Chapter 4
Municipal Sewage Sludge Incineration: Challenges and Strategies for Air Pollution Control

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Abstract The formation of municipal sewage sludge, a significant waste product of conventional municipal wastewater treatment processes, has surged dramatically due to increasing urbanization and industrialization. As a result, the safe recycling and resource recovery of municipal sewage sludge has become a pressing environmental challenge. On the other hand, incineration has long been regarded as an effective method for the secure disposal of this sludge, despite its high operational costs and challenges related to the emission of pollutants. Sludge can also be co-incinerated in facilities such as cement kilns, coal-fired power plants, and municipal solid waste (MSW) incinerators. This co-combustion approach is advantageous because it reduces the need for additional flue gas treatment systems and incineration equipment, and in some cases, it can even be more environmentally sustainable. The incineration process itself can be further optimized to reduce nitrogen oxide emissions through methods such as staged air combustion and low-oxygen dilution combustion. Additionally, the removal of sulfur can be enhanced by the use of calcium-based additives, while the volatilization of toxic metals and the formation of harmful components, such as polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, is influenced by chlorine-containing compounds. This chapter will provide an in-depth examination of these issues, with particular emphasis on the ecotoxicological risks associated with pollutants in sewage sludge. It will systematically review and analyze the latest research on pyrolysis of municipal sewage sludge

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and the strategies for managing its associated pollution. Furthermore, the chapter will explore potential treatment technologies to facilitate the long-term reuse of sewage sludge within a circular economy framework, as well as the environmental risks related to the utilization of sludge to soils.

Keywords Air pollution · Municipal solid waste sludge · Incineration · Co-combustion

4.1 Introduction

In recent years, both global effluent production and treatment capacities have experienced substantial growth, driven largely by increasing urbanization, industrialization, and the expanding demand for wastewater treatment. Concurrently, the generation of municipal solid waste sludge (MSS), a by-product of wastewater treatment processes, has seen a significant rise. This phenomenon has raised concerns regarding the safe and sustainable management of MSS. For instance, in 2020, China's daily wastewater treatment capacity reached an estimated 2.09×10^8 m^3, with an annual production of MSW surpassing 60 million tons (Liu et al. 2018). Similarly, it was forecasted that by 2020, the European Union's 27 member states (EU27) would collectively produce over 13 million tons of MSS. Despite substantial progress in developing various treatment technologies, the management of MSS remains a formidable environmental challenge. This is because MSS not only contributes to air pollution but also poses significant risks to water and soil quality, making its disposal and resource recovery critical areas of concern. The principal characteristics of MSS include a substantial quantity of volatile carbon (ranging from 60 to 80% of its solid mass), a high organic matter content, and a considerable moisture content, which can reach up to 99%. These features, coupled with large geographical variations in its composition, complicate the effective management of MSS. For instance, organic matter constitutes 30–50% of MSS in China, while in more developed nations, this percentage rises to 60–70% (Xiao et al. 2018). The variability in MSS composition is a major factor influencing the complexity of treatment and disposal strategies, and it further emphasizes the need for region-specific approaches to sludge management.

Hydrothermal carbonization (HTC) has also become a viable substitute for conventional sludge treatment techniques including decomposition, landfilling, and incineration. HTC provides enhanced sustainability advantages and offers a broader range of potential applications. Studies have shown that HTC can produce high-quality carbonized products that can be used as biofuels or soil conditioners, thus contributing to a more circular approach to sludge management. However, Zhou et al. (2020) have shown that the most advantageous environmental, economic, and social results are obtained when treated sludge is applied to land. A multi-criteria decision-making model was developed utilizing LCA data, illustrating that, when managed effectively, land application provides significant advantages in reducing carbon footprints and fostering sustainable agricultural practices. Nonetheless, this approach necessitates thorough evaluation of the possible hazards associated with soil contamination and the buildup of pollutants. Despite these advancements, earlier investigations into the environmental impacts of different wastewater treatment and disposal techniques have faced challenges due to inconsistencies in system boundaries and data assumptions. The inconsistencies observed have posed difficulties in aggregating and contrasting findings from various studies, given that the environmental effects frequently differ based on the particular data inputs utilized. Furthermore, a thorough evaluation of the life cycle of sludge treatment methods utilized in China, including co-incineration for energy generation or the production of construction materials, as well as alkaline thermal hydrolysis for protein recovery, remains to be undertaken. The lack of understanding in this area has constrained the capacity to make well-informed choices about the best sludge management approaches in the region. This study seeks to conduct a comprehensive assessment of the environmental effects associated with different sludge treatment and disposal techniques presently employed in China.

This study also builds upon earlier research by providing an integrated approach to sludge treatment, combining environmental, economic, and social considerations. It aims to provide actionable insights for policy-makers, engineers, and environmental managers seeking to minimize the environmental footprint of municipal sewage sludge while ensuring that treatment technologies remain economically viable and socially acceptable. Through this analysis, it is hoped that more sustainable sludge management practices can be developed, contributing to reduce carbon emissions and pollution, while supporting the long-term goals of a circular economy.

Municipal solid waste incineration (MSWI) within waste-to-energy (WtE) facilities has become a cornerstone of waste management strategies across most developed nations. Over recent decades, technological advancements in energy recovery from MSW have been substantial, leading to the integration of sophisticated air pollution control (APC) systems designed to meet stringent environmental standards. These APC systems are essential in minimizing the environmental impact of WtE processes, ensuring that gaseous emissions comply with rigorous regulatory requirements. This chapter offers a comprehensive examination of MSWI technologies and APC mechanisms, focusing on their function in removing key pollutants such as dioxins and furans, which are pivotal concerns in emission control. Furthermore, the chapter briefly considers the potential health risks associated with these emissions, situating MSWI's role within the broader MSW management framework and underlining its importance in sustainable WtE conversion (Fu et al. 2019). Figure 4.1 showing the impact of sewage sludge on environment sustainability.

