et al.* (2013), Foley *et al.* (2010), also found that dewatering and landfilling sewage sludge produce the most greenhouse gases (about 500–1300 kg CO2-eq/t sludge) compared to the other methods. Dewatering and landfilling have a major impact on the environment due to the significant emission of methane during the landfill. The major GHG released by landfills is CO_2 (647.25 kg CO_2-eq), but they also release a substantial amount of CH_4 (617.65 kg CO_2-eq), which makes up to 86.1% of their overall emissions. However, landfills release relatively low CO and N_2O which accounts to 10.85 and 7.01 kg CO_2-eq respectively. In contrast to landfills, dewatering, followed by land application (agricultural application), involves using the sludge as fertiliser or soil amendment. Researchers have found that using sewage sludge for agriculture produces fewer greenhouse gases (GHGs) than landfills. This is because landfills release high amounts of methane (CH4), which is considered to have a higher Global Warming Potential (GWP) value. Recently, Hu *et al.*, (2024) evaluated the GHG emissions of sludge dewatering and landfill, and compared them with those of land application, observing that land application results in lower GHG emissions. Various studies estimated the CO2e of sewage sludge dewatering and land application to range between 583 and 277 kg CO2-eq/t sludge (Hu *et al.*, 2024; Yoshida *et al.*, 2013; Houillon and Jolliet, 2005).

However, researchers found that the pyrolysis of sewage sludge for fuel production produces less CO2eq. Pyrolysis prevents combustion by heating sewage sludge without oxygen. During the pyrolysis operation, the sludge is broken down into biochar, bio-oil, and syngas, with less emission of CO2 and CH4. Gievers *et al.* (2021); Meyer *et al.* (2011); Houillon and Jolliet (2005) approximate the CO2e of sewage sludge pyrolysis within 250–400 kg CO2-eq/t sludge.

3.4. Actual Comparison between Carbon Footprints of Sludge Treatment Methods

Recently, there has been an increase in the use of various techniques in waste water (sewage sludge) treatment around the globe. This is due to the higher volume of sludge production, which results from the general increase in the population. Although these processes have proven to be effective when it comes to sludge management, there is a need to compare the energy consumption and carbon footprint of the techniques. This comparison will give an insight into the most sustainable and environmentally friendly method to choose when it comes to sewage sludge treatment. The energy requirements and GHG emissions vary depending on the sludge treatment technique as shown in Table 3.3 and figure 3.4. The composition of GHG emissions and the contribution of various emission sources varied among the approaches, underscoring the necessity of considering these elements when evaluating the environmental impact of sludge treatment.

Table 3.3- Waste-water (Sewage-Sludge) Treatment Techniques and their CO2e per tonne of sludge

Method	kg CO2e per tonne sludge	Reference
Thermal treatment for fuel production (pyrolysis)	250	Gievers *et al.*, 2021; Houillon, and Jolliet (2005)
Dewatering and land application	276.41 - 583	Hu *et al.*, (2024); Houillon, and Jolliet (2005)
Smouldering	470	
Incineration	232 – 920	Zhao *et al*., (2022); Hu *et al*., (2024); Wang *et al.*, 2013; Houillon, and Jolliet (2005)
Dewatering and landfill	296 - 1303	Hu *et al.*, (2024); Wang *et al.*, 2013; Houillon, and Jolliet (2005)

This study found that among the five sewage sludge treatment approaches, incineration has the highest overall energy requirement, ranging from 555 to 1068 kWh/t sludge. The majority of this energy comes from the sludge drying process. The process, which operates in the presence of sufficient oxygen and at a very high temperature, releases lots of GHGs (600–1200) kg/t of sludge during sewage sludge treatment, particularly N2O and CO2. As opposed to incineration, the pyrolysis technique, which operates at a lower temperature and in an oxygen-limited environment, produces fewer CO2eq emissions during sewage sludge treatment (250–400 kg CO2-eq/t sludge). Due to the absence of air in the reaction, the technique releases less CO2 and CH4, with further production of biochar and syngas as by-products. Also, the process has a lower energy requirement (250–400 kWh/t sludge), depending on the specific conditions and the moisture content of the sludge.

All techniques revealed that sludge dewatering and landfilling produced the highest GHG emissions (500–1300 kg CO2-eq/t sludge). This is due to landfills' high release of CH4, which is considered to have a high GWP value of 28–36 over 100 years. However, the process was found to have a lower energy requirement. The overall consumption energy for sludge dewatering and landfill was revealed to be around 120–131 kWh/t of sludge. On the other hand, sludge dewatering and land application was discovered to have a lower CO2eq (276.41–583 kg CO2-eq/t sludge) compared with the sludge dewatering and landfill approach.

Overall, when comparing the GHG emissions and energy requirement of pyrolysis, incineration, dewatering and landfill, and dewatering and land application with that of smouldering combustion, those processes were found to emit more CO2eq, most especially sludge incineration and dewatering and landfill. In this study, smouldering emission was found to be within the range of 345.34–595.47 kg/t of sludge (process emission). The emissions ranges may be due to differences in moisture content and sludge nature. Figure 4.4- shows the average energy requirement and CO2eq emission in increasing order across the five sludge treatment techniques.

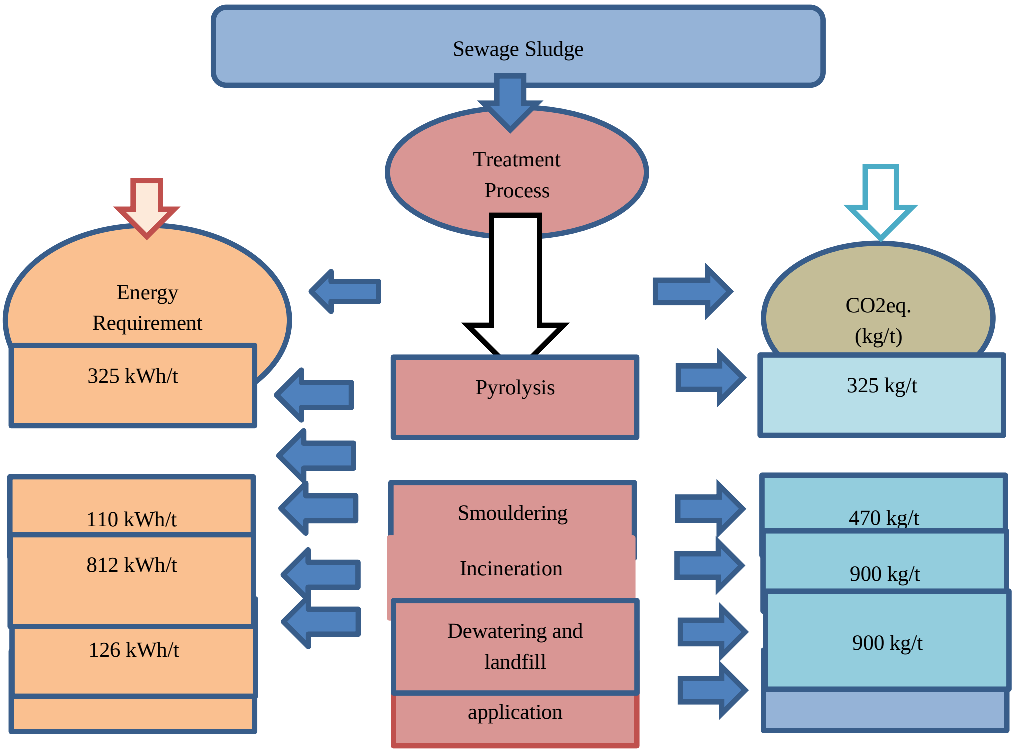

Figure. 3.4- The average energy requirement and CO2eq emission from lowest to highest across various sludge treatment techniques.

3.5 Summary of Key Findings

When the sludge-to-sand ratio is high and the ash content is low, the process tends to emit more CO2eq because of the high organic matter content in the sludge, as observed in LAB S6 and LAB S7. However, a higher emission can occur even when the ash content of the sludge is high and the moisture content is very low because very low moisture content enhance combustion efficiency, this can allow the sludge to fully oxidized, leading to higher CO2 emissions. . This could be due to sludge composition or a very high sand ratio compared to sludge in the combustion. Although LAB 12(1) and LAB 12(2) have the same moisture content, ash content, sludge-to-sand ratio, and energy input, their CO2eq emissions differ. This variation in emission might be due to the nature of the sludge or mixing problem. Also, it was discovered that energy input during sewage sludge smouldering varies with changes in sludge moisture content and fuel to-sand ratio. The lower the moisture content and sand-to-sludge ratio, the more energy is consumed primarily due to higher organic load, and the needs for higher temperatures to ensure complete oxidation.

4. Conclusion and Recommendation

This section discusses the final conclusion to this study while at the same time citing recommendations from the current study for future research consideration.