4.2 Incineration

A byproduct of treating wastewater in cities or businesses is sludge. The safe and environmentally responsible disposal of sludge has grown in importance as environmental protection has gained more public consciousness. According to China's Ministry

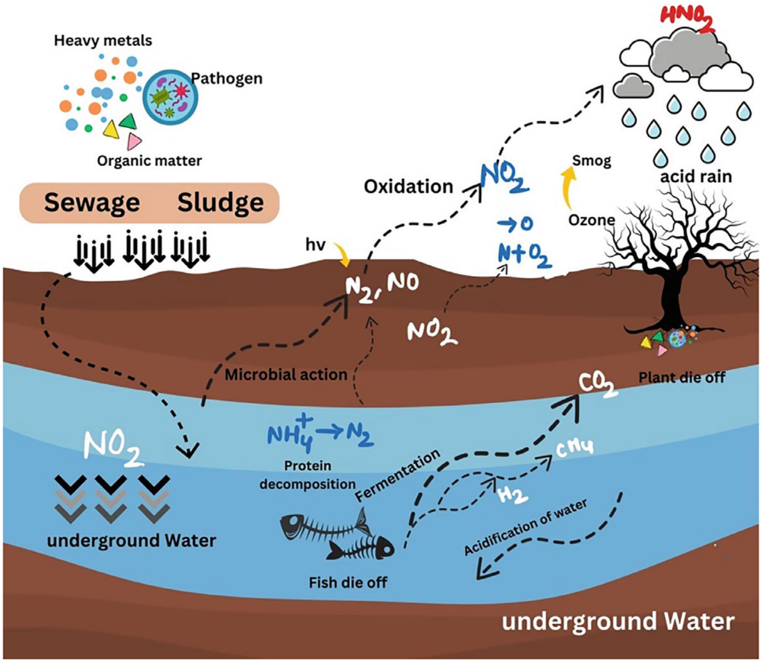

Fig. 4.1 Impact of sewage sludge on environment sustainability

of Environmental Protection's National Standard, the primary ways to dispose of sludge include incineration, land application, sanitary landfilling, and using sludge as construction material (Teoh and Li 2020). Figure 4.2 shows the different fundamental steps for treatment and disposal of Municipal sludge Incineration. Although sanitary landfilling is still the most popular method in China, problems like the sludge's unstable physical characteristics and the scarcity of landfill sites in major cities like Shanghai and Shenzhen cast doubt on its future. The regaining of N_2 from sludge has shown promise as a workable disposal option in terms of land application (Geng et al. 2020).

4.2.1 Mono-incineration

Feeding municipal solid waste sludge (MSS) with elevated moisture content directly into an incinerator can lead to combustion challenges, including temperature drops, ignition delays, and variations in furnace temperature. Figure 4.3 illustrates a schematic representation of a standard MSS incineration process. To ensure the stability of MSS incineration, the sludge is typically moved to a dryer following mechanical dewatering before it is subjected to combustion in the incinerator. In

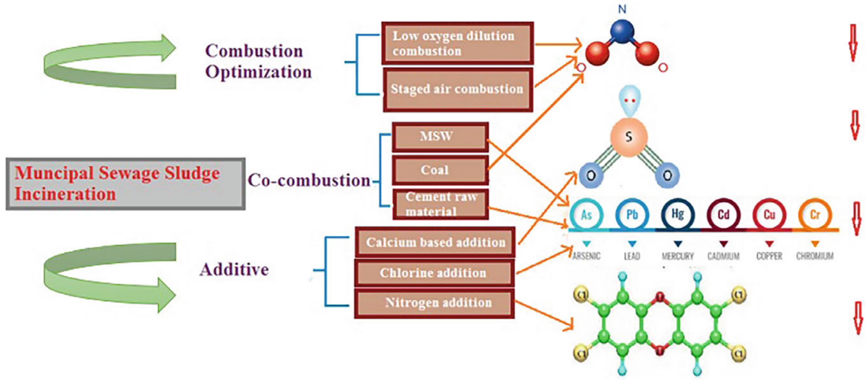

Fig. 4.2 The different fundamental steps for treating and disposing of municipal sludge incineration

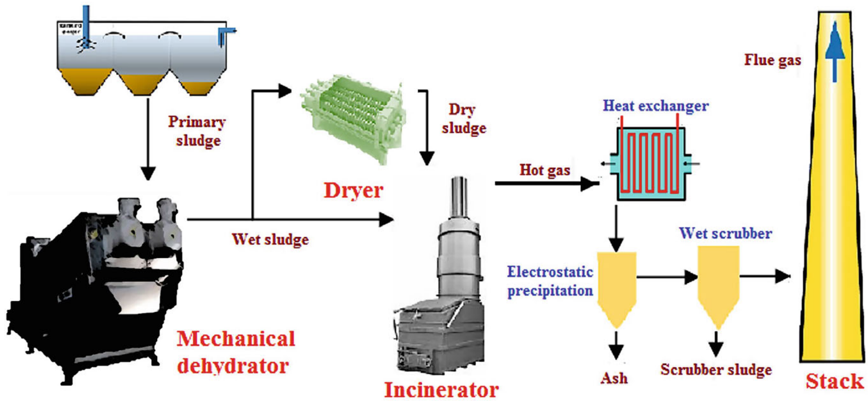

Fig. 4.3 Diagram showing systematic incineration of municipal sewage sludge

certain instances, wet MSW is transported directly to a fluidized bed incinerator, where additional fuel is incorporated. Ensuring that combustion byproducts undergo proper treatment and cleaning prior to their release in the nature is crucial (Akdag et al. 2018). Table 4.1 presents a comprehensive analysis of the benefits and drawbacks related with MSWI (Quina et al. 2011).

4.2.1.1 Combustion of Wet Municipal Sewage Sludge

A study has been carried out on the combustion properties of wet municipal solid waste sludge (MSS) in semi-pilot scale fluidized bed burners. MSS exhibits a greater

Table 4.1 Advantages and disadvantages of municipal solid waste incineration

Advantages	Disadvantages
Manage municipal sewage waste without initially treating it	APC residues are hazardous trash that has to be disposed of safely
Reduce the need for municipal sewage waste to be dumped in landfills	
90% Less waste	Slags of origin (bottom ashes)
70% Less waste weight	Source of a massive amount of flue gasses
Potential for energy recovery (heat or electricity)	High operating and investment expenses
	Expensive upkeep
Low levels of air pollution are emitted when properly regulated	Need qualified personnel
Eliminate hazardous organic pollutants and possible infections	Need the right composition in order to autocombust
May be situated near the MSW generating center of gravity	Unfavorable public opinion
Lower the cost of garbage transportation	
Minimum land requirements	
There are no odors from stack emissions	
Primarily convert organic molecules to CO_2 instead	

volatile content relative to other fuels, which influences its distinct combustion characteristics. With rising temperatures, the moisture within the MSS undergoes evaporation, subsequently leading to the volatilization of organic compounds. The elevated moisture content in wet MSS results in a considerable generation of water vapor, and the endothermic nature of water evaporation indicates that drying and primary devolatilization take place at reduced particle temperatures. Upon reaching a specific temperature threshold following the evaporation of water, these volatile compounds ignite, leading to the final combustion stage on the remaining coke (Akdag et al. 2018). Figure 4.4 showing proposed ways for sewage sludge disposal and utilization.