4.1. Conclusions

Though smouldering has been shown to be a good option for wastewater sewage sludge treatment. However, there is a need to assess its impact and further compare it with the other sludge treatment technique. Therefore, this study assessed the GHG emissions and the energy requirement between the commonly used sewage sludge treatment methods. Due to the current problem of global warming, there is a need to determine the most sustainable and environmentally friendly treatment method by comparing the CO2eq emissions of the processes, Energy Consumption, Resource Efficiency, Economic Feasibility, Social Acceptance and Community Impact, Environmental Sustainability. Overall, this study assesses the impact of the smouldering technique by looking into operational, embodied carbon, and its overall energy requirements using wastewater sewage sludge. This study provides good information on the GHGs emission and energy requirement of various waste-water treatment techniques, and it can be used to develop a guidance when choosing the most sustainable sewage sludge treatment method among the commonly used options.

A comprehensive impact assessment of the smouldering technique must consider several additional factors beyond the operational and embodied carbon. These factors include environmental sustainability, resource efficiency, economic feasibility, social acceptance, and policy alignment.

Multiple studies have determined that sludge dewatering and landfills have the highest GHG emissions, followed by sewage sludge incineration. On the other hand, this study considers a pyrolysis process, which treats sludge in an oxygen-limited condition, to have the least CO2eq emission. The smouldering technique of sludge treatment was found to have lower CO2 emissions than incineration and dewatering and landfills, but higher than pyrolysis and sludge dewatering and land application.

Energy consumption is another aspect to consider when choosing the best alternate technique for waste treatment. This study observed that the smouldering technique had the lowest overall energy requirement among the four sludge treatment methods discussed. These energy requirements differ depending on the moisture content and sludge-to-sand ratio. The study found that among the five processes discussed, sludge incineration had the highest energy requirement, unlike smouldering. Similarly, the pyrolysis method for sewage sludge treatment has a high requirement. However, the energy consumption for sludge dewatering, landfilling, and land application is nearly identical.

4.2. Recommendation for Future Work

This study has evaluated and contrasted the effects of different sludge treatment alternatives according to their energy consumption and greenhouse gas emissions. However, the consideration of other factors should not be overwhelming. Choosing a particular technique as a waste treatment option requires a thorough evaluation of both its environmental, economic, and social factors.

As previously discussed in section 2.1, sewage sludge is a heterogenous mixture of various compounds. Therefore, similar studies are needed to assess the performance of these waste techniques with different waste types, such as oil-contaminated land and hazardous waste. In some cases, smouldering may have unanticipated environmental effects, such as soil contamination and water pollution. Future studies can assess the impact of this technique by focussing on the long-term environmental monitoring of sites where smouldering waste treatment is carried out to examine the impact on soil and air over time.

Notably, the infrastructure of most of these waste treatment techniques, particularly incineration and pyrolysis, requires significant financial investment, making them capital-intensive. Therefore, future studies can incorporate the economic and environmental impacts of smouldering combustion and compare it with the other waste treatment techniques. Assessing the impact of these waste treatment methods based on costs and their carbon footprint will give potential investors, policymakers, and the government insight into selecting the most economically viable waste treatment option.

Today's technological advancements have led to the use of diverse waste treatment techniques to produce valuable byproducts during waste conversion (waste to energy). Valuable materials like fuel, heat, fertiliser, and CO2 resources for possible utilisation can be generated through these sludge treatment methods. Recent studies have shown that smouldering combustion can become a potential viable waste-to-energy option. Therefore, future research can focus on assessing the impact of these waste treatment techniques based on the valuable material they produced.

Finally, the adoption of new waste treatment technologies often hinges on public perception and community. In many instances people have shown their resistance regarding the siting of a new waste treatment plants, mostly especially nearby residents due the odor and trace pollutants produced. Therefore, future research can conduct a Social Impact Assessments (SIA) and surveys to gauge public attitudes and identify potential concerns.

REFERENCES

1. Abaecherli, M., Capón-García, E., Steinleitner, P., Weder, O., Szijjartô, A., & Hungerbühler, K. (2017). Hierarchical integration of planning and scheduling for industrial waste incineration. Industrial & Engineering Chemistry Research, 56(27), 7783-7798. https://doi.org/10.1021/acs.iecr.7b01250
2. Ahmetoğlu, S. and Tanık, A. (2020). Management of carbon footprint and determination of ghg emission sources in construction sector. International Journal of Environment and Geoinformatics, 7(2), 191-204. https://doi.org/10.30897/ijegeo.726913
3. Boundy, R.G., Diegel, S.W., Wright, L.L. and Davis, S.C., 2011. Biomass energy data book: Edition 4 (No. ORNL/TM-2011/446). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). https://info.ornl.gov/sites/publications/files/Pub33120.pdf
4. Buonocore, E., Mellino, S., De Angelis, G., Liu, G., & Ulgiati, S. (2018). Life cycle assessment indicators of urban wastewater and sewage sludge treatment. *Ecological indicators*, *94*, 13-23.
5. Buss, W. (2021). Pyrolysis solves the issue of organic contaminants in sewage ludge while retaining carbon—making the case for sewage sludge treatment via pyrolysis. Acs Sustainable Chemistry & Engineering, 9(30), 10048-10053. https://doi.org/10.1021/acssuschemeng.1c03651
6. Buss, W., Bogush, A., Ignatyev, K., & Mašek, O. (2020). Unlocking the fertilizer potential of waste-derived biochar. Acs Sustainable Chemistry & Engineering, 8(32), 12295-12303. https://doi.org/10.1021/acssuschemeng.0c04336
7. Certified Material Testing Products, 2024. Density of Sand: A Guide for Practical Applications, https://blog.certifiedmtp.com/density-of-sand-a-guide-for-practical-applications/
8. Chai, C., Zhang, D., Yu, Y., Feng, Y., & Wong, M. S. (2015). Carbon footprint analyses of mainstream wastewater treatment technologies under different sludge treatment scenarios in china. Water, 7(3), 918-938. https://doi.org/10.3390/w7030918
9. Chen, S., Liu, Z., Chen, B., Zhu, F., Fath, B. D., Liang, S., … & Yang, J. (2019). Dynamic carbon emission linkages across boundaries. Earth's Future, 7(2), 197-209. https://doi.org/10.1029/2018ef000811
10. Chen, Y., 2023. *Smouldering Fuel Processing, Emission Flammability, and Carbon Footprint* (Doctoral dissertation).
11. Dania, W. A. P., Nurfitriani, E. A., & Septifani, R. (2021). Value chain analysis of jackfruit chips in green supply chain management perspective using the value chain operations reference method. Industria: Jurnal Teknologi Dan Manajemen Agroindustri, 10(2), 125-134. https://doi.org/10.21776/ub.industria.2021.010.02.4
12. Demirbaş, F. and Ateş, N. (2021). Evaluation of carbon footprint in a waste recovery/recycle facility. ENERGY, ENVIRONMENT &Amp; STORAGE, 1(1). https://doi.org/10.52924/yana8929
13. Downie, J. and Stubbs, W., 2013. Evaluation of Australian companies' scope 3 greenhouse gas emissions assessments. *Journal of Cleaner Production*, *56*, pp.156-163.
14. Đurđević, D., Blecich, P., & Jurić, Ž. (2019). Energy recovery from sewage sludge: the case study of croatia. Energies, 12(10), 1927. https://doi.org/10.3390/en12101927
15. Ebrahimzadeh, M., Tsourlos, P., & Gerhard, J. (2017). Self-potential for monitoring soil remediation by smouldering: a proof of concept. Near Surface Geophysics, 15(5), 475-485. https://doi.org/10.3997/1873-0604.2017021
16. European Commission, Joint Research Centre, Pinasseau, A., Zerger, B., Roth, J. et al., 2018. Best available techniques (BAT) reference document for waste treatment – Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2760/407967 [Accessed 26 July 2024].
17. Fabris, I., Cormier, D., Gerhard, J., Bartczak, T., Kortschot, M., Torero, J., & Cheng, Y. (2017). Continuous, self-sustaining smouldering destruction of simulated faeces. Fuel, 190, 58-66. https://doi.org/10.1016/j.fuel.2016.11.014
18. Feng, C., Huang, J., Yang, C., Li, C., Luo, X., Gao, X., Qiao, Y.u., 2021. Smouldering combustion of sewage sludge: Volumetric scale-up, product characterization, and economic analysis. Fuel 305, 121485. https://doi.org/10.1016/j.fuel.2021.121485
19. Foley, J., de Haas, D., Yuan, Z., & Lant, P. (2010). Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. Water Research, 44(3), 831-844.
20. Fournie, T., Rashwan, T., Switzer, C., & Gerhard, J. (2022). Phosphorus recovery and reuse potential from smouldered sewage sludge ash. Waste Management, 137, 241-252. https://doi.org/10.1016/j.wasman.2021.11.001
21. Geostability of dewatered sludge as landfill cover material. (2022). Global NEST: The International Journal. Available at: https://doi.org/10.30955/gnj.004498 [Accessed 2 Aug. 2024].
22. Gievers, F., Loewen, A., & Nelles, M. (2021). Life cycle assessment of sewage sludge pyrolysis: environmental impacts of biochar as carbon sequestrator and nutrient recycler. Detritus, (16), 94-105. https://doi.org/10.31025/2611-4135/2021.15111
23. Grant, G., Major, D., Scholes, G., Horst, J., Hill, S., Klemmer, M., & Couch, J. (2016). Smoldering combustion (star) for the treatment of contaminated soils: examining limitations and defining success. Remediation Journal, 26(3), 27-51. https://doi.org/10.1002/rem.21468
24. Harusi, N. (2023). Analysis of carbon footprint in faculty of mathematics and natural sciences (mipa), university of hasanuddin. Iop Conference Series Earth and Environmental Science, 1272(1), 012038. https://doi.org/10.1088/1755-1315/1272/1/012038
25. He, S., Chen, K., Zhang, Y. et al. (2023). The coincineration of sewage sludge and municipal solid waste in an industrial scale incineration power plant. Int. J. Environ. Sci. Technol. 20, 2919–2928. https://doi.org/10.1007/s13762-022-04134-7
26. Houillon, G.; Jolliet, O. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. *J. Clean Prod.* 2005, *13*, 287–299.
27. Hu, D.; Jiang, P.; Chen, Y.; Gao, F.; Liu, S. (2024). Sustainable Sludge Management in China: Quantifying GHG Emissions and Exploring Its Reduction Strategies. Processes, 12, 1481.