Huang et al. (2016) performed experiments involving the combustion of MSS for a duration of 3 min at a temperature of 600 °C, followed by rapid cooling in a reducing atmosphere. The observation revealed that dry, devolatilized, and combustion layers existed concurrently without distinct boundaries throughout the four stages of combustion. It is crucial to emphasize that approximately 80% of the carbon in MSS is evaporative, making the gas-phase ignition of these volatiles an essential aspect of the overall ignition procedure. On the other hand, in the case of coal combustion, these percentages represented 9 and 88% of the total duration of the process (Kijo-Kleczkowska et al. 2016).

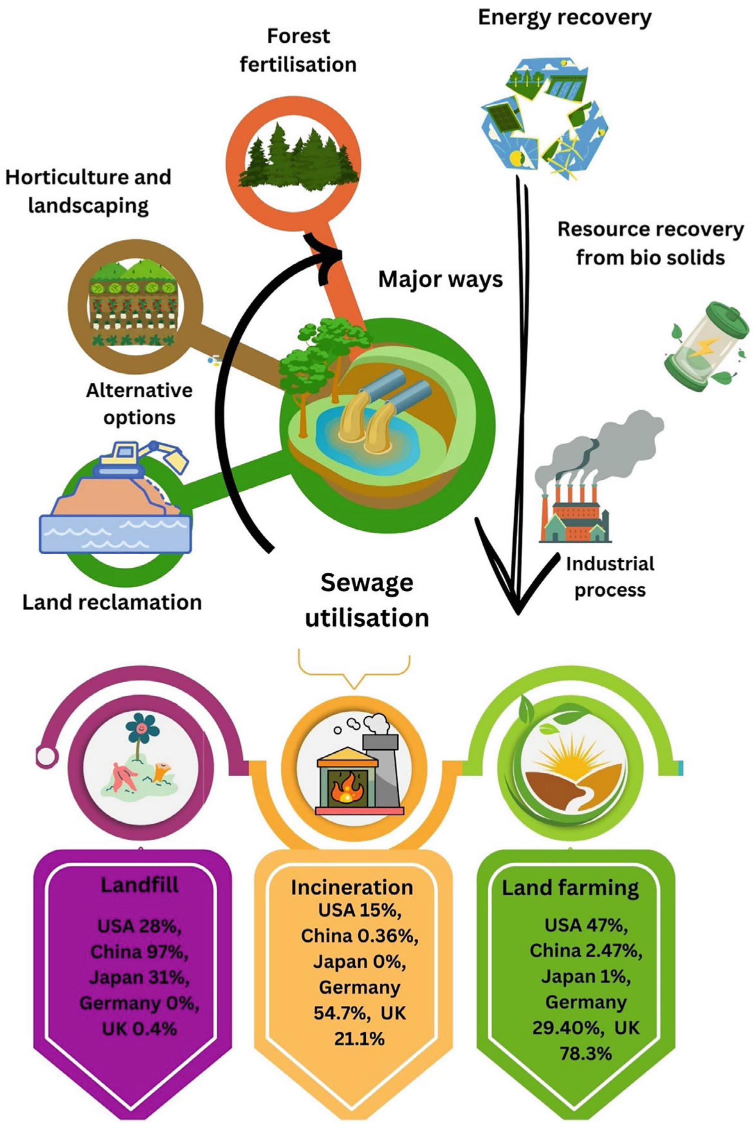

Fig. 4.4 Proposed ways for sewage sludge disposal and utilization

4.2.1.2 Incineration Following the Drying Process

Municipal solid waste sludge (MSS) maintains 80–85% moisture after mechanical dewatering, requiring further drying to reach 10–30% moisture (Ma et al. 2016). High temperatures and high pressures are often used in thermal drying, which improves MSS's dewatering qualities and aids in the discharge of leap water. Nonetheless, traditional thermal drying techniques for water evaporation are energy-intensive. Conversely, biological drying is a more energy-efficient method as it makes use of the metabolic heat produced by aerobic microbes decomposing organic debris in MSS. Cai et al. (2016) state that during biological drying, the first stage's water removal rate makes up 62% of the total removal, while the second stage's rate is 28%. Furthermore, MSS particles develop irregular holes as a result of the breakdown of viscous components during biological drying, which makes it easier for air to transfer for later burning. Biological drying is a promising drying approach for MSS because it successfully lowers the moisture content of MSS while creating a biostabilized and dried material, as several research have shown (Hao et al. 2018).

4.2.2 Co-combustion

Wet or semi-dry sludge has a lower calorific value than dry sludge, which makes steady combustion challenging. Burning sludge with other fuels is advised as a solution to this problem. Municipal solid waste sludge (MSS) is often ignited with coal as a component of cement raw materials, according to which reveals the calorific values of different sludge sorts. By reducing the ignition temperature and increasing combustion efficiency, the use of coal improves MSS's combustion performance. The following sections describe the various emissions produced by co-combustion in fluidized bed burners and thermal power plants. The fuel consumption of the original equipment may be considerably reduced by integrating MSS into cement kilns or MSW incinerators (Hu et al. 2016).

4.2.2.1 Co-combustion of Coal and Municipal Sewage Sludge

Municipal solid waste sludge (MSS) co-combustion affects a number of variables, such as ignition time, combustion length, emissions of pollutants (such SO_2 and NO_x), and overall combustion efficiency. Both char and volatile matter combustion have an impact on MSS's combustion since it includes more volatile chemicals. The volatile components present in municipal sewage sludge (MSS) have the potential to enhance the combustion process by facilitating rapid ignition, thereby potentially reducing combustion time. However, the moisture content in MSS, which can be considerable, plays a crucial role during the evaporation stage of incineration. As moisture evaporates, it absorbs a significant amount of heat, which increases the energy required to reach the ignition point. This results in a mixed fuel that exhibits a prolonged ignition time and a higher ignition temperature compared to dry materials (Kijo-Kleczkowska et al. 2016). Consequently, the presence of moisture in MSS can affect the overall efficiency and energy dynamics during the combustion process. During the incineration of municipal solid sludge (MSS), specific heavy metals, exhibit a higher tendency for volatilization as a result of increased chlorine concentrations in the sludge. Chlorine compounds, especially in substantial amounts, can promote the volatilization of these metals into the gaseous phase, leading to considerable environmental risks, such as air pollution and ecosystem contamination. The significant ash amount of MSS, along with the creation of inert alkali metal aluminosilicates, can obstruct char combustion at elevated temperatures, thereby reducing the potency of the incineration process. The retention of arsenic in combustion systems is affected by specific minerals, including calcite and clay, which notably improve arsenic retention in coal slurry during combustion (Fu et al. 2019). These minerals can bind to arsenic, inhibiting its environmental release; however, their presence complicates the overall process by potentially contributing to the formation of undesirable by-products. The co-combustion of municipal solid waste (MSS) presents a significant drawback due to its elevated levels of copper and chlorine, which can facilitate the production of hazardous substances, including dibenzofurans and polychlorinated dibenzo-p-dioxins (PCDD/Fs). Such compounds exhibit significant environmental persistence and present considerable ecotoxicological risks, including cancer causing and mutagenic impacts. Increasing the concentration of MSS in the co-combustion mix elevates the probability of generating harmful compounds, thereby intensifying the environmental consequences of the incineration process. Furthermore, an increase in the quantity of MSS in the combustion combination correlates with a significant rise in carbon monoxide (CO) emissions, which is a detrimental air pollutant. Akdag et al. (2018) identified a direct correlation between the proportion of MSS in the fuel mix and the rise in CO emissions. When the MSS content expand from 5 to 30%, combustion productiveness reduced from 99.5 to 97.5%. The observed decrease in efficiency indicates incomplete combustion, suggesting that the incorporation of MSS into the incineration process may reduce overall performance, leading to increased emissions and diminished energy recovery efficiency. The significant slagging and scaling potential of MSS complicates its application in the ignition method. The significant content of ash and inorganic material in municipal solid waste (MSS) can result in clinker formation, which accumulates on furnace walls or other heat exchange surfaces, thereby diminishing heat transfer efficiency and posing a risk to equipment integrity. This phenomenon, commonly known as "slagging," presents considerable operational difficulties, necessitating regular maintenance and adjustments in operations.

4.2.2.2 Co-incineration of and Municipal Solid Waste and Municipal Sewage Sludge

The synergistic treatment of MSS and MSW, the removal of the requirement for fossil fuels, and the reduction of Hg emissions are only a few advantages of incineration as an efficient way of treating MSW (Sun et al. 2020). Ignition of MSS with MSW presents a promising solution to generate sufficient thermal energy without increasing fossil fuel use. This process can dry MSS feedstock in situ, facilitate combustion, and support process steam production. However, increasing the proportion of MSS can significantly elevate combustible levels and may lower the combustion temperature, posing challenges for incinerator efficiency. To mitigate these issues, semi-dried

MSS, with its higher heating value and reduced moisture content, proves to be more effective when burned alongside MSW in grate furnace incinerators. With the adoption of a new integrated treatment system, such an incinerator can now process up to 1200 tons of MSW and 300 tons of MSS daily, optimizing the combustion process and energy recovery (Chen et al. 2019). Compared to processing MSS and municipal solid trash separately, this co-combustion technique efficiently uses waste heat to eliminate moisture from MSS, making it an efficient way to dispose.

4.2.2.3 Co-combustion of Raw Cement and Municipal Sewage Sludge

Hazardous materials included in organic waste are efficiently broken down by high-temperature incineration in cement kilns, while inorganic materials, including ash residue, may be fully used in a variety of products. Lime drying is a basic pretreatment method used in wastewater treatment facilities. The calcium found in lime-dried MSS may be used as a raw material to make cement. This suggests that co-processing MSS in cement kilns is feasible. MSS is a feasible substitute fuel for the manufacture of cement because of the organic materials it contains, which also adds extra heating value. With a calorific value of around 8.3 MJ/kg, MSS may replace up to 14% of the raw matter utilized in the formation of cement, meeting the industry's requirement of 6.25 MJ/kg. According to estimates, adding MSS to contemporary cement kilns may cut the use of fossil fuels by around 70% (Xu et al. 2014, 2019). Table 4.2 represents the comparative investigation of different methods applied for sewage sludge utilization.

4.2.2.4 Pyrolysis

For the management of MSS and energy recovery, pyrolysis the thermal breakdown of waste in an oxygen-free environment is a strong substitute for combustion (Dong et al. 2019). In addition to removing pathogens and harmful substances from sewage sludge, this method build chemicals and energy while reducing the amount of carbonaceous waste. Pyrolysis produces high-quality products and has major economic and environmental advantages when it is maximized. Based on heating rates, there are different type of primary forms of pyrolysis: slow pyrolysis and quick pyrolysis. Fast pyrolysis, which is more often employed for biomass processing, completes in seconds and optimizes the output of liquid products, whereas slow pyrolysis takes several hours and mostly creates charcoal. Fast pyrolysis, which is generally accomplished in fluidized bed reactors for sewage sludge, may produce liquid oil at temperatures between 450 and 550 °C that ranges from 30 to 72% (on a dry and ash-free basis) (Wei et al. 2015). Although the primary goal of pyrolysis is to produce pyrolysis oil, other processes that maximize the generation of solids and gases, respectively, include carbonization and gasification. Approximately 90% of the sewage sludge feedstock is converted to char by carbonization, which needs

Table 4.2 Comparative investigation of different methods applied for sewage sludge utilization