28. Huang, X. and Rein, G. (2016). Interactions of earth's atmospheric oxygen and fuel moisture in smouldering wildfires. The Science of the Total Environment, 572, 1440-1446. https://doi.org/10.1016/j.scitotenv.2016.02.201

29. IPCC, 2007. Fourth Assessment Report: Climate Change. Working Group I: The Physical Science Basis. Available at, https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-3-2.html

30. Kang, S., Cho, C., Kim, K., & Jeon, E. (2018). Fossil carbon fraction and measuring cycle for sewage sludge waste incineration. Sustainability, 10(8), 2790. https://doi.org/10.3390/su10082790

31. Kang, S., Kim, S., Lee, J., Jeon, Y., Kim, K., & Jeon, E. (2017). A study on applying biomass fraction for greenhouse gases emission estimation of a sewage sludge incinerator in korea: a case study. Sustainability, 9(4), 557. https://doi.org/10.3390/su9040557

32. Kui, W. (2023). Study on life-cycle carbon footprint assessment of substation.. https://doi.org/10.1117/12.2688314

33. Lathan, R. (2024). Telemedicine for sustainable postoperative follow-up: a prospective pilot study evaluating the hybrid life-cycle assessment approach to carbon footprint analysis. Frontiers in Surgery, 11. https://doi.org/10.3389/fsurg.2024.1300625

34. Lee, S., Ryu, I., Jeon, S., & Moon, S. (2015). Simultaneous catalytic reduction of n2o and nox produced in a fluidized bed incineration of sewage sludge. Greenhouse Gases Science and Technology, 5(3), 347-355. https://doi.org/10.1002/ghg.1504

35. Lin, C. (2009). Hybrid input–output analysis of wastewater treatment and environmental impacts: a case study for the Tokyo Metropolis. Ecological Economics, 68(7), 2096-2105.

36. Liu, X., Wang, X., Song, J., Duan, H., & Wang, S. (2019). Why are the carbon footprints of china's urban households rising? an input–output analysis and structural decomposition analysis. Sustainability, 11(24), 7157. https://doi.org/10.3390/su11247157

37. Lü, H., Wu, D., Tang, D. Y., Chen, G., Loosdrecht, M. v., & Ekama, G. A. (2011). Pilot scale evaluation of sani® process for sludge minimization and greenhouse gas reduction in saline sewage treatment. Water Science and Technology, 63(10), 2149-2154. https://doi.org/10.2166/wst.2011.342

38. Lu, Q., Li, W. Z., & Zhu, X. F. (2009). Overview of fuel properties of biomass fast pyrolysis oils. Energy Conversion and Management, 50(5), 1376-1383. DOI: 10.1016/j.enconman.2009.01.001

39. Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E., 2020. Environmental and health impacts of air pollution: a review. Frontiers in public health 14.