Technologies	Target products	Byproduct	Pros	Cons	References
Incineration	Heat and power	Ash	Significant quantity reduction; organics and pathogens are almost entirely removed	1. Dewatering and drying of sewage to a solids matter of 41–65 weight percent is necessary 2. Greenhouse gas emissions (GHG, NO_x, SO_x, and PMs) 3. A low energy efficiency; A waste rate that is not close to zero	Hu et al. (2016)
Gasification	Syngas	Tar char	High carbon balance and thermal efficiency; Syngas is beneficial for chemical synthesis as well as fuel; tars and biochar with possible extra benefits; Steer clear of SO_x and NO_x emissions	1. The need for dewatering and drying to a solids content of more than fifty weight percent 2. The presence of heavy organic pollutant chemicals in tar 3. The presence of extensive syngas cleaning requirements 4. The high investment and operating expenses	Raheem et al. (2018)

(continued)

Table 4.2 (continued)

Technologies	Target products	Byproduct	Pros	Cons	References
Gaseous phase char	·Mostly at benchscale; high	–	A unique reactor and feeding mechanism are needed for the direct utilization of operating pressure; catalyst recovery is challenging, particularly for homogeneous catalysts; and organics are lost in watery byproducts	–	Gollakota et al. (2018)
Hydrothermal	Operating	–	For wet sewage sludge, the temperature range is between 250 and 375 degrees Celsius; the pressure range is between 5 and 20 megapascals; the atmosphere is composed of nitrogen dioxide	Bio-crude oil	Hu et al. (2021)
Pyrolysis	Bio-oil	Gas char	It has the potential to reduce volume; it has lower greenhouse gas emissions than incineration; it can deactivate genes that are resistant to antibiotics; it can remove bioactive substances; it can produce biochar and syngas, all of which have the potential to add value	In comparison to incineration, dewatering and drying are necessary; the process is more complicated; air pollutants and heavy metals are retained in biochar; the expenses of capital and investment are high	Cao et al. (2024)

longer residence periods and lower operating temperatures (approximately 300 °C) (Zheng et al. 2020).

4.2.3 Significance of Controlling Air Pollution from Municipal Sewage Sludge Incineration

Due to land resource limitations and increasing energy demands, incineration is acknowledged as an efficient and broadly applicable pocess for reducing the volume and hazardousness of municipal solid waste (MSW) while recovering energy (Zhang et al. 2020). Currently, MSW incineration surpasses other thermal processing technologies in terms of equipment and techniques. Nonetheless, it is imperative to manage pollution emissions (e.g., SO_2 and NO_x) and mitigate disposal costs arising from the high energy consumption linked to drying processes. Municipal solid waste incineration (MSWI) within waste-to-energy (WtE) systems is a crucial waste management strategy in many developed countries, offering the dual benefits of minimizing landfill volumes and recovering energy from MSW. This method is especially beneficial in areas with high population density and restricted landfill capacity. MSWI operations encounter significant environmental challenges stemming from the emission of various air pollutants and residues, which can adversely affect ecosystems and human health if not properly managed. MSWI produces a range of pollutants, including particulate matter (dust), CO, NO_x, SO_2, hydrochloric acid, hydrofluoric acid, and volatile heavy toxic metals (Hu et al. 2021). These pollutants result from the breakdown and volatilization of materials within MSW during combustion, with heavy metals and dioxins presenting specific challenges due to their toxicity and potential for atmospheric dispersion. Key heavy metals like Pb and Cd are more prone to volatilization at high temperatures, especially in the presence of chlorine, which forms volatile metal chlorides. This necessitates advanced pollution controls to capture these compounds before they enter the environment. To address these challenges, modern MSWI facilities employ a suite of APC technologies that ensure compliance with strict environmental standards. Electrostatic precipitators, fabric filters, and wet scrubbers are widely used to capture particulate matter. To control gaseous emissions, flue gas desulfurization reduces SO_2 levels, and SCR significantly lowers NO_x emissions. Additionally, activated carbon and lime injection systems are utilized to capture heavy metals and acidic gases, converting them into solid residues that can be safely contained rather than emitted as gas (Chen et al. 2019). The behavior of pollutants during incineration is governed by thermodynamic factors such as boiling and sublimation points, which dictate whether a metal or compound will remain in solid ash or volatilize into flue gas. For instance, volatile heavy metals like Pb and Cd readily form chlorides with low sublimation points, enhancing their release into the flue gas unless captured by APC systems. Meanwhile, metals like nickel (Ni) and chromium (Cr), which are less volatile, tend to remain in ash residues, reducing their atmospheric emissions (Milhé et al. 2015).

Economic feasibility remains a critical consideration in adopting these advanced technologies, as they increase the cost per ton of waste processed. However, the health and environmental benefits of reduced emissions often justify these costs, especially as regulations evolve to require lower thresholds. Research indicates that, with adequate APC systems, MSWI poses minimal health risks, demonstrating that current technologies can effectively manage emissions and align with sustainability goals. Where stricter limits are needed, MSWI facilities can enhance gas cleaning systems further, positioning MSWI as an efficient, environmentally sound waste management method in WtE systems.

4.3 Features and Management of Pollutant Emissions

4.3.1 Heavy Metals

Approximately 0.5–2%, and in certain instances up to 4.0%, of the overall dry weight of municipal solid sludge (MSS) consists of heavy metals. MSS exhibits significant content of heavy metals. The primary heavy metals identified in MSS include nickel, zinc, chromium, cadmium, copper, lead, mercury and arsenic, as detailed in Table 4.3. The ignition of MSS results in varying behaviors of heavy metals in the resulting inorganic content and flue gas emissions. Although some toxic metals are volatilized and emitted with the flue gas, the majority are retained in the ash residue. Chimney emissions often contain volatile metals, specifically cadmium, lead, and mercury, owing to their significant volatility. The volatilization of these metals is affected by intricate chemical interactions with various elements and compounds. Additionally, elements such as residence time, temperature of combustion and the chemical composites of the MSS feedstock are also significant contributors. The parameters outlined collectively influence the degree to which heavy metals convert to gaseous or solid phases during the combustion process (Velden et al. 2008; Li et al. 2014).