40. Manyuchi, M. M. and Sukdeo, N. (2023). Recovery of phosphate from municipal sewage sludge. Proceedings of the International Conference on Industrial Engineering and Operations Management. https://doi.org/10.46254/in03.20230098

41. Matthews, H. S., Hendrickson, C., & Weber, C. L. (2008). The importance of carbon footprint estimation boundaries. Environmental Science &Amp; Technology, 42(16), 5839-5842. https://doi.org/10.1021/es703112w

42. Meyer, S., Glaser, B., & Quicker, P. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environmental Science & Technology, 45(22), 9473-9483.

43. Mohamed, B., Ruan, R., Bilal, M., Khan, N., Awasthi, M., Amer, M., … & Li, J. (2022). Co-pyrolysis of sewage sludge and biomass for stabilizing heavy metals and reducing biochar toxicity: a review. Environmental Chemistry Letters, 21(2), 1231-1250. https://doi.org/10.1007/s10311-022-01542-6

44. Müller, M., Vidal, D., Guanaes, E. A., & De Freitas, M. R. (2023). Sludge dewatering with geotextile refill in a draining container: case study in a water treatment plant. Delos: Desarrollo Local Sostenible, 16(45), 1732-1747. https://doi.org/10.55905/rdelosv16.n45-016

45. O'Kelly, B. C. (2004). Geotechnical aspects of sewage sludge monofills. Proceedings of the Institution of Civil Engineers - Municipal Engineer, 157(3), 193-197. https://doi.org/10.1680/muen.2004.157.3.193

46. Onabanjo, T., Patchigolla, K., Wagland, S., Jurado, N., Hanak, D., Parker, A., & Cartmell, E. (2016). An experimental investigation of the combustion performance of human faeces. Fuel, 184, 780-791. https://doi.org/10.1016/j.fuel.2016.07.077

47. Pinasseau, A., Zerger, B., Roth, J., Canova, M., & Roudier, S. (2010). Best available techniques (BAT) reference document for waste treatment. *Industrial Emissions Directive*, *75*, 2019-11.

48. Protocol, G.H.G., 2013. Technical Guidance for Calculating Scope 3 Emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard. *World Resources Institute and World Business Council for Sustainable Development*.

49. Rashwan, T. L., Fournie, T., Torero, J. L., Grant, G. P., & Gerhard, J. I. (2021a). Scaling up self-sustained smouldering of sewage sludge for waste-to-energy. Waste Management, 135, 298-308. https://doi.org/10.1016/j.wasman.2021.09.004

50. Rashwan, T. L., Torero, J. L., & Gerhard, J. I. (2021b). Heat losses in a smouldering system: the key role of non-uniform air flux. Combustion and Flame, 227, 309-321. https://doi.org/10.1016/j.combustflame.2020.12.050

51. Rashwan, T. L., Zanoni, M. A., Wang, J., Torero, J. L., & Gerhard, J. I. (2023). Elucidating the characteristic energy balance evolution in applied smouldering systems. *Energy*, *273*, 127245.

52. Rashwan, T., Gerhard, J., & Grant, G. (2016). Application of self-sustaining smouldering combustion for the destruction of wastewater biosolids. Waste Management, 50, 201-212. https://doi.org/10.1016/j.wasman.2016.01.037

53. Rybl, V. (2020). Does eui fully capture the carbon footprint of a vrf system? using a life cycle approach to assess vrf system emissions. 2020 AIA/ACSA Intersections Research Conference: CARBON. https://doi.org/10.35483/acsa.aia.fallintercarbon.20.13

54. Sajdak, M., Zajemska, M., Ouadi, M., Mucha, W., Misztal, E., Pieszko, C., … & Gałko, G. (2023). Perspectives of using sewage sludge char in co2 sequestration on degraded and brownfield sites. Energies, 16(9), 3945. https://doi.org/10.3390/en16093945

55. Sapmaz, S. and Kılıçaslan, İ. (2023). Energy analysis of sewage sludge energy conversion processes for Turkey—investigation of existing drying and combustion plants. Biomass Conversion and Biorefinery, 13(3), pp.2449-2458. https://link.springer.com/article/10.1007/s13399-022-02773-x

56. Siddeeg, S., Tahoon, M., & Rebah, F. (2019). Agro-industrial waste materials and wastewater as growth media for microbial bioflocculants production: a review. Materials Research Express, 7(1), 012001. https://doi.org/10.1088/2053-1591/ab5980