4.3.1.1 Heavy Metal Properties

The decomposition of toxic metals is strongly affected by the distinct properties of each metal and its compounds at different temperatures. For instance, metals like lead (Pb) and zinc (Zn) are particularly sensitive to high temperatures. As the degree of heat rises from 850 to 1000 °C, their combustion rates increase markedly, with lead nearly doubling its rate. This temperature sensitivity highlights the reactive nature of these metals in combustion environments, where even moderate increases in temperature can significantly enhance their transition to the gaseous phase. (Liu et al. 2015). Similarly, within a comparable temperature range, the volatilization rate of chromium (Cr) increases significantly, from 65.7 to 74.9%. In contrast, transition metals exhibit relatively low sensitivity to temperature fluctuations. Research

Table 4.3 Summarization of metal catalysts benefits and drawbacks

Metal catalysis	Benefits	Drawbacks	References
Alkali metals	The steam reformation of tar is very efficient, and it possesses the ability to enhance the quality of gaseous emission	It is simple to disappear, but difficult to recover	Faba et al. (2015)
Biochar	It is inexpensive, it is produced naturally inside the gasifier, and it has a high tar conversion and is equivalent to dolomite	Consumption as a result of processes involving gasification	Huet al. (2018)
Nickel	Increased activity in the degradation of tar; reversal of the ammonia reaction; reduction of NO_x emission An advantageous condition for the reforming of methane and the water–gas shift process; Cost-effective; simple to generate new	Sintering of metal particles and the deposition of coke both contribute to the rapid deactivation of the material	Noichiet al. (2010)
Noble metal	An very high catalytic activity, together with a strong resistance to sulfur and long-term stability	At a very high cost	Cordero-Lanzacet al. (2018)
transition metals	In situations when there is a large concentration of heavy tar in the tar, it is quickly deactivated by carbon deposition	Moderately active for the breakdown of biomass tar; some exhibited greater catalytic activity compared to the Ni catalyst	Wang et al. (2012)
Zeolites	Excellent thermal stability, in addition to a reasonably high resistance to sulfur and nitrogen chemicals, and a simple regeneration process	Quick loss of activity due to coke buildup	Chenet al. (2018)

indicates that metal cadmium (Cd) demonstrates notably higher volatility than other toxic metal within the 500–1100 °C range, underscoring Cd's propensity for gaseous phase transitions at elevated temperatures.

4.3.1.2 Impact of Chlorine on Heavy Metals

The effect of chlorine on the volatility of heavy toxic metals during incineration processes has been the subject of much research. For instance, it has been shown that addition of $FeCl_3$/CaO to municipal sewage sludge (MSS) increases the volatilization of copper and chromium while concurrently decreasing the levels of lead, zinc and copper in remaining ash (Liu et al. 2016). The significant propensity of chlorine for interacting with toxic metals to generate metal chlorides is the cause of this phenomena. Metal chlorides are more volatile and simpler to discharge into the gas phase during cremation because they typically have lower boiling and sublimation temperatures than their oxide or elemental equivalents. The transition temperatures from gas to solid for some metals, like as arsenic, copper, magnesium, and sodium, are significantly reduced with the addition of 5% calcium chloride to MSS. This decrease in transition temperatures implies that the distribution and volatilization of these metals during incineration are significantly influenced by chlorine. Chlorine compounds change the partitioning behavior of certain metals and increase their volatilization, both of which may have serious environmental effects. The intricacy of chlorine's function in altering heavy metal behavior during incineration is shown by this differential impact. According to Han et al. (2008), Lead volatilization is impacted by chlorine chemicals like PVC and NaCl via several ways. While sodium chloride combines with lead in the gas phase to generate lead chloride ($PbCl_2$), PVC probably reacts with lead to form lead chlorides like $PbCl_2$, $Pb(ClO_4)_2$, and $PbCl_2O_4$.At least 10% of the ash additive mixture must include chlorine in order to transform semi-volatile heavy metals into chlorides for improved volatilization. The incorporation of 10% chlorine does not significantly enhance the volatility of low-volatile heavy metals. Chlorine's ability to increase the volatility of various heavy metals is contingent upon each metal's intrinsic volatility properties. Therefore, in order to better regulate the volatilization of heavy metals, future research should concentrate on improving the process of adding chlorine to MSS with varying compositions. In order to prevent the addition of chlorine from unintentionally increasing the release of hazardous compounds, such study would also seek to reduce the influence on other emissions (Liu et al. 2015).

4.3.2 Polychlorinated Dibenzofurans

Two important harmful air pollutants produced by the burning of municipal sludge (MSS) are dioxins and furans. Dioxins refer to a group of polychlorinated aromatic chemicals that share similar structures and properties, which include 75 varieties of polychlorinated dibenzo-p-dioxins (PCDDs) and 135 types of polychlorinated dibenzofurans (PCDFs). Since PCDD/Fs are polychlorinated chemicals, the emissions of these compounds are greatly impacted by the presence of chlorine in MSS (Chen et al. 2008; Gao et al. 2009). Chlorine and oxygen interact at the carbon surface during burning, resulting in redox reactions that create a variety of organic molecules containing chlorine. The toxicity and damage of the emissions from the incineration process are increased by these substances, which may include chloromethanes, chloroethanes, and chloroaldehydes.

4.3.3 Sulfur Oxides

Researchers have shown significant interest in studying sulfur transformation during the co-combustion of MSW in cement kilns. Key topics include the total sulfur content of the system, the primary chemical processes involved, strategies for mitigating or regulating sulfur incorporation, and the sulfur emission from heated cement basic components in both oxidizing and reducing conditions (Nielsen et al. 2011). Sulfur undergoes transformation into a range of compounds that contain sulfur during MSS incineration and is ultimately emit into the environment as solid residues in MSS ash or as gaseous emissions. Comparative analyses between MSS and coal combustion have shown minor discrepancies, although the comprehensive characterization of sulfur conversion in coal combustion. Additional studies have shown that MSS comprises sulfoxide, sulfone, and sulfate functional groups (Merino et al. 2007).