57. Solinger, R., Grant, G., Scholes, G., Murray, C., & Gerhard, J. (2020). Starx hottpad for smoldering treatment of waste oil sludge: proof of concept and sensitivity to key design parameters. Waste Management & Research the Journal for a Sustainable Circular Economy, 38(5), 554-566. https://doi.org/10.1177/0734242x20904430
58. Song, Q., Wang, X., Zhang, W., Qian, B., Ye, Y., Xu, K., & Wang, X. (2024). Digital twin technology for sewage sludge smoldering process and CO/NOx emissions based on back propagation neural network: A laboratory experimental study. *Process Safety and Environmental Protection*.
59. Suez Water Handbook (n.d.) Dedicated fluidised bed incineration: the Degremont® Thermylis-HTFB incinerator. Available at: https://www.suezwaterhandbook.com/processes/thermal-processes/sludge-incineration/dedicated-fluidised-bed-incineration-the-degremontr-thermylis-htfb-incinerator (Accessed: 24 July 2024).
60. Sun, H., Luo, L., Wang, D., Liu, W., Lan, Y., Yang, T., & Liu, Z. (2022). Carbon balance analysis of sewage sludge biochar-to-soil system. Journal of Cleaner Production, 358, 132057.
61. Surawski, N. C., Sullivan, A. L., Meyer, C. P., Roxburgh, S. H., & Polglase, P. J. (2015). Greenhouse gas emissions from laboratory-scale fires in wildland fuels depend on fire spread mode and phase of combustion. Atmospheric Chemistry and Physics, 15(9), 5259-5273. https://doi.org/10.5194/acp-15-5259-2015
62. Switzer, C., Paolo, P., Jaoson, I., Guillermo, R. and Jose, T. (2014). Volumetric scale-up of smouldering remediation of contaminated materials. Journal of hazardous materials 268: 51–60.
63. Switzer, C., Pironi, P., Gerhard, J.I., Rein, G. and Torero. J.R (2009) Self-sustaining Smoldering combustion: A novel remediation process for non-aqueous-phase liquids in porous media. Environmental Science and Technology 43(15): 5871–5877
64. Switzer, C., Zihms, S. and Tarantino, A. (2015) Effects of high temperatures on soil properties: lessons to share from smouldering remediation experience.
65. Tang, S., Yin, S., Shan, Y., Yu, B., Cui, C., & Cao, L. (2023). The characteristics of gas and particulate emissions from smouldering combustion in the pinus pumila forest of huzhong national nature reserve of the daxing'an mountains. Forests, 14(2), 364. https://doi.org/10.3390/f14020364
66. Tchobanoglous, G., Burton, F.L. and Stensel, H.D. (2003) Wastewater Engineering: Treatment and Reuse. 4th ed. New York: McGraw-Hill.
67. Teh, C. Y., Budiman, P. M., Shak, K. P. Y., & Wu, T. Y. (2016). Recent advancement of coagulation–flocculation and its application in wastewater treatment. Industrial &Amp; Engineering Chemistry Research, 55(16), 4363-4389. https://doi.org/10.1021/acs.iecr.5b04703
68. Temireyeva, A., Zhunussova, K., Aidabulov, M., Venetis, C., Sarbassov, Y., & Shah, D. (2022). Greenhouse gas emissions-based development and characterization of optimal scenarios for municipal solid and sewage sludge waste management in astana city. Sustainability, 14(23), 15850. https://doi.org/10.3390/su142315850
69. Torero, J. L., Gerhard, J. I., Martins, M. F., Zanoni, M. A., Rashwan, T. L., & Brown, J. K. (2020). Processes defining smouldering combustion: integrated review and synthesis. Progress in Energy and Combustion Science, 81, 100869. https://doi.org/10.1016/j.pecs.2020.100869
70. Touzani, A. (2024). The production of biochar from sewage sludge pyrolysis and its use: a mini review. E3s Web of Conferences, 527, 01024. https://doi.org/10.1051/e3sconf/202452701024
71. Vinci, G. and Rapa, M. (2019). Hydroponic cultivation: life cycle assessment of substrate choice. British Food Journal, 121(8), 1801-1812. https://doi.org/10.1108/bfj-02-2019-0112
72. Wang, G., Liao, M., & Jiang, J. (2020). Research on agricultural carbon emissions and regional carbon emissions reduction strategies in china. Sustainability, 12(7), 2627. https://doi.org/10.3390/su12072627
73. Wang, N., Shih, C., Chiueh, P., & Huang, Y. (2013). Environmental effects of sewage sludge carbonization and other treatment alternatives. Energies, 6(2), 871-883. https://doi.org/10.3390/en6020871
74. Wang, Z., Chen, D., Song, X., & Zhao, L. (2012). Study on the combined sewage sludge pyrolysis and gasification process: mass and energy balance. Environmental Technology, 33(22), 2481-2488. https://doi.org/10.1080/09593330.2012.683816
75. Werther, J. and Ogada, T. (1999). Sewage sludge combustion. Progress in Energy and Combustion Science, 25(1), 55-116. https://doi.org/10.1016/s0360-1285(98)00020-3
76. Wu, D. and Li, X. (2021). Toward energy neutrality in municipal wastewater treatment: a systematic analysis of energy flow balance for different scenarios. ACS ES&T Water, 1(4), 796-807. https://doi.org/10.1021/acsestwater.0c00154
77. Wyn, H. K., Konarova, M., Perkins, G., & Yermán, L. (2021). Fuel gas production from self-sustaining smouldering combustion of lignocellulosic waste.. https://doi.org/10.21203/rs.3.rs-817595/v1
78. Wyn, H., Konarova, M., Olaya, S., & Yermán, L. (2023). Effect of zro2/ceo2 mixed oxides on fuel gas production during self-sustaining smouldering combustion of lignocellulosic wastes. Sustainable Energy & Fuels, 7(10), 2390-2396. https://doi.org/10.1039/d3se00307h
79. Xie, Q., Chen, Z., Zhou, Y., Pan, T., Duan, Y., Yu, S., & Nie, Y. (2023). Efficient treatment of oily sludge via fast microwave-assisted pyrolysis, followed by thermal plasma vitrification. Molecules, 28(10), 4036. https://doi.org/10.3390/molecules28104036
80. Xu, L., Shen, C., Li, H., & Wen, Y. (2014). Rapid removal of dyes by carbonized sludge: process, effects of environmental factors, and mechanism. Separation Science and Technology, 49(16), 2574-2585. https://doi.org/10.1080/01496395.2014.928892
81. Xue-wen, M., Weng, H., Su, M., & Pan, L. (2011). Drying sewage sludge using flue gas from power plants in china. Environmental Earth Sciences, 65(6), 1841-1846. https://doi.org/10.1007/s12665-011-1166-x
82. Yermán, L. (2016). Self-sustaining smouldering combustion as a waste treatment process. Developments in Combustion Technology. https://doi.org/10.5772/64451
83. Yoshida, H., Christensen, T. H., & Scheutz, C. (2013). Life cycle assessment of sewage sludge management: a review. Waste Management & Research, 31(11), 1083-1101.