4.3.3.1 Conversion of Sulfur During the Incineration of Municipal Sewage Sludge

While thiophene and sulfone levels first rise and then decline after coal combustion, mercaptans and sulfides levels fall. During the process, the amount of sulfoxides grows while the concentration of sulfate just slightly changes. The development of functional groups during MSS combustion follows a similar trend. The behavior of thiophenes and sulfoxides varies, but MSS combustion shows consistent patterns in mercaptan, sulfide, sulfone, and sulfate concentration when compared to coal combustion (Li et al. 2009). In MSS combustion, sulfate concentrations are greater and range between 10 and 15%. The production of sulfate from SO_2 generated during combustion is facilitated by the substantial levels of CaO and Mg found in MSS ash (Folgueras et al. 2004). Interestingly, sulfoxide levels increase during the beginning of combustion and decrease at the conclusion. This pattern might be explained by sulfoxides' capacity to change thiols and sulfides at lower temperatures when oxygen is present, then decompose into other forms at higher temperatures as burning proceeds. In contrast to coal burning, MSS combustion results in a reduction in the amount of thiophene. According to researchers, polycyclic structures, which are created during coal formation under circumstances of high temperature, high pressure, and extended time, are often found in thiophenes in coal. Coal and MSS combustions behave differently because MSS primarily comprises monocyclic thiophenes, which are more quickly broken down at the beginning of combustion, whereas coal's polycyclic thiophenes are more stable and likely to stay in coke (Liu et al. 2007).

4.3.3.2 Removal and Capture of Sulfur

Multiple studies have investigated the impact of conditioning agents on the transformation and emission of sulfur (S) during the burning of municipal sewage sludge (MSS), demonstrating efficacy in reducing pollutant emissions in coal combustion. Qin et al. (2017) indicate that calcium-based additives, including CaO, $Ca(OH)_2$, and $CaCO_3$, may eliminate up to 86.9% of SO_2, 38.9% of PAHs, and 75.2% of toxic equivalent quantities (TEQs) at 850 °C when incorporated into an MSS fluidized bed combustor. This suggests that CaO is especially good in lowering emissions of SO_2 and PAHs. Additionally, CaO has been shown to improve the creation of hydrogen during incineration and collect CO_2 (Milhé et al. 2015). Han et al. (2015) created a porous calcium-based adsorbent characterized by a high particular area of surface. They discovered that as porosity and surface area rose, so did the adsorbent's ability to remove SO_2, and that higher reaction temperatures also improved SO_2 reduction. FeO_3 may help SO_2 react with coal's minerals, which increases coal ash's ability to retain sulfur and lowers SO_2 concentrations in the flue gas during coal burning (Elled et al. 2006).

4.3.4 Nitrogen Oxides

The burning of municipal sewage sludge (MSS) raises serious concerns about the production of NO_x and other dangerous contaminants. Compared to other fuels like coal (0.5–1.5%) and biomass (0.3–1.0%), MSS has a much greater nitrogen concentration, ranging from 4 to 9% (Zhu et al. 2015). Among these pollutants, N_2O is a powerful greenhouse gas that has a much higher potential to cause global warming than CO_2. The high nitrogen concentration and the presence of Fe_2O_3 and MnO_2, in the feedstock are the main causes of the increased NO_x emissions during MSS combustion. By encouraging the oxidation of substances like HCN and NH_3 into NO_x, these metal oxides have been shown to promote the generation of NO_x during coal combustion (Champion et al. 2013).

4.3.4.1 Features of NO_x Emissions

The combustion and gaseous emission characteristics of municipal sewage sludge (MSS) are profoundly influenced by the water content, which in turn affects both the efficiency of the combustion process and the types and quantities of emissions produced. In dry MSS combustion, akin to coal combustion, the formation of nitrogen oxides (NO_x) generally increases with a higher surplus air ratio. This occurs because the surplus air leads to increased oxygen availability, promoting the oxidation of nitrogen in the fuel to form nitric oxide (NO) and nitrogen dioxide (NO_2). As the combustion temperature escalates, the emission of NO and NO_2 tends to rise due to enhanced thermal formation, while nitrous oxide (N_2O) emissions typically decrease, as N_2O is thermally decomposed into nitrogen and oxygen at high temperatures. This behavior aligns with the established understanding of high-temperature combustion processes, where the formation of NO_x is primarily driven by thermal reactions (thermal NO_x) and the availability of oxygen. In contrast, the combustion characteristics of wet MSS reveal distinct emission patterns due to the substantial moisture content. Despite the higher levels of water-soluble ammonia present in wet MSS compared to dry MSS, the NO_x emissions from wet MSS combustion generally remain below 200 mg/m^3, suggesting a potential mitigating effect of water on NO_x formation. The moisture content in wet MSS acts as a thermal buffer, absorbing heat and lowering the peak combustion temperatures, which can reduce the formation of NO_x. Furthermore, the water-soluble ammonia can undergo reactions with NO_x in the combustion chamber, contributing to the reduction of NO_x emissions via a selective non-catalytic reduction (SNCR) process. This indicates that the presence of moisture in the MSS plays a significant role in moderating the formation of NO_x, providing an advantage in terms of environmental impact, as compared to dry MSS combustion (Mannina et al. 2024). The dynamics of NO_x emissions from wet and dry MSS highlight the importance of water content in the overall environmental footprint of MSS incineration. The water in wet MSS likely facilitates the conversion of NO to nitrogen through reactions with ammonia, a process that reduces the overall NO_x emissions. This phenomenon is further corroborated by the application of advanced combustion techniques, such as staged air combustion and oxygen dilution, which are designed to optimize the oxygen concentration and temperature profiles in the combustion chamber. These methods have been shown to reduce NO_x emissions by limiting the oxygen available at critical stages of combustion, thereby curtailing thermal NO_x formation. However, the combustion of MSS is not without challenges. One significant issue is the accumulation of ash, which can interfere with combustion efficiency and influence NO_x generation. Arrobas et al. (2024) highlighted that the presence of ash buildup, particularly when semi-dry MSS treated with calcium-based inorganic materials is burned in a fluidized bed system, can exacerbate NO_x emissions. Ash particles can act as thermal barriers, reducing the effective temperature in the combustion zone and hindering the complete combustion of organic matter, thus increasing the potential for NO_x formation. Additionally, the calcium-based additives used for ash management may themselves contribute to the generation of NO_x, as they can alter the local chemical environment in the combustion chamber, complicating emission control strategies. Further advancements in understanding the dynamics of nitrogen emissions during MSS combustion have been made through the development of sophisticated mathematical models. Marias et al. created a model that simulates nitrogen emissions based on various operational parameters, enabling the prediction of the concentrations of different nitrogen compounds (NO, N_2O, NO_2, HCN, and NH_3) at different points within the combustion chamber. This model provides valuable insights into the chemical processes that govern the generation and reduction of nitrogen oxides, offering a robust tool for optimizing combustion conditions and reducing nitrogen emissions during MSS incineration. By simulating the behavior of nitrogen species in the reactor, the model helps identify critical parameters that influence the effectiveness of emission control strategies, such as the temperature, oxygen availability, and the presence of ammonia.

4.3.4.2 Technology for Reducing NO_x Emissions

The strategies used to reduce NO_x emissions from MSWI may be divided into two main groups based on how NO_x emissions are managed in coal combustion. The first strategy focuses on flue gas treatment technologies designed to remove NO_x from the exhaust gases. However, they require careful control of operational parameters to maintain their effectiveness and are often costly to implement (Liu et al. 2012). The second strategy aims to reduce NO_x formation during the combustion process itself. This can be accomplished using technologies like air-staged combustion, which divides the air supply into two stages. The initial stage operates under oxygen-limited conditions, which promotes the formation of compounds like HCN and ammonia (NH_3) rather than NO_x. In the second stage, additional air is introduced to further facilitate combustion, allowing HCN and nitrogen radicals to react and form nitrogen (N_2), thereby lowering NO_x emissions. This method can reduce NO_x emissions by 50–80% when the excess air ratio is properly managed. Other methods, such as low-oxygen dilution combustion, have also shown promise in reducing NO_x emissions. Studies have shown that by optimizing burner design and operational conditions, NO_x emissions can be reduced to below 75 ppm at a lower operating cost compared to SCR techniques. Additionally, co-combustion of MSW with coal stabilizes the combustion process and helps modify the production of contaminants. Research indicates that adding coal improves the conversion rate of nitrogen oxides, particularly in fuels with higher fixed carbon content (Tang et al. 2022). Moreover, a two-step incineration and gasification process has demonstrated an average NO_x concentration of around 220 mg/Nm^3, with high combustion efficiency (Zhu et al. 2015). Reducing NO_x emissions from MSW incineration requires optimizing combustion and co-combustion methods.

4.4 Opportunities and Obstacles

Concerns about possible hazardous material emissions are now one of the main obstacles preventing MSWI from being widely used. Furthermore, lowering the expenses related to cleaning the incineration's flue gases might provide a significant benefit for the technology's future use. Notably, co-combustion improves economic efficiency by eliminating the need for separate incineration equipment for flue gas treatment systems and MSW. Moreover, co-combustion is more advantageous for the environment in certain situations. The resultant ash may be used as a raw material for cement manufacture, and MSW can increase the calorific value of cement kilns (Pan et al. 2019). Improving combustion methods, such as low-oxygen dilution combustion, staged air combustion, and flue gas recirculation, may greatly increase incineration efficiency while lowering emissions. By using conditioners, additives, and catalysts, chemical treatments may also improve the dehydration and combustion efficiency of MSW and reduce emissions from its incineration (Yoshida et al. 2018; Roldán et al. 2020).Sludge drying often uses indirect thermal drying, which offers a number of benefits including reduced exhaust gas emission and the capacity to recycle heating media.

It has been shown that these techniques improve pollution control in MSW incineration. However, prior to broad implementation, more operating condition optimization is necessary to improve efficacy and lower costs. A number of crucial areas should be the focus of future advancements in MSW incineration (Yu et al. 2021). Existing cement kilns, municipal solid waste incinerators, and coal power plants shouldn't see significant reductions in emissions or performance as a result of co-incineration. The co-incineration ratios, elevated emissions, and equipment and technology compatibility should be the main topics of future study. The reaction processes in MSW combustion, the impact of equipment, temperature, and other combustion variables on pollutant production, and methods for reducing emissions at the source should all be highlighted in thorough studies into improving combustion technologies. Furthering MSW incineration also requires investigating more efficient and environmentally acceptable additives and creating substitute thermochemical treatment techniques. Each of these research directions seeks to contribute to cleaner manufacturing processes by lowering the expenses and emissions related to MSW incineration. Ash treatment and pollutant gas management are the two primary issues with MSW incineration. Cutting-edge thermochemical treatment techniques like gasification and pyrolysis have drawn interest because of their positive environmental effects. The solution with the greatest calorific value among pyrolysis products may be produced by pyrolysis in a medium-temperature inert environment and include 30–40% organic matter (Zhou et al. 2020). Rapid pyrolysis at medium temperatures is the focus of certain investigations in order to maximize the output of bio-oil (Abraham et al. 2021). Pyrolysis emits less NO_x, PCDD/Fs, and heavy metals than incineration because of its lower temperatures and oxygen shortage (Linkov et al. 2017). However, the intricacy of the process and the system's economic feasibility are issues with pyrolysis. The pyrolysis of MSW may provide gases, liquids, and solids that can be utilized as biofuels, increasing the both quantity and quality of these valuable goods and making the pyrolysis process more economically viable. The effective production of clean combustible gases is the goal of gasification (Liu et al. 2021). Furthermore, the ash generated during gasification may provide a significant recovery of phosphorus (Li and Feng 2018). For sludge management in the future, resource recovery from sludge must be maximized. Before being widely used, emerging methods for recovering sludge resources, such as acidogenic fermentation, polyhydroxybutyrate synthesis, alginate-like exopolymers, and hydrothermal humification, need to be thoroughly assessed from a life cycle viewpoint. Therefore, estimating the environmental advantages of resource goods is a difficult task.

4.5 Conclusion

Municipal solid waste (MSW) burning may successfully prevent the production of nitrogen oxides (NO_x) by using staged air combustion and low-oxygen dilution combustion. Further investigation is necessary regarding the combustion conditions, particularly the sequential conveyance and distribution of air, as well as the establishment of a uniformly distributed temperature field in low-oxygen dilution combustion phenomena. Calcium compounds along with additional calcium-containing regulators or adsorbents, can effectively immobilize sulphur and reduce sulphur dioxide emissions. The incorporation of chlorine in different forms and techniques significantly influences the distribution of highly volatile heavy metals. The incineration of municipal solid waste necessitates attention to PCDD/PCDFs because of their hazardous characteristics as contaminants. The reduction of PCDD and PCDF emissions can be achieved through the application of nitrogen-containing compounds such as CH_4N_2O, ammonia and hydrogen cynide others. Evaluating the coupling effects of specific chemicals on various pollutants is essential in the subsequent work. The advancement in investigation modern technology has led to the development of processes of treatment like combustion, gasification, and biological reusing materials, which demonstrate significant potential for enhancement.

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