84. Yoshida, N., Wu, Y., Kanazawa, T., Yamamoto, Y., Fujita, T., Okadera, T., … & Geng, Y. (2013). Multi-regional carbon footprint reduction in steel sector in china due to low carbon technology implementation. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research), 69(6), II_383-II_390. https://doi.org/10.2208/jscejer.69.ii_383

85. Yuan, S. and Dai, X. (2015). Heteroatom-doped porous carbon derived from "all-in-one" precursor sewage sludge for electrochemical energy storage. RSC Advances, 5(57), 45827-45835. https://doi.org/10.1039/c5ra07178j

86. Zaharioiu, A., Bucura, F., Marin, F., Ionete, R., Oancea, S., & Constantinescu, M. (2021). Sustainable fuels obtained from the pyrolysis process of sewage sludge. Current Trends in Natural Sciences, 10(19), 16-24. https://doi.org/10.47068/ctns.2021.v10i19.002

87. Zanoni, M., Torero, J., & Gerhard, J. (2020). Experimental and numerical investigation of weak, self-sustained conditions in engineered smouldering combustion. Combustion and Flame, 222, 27-35. https://doi.org/10.1016/j.combustflame.2020.08.020

88. Zhang, X. Y., Chen, X., Xiao, J., Peng, X., Wang, J., Ma, J., & Liang, C. (2023). Comparative study of different sewage sludge incineration treatments based on environmental and economic life cycle assessment. Waste Management &Amp; Research: The Journal for a Sustainable Circular Economy, 42(5), 418-429. https://doi.org/10.1177/0734242x231187560

89. Zhao, G., Tang, J., Zhou, C., Xiaojie, M., Wei, Y., & Xu, J. (2022). A megacity-scale analysis of sludge management and carbon footprint in china. Polish Journal of Environmental Studies, 31(3), 2451-2460. https://doi.org/10.15244/pjoes/143510