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Optimizing Sludge Incineration for Thermal Energy Recovery: A Sustainable Approach to Industrial Waste Management

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Abstract: This research investigates the effectiveness of incineration as a sustainable solution for converting industrial sludge into thermal energy. A modular sludge incinerator integrating Bubbling Fluidized Bed (BFB) drying with Circulating Fluidized Bed (CFB) combustion is modelled by numerical simulation and validated empirically or experimentally. The system enhances sludge drying efficiency, enabling a seamless transition to combustion, and maximizing energy recovery while minimizing emissions.

Findings show up to 95% sludge volume reduction, effective pathogen destruction, and energy values comparable to low-rank fuels like biomass are possible. Optimized combustion conditions, regulated sludge feeding, air-fuel and return air ratios, sludge recirculation, and controlled temperature profiles enhance efficiency and mitigate Carbon Monoxide (CO), Nitrogen Oxides (NOx), Dioxins, and Furans. Inbuilt advanced flue gas cleaning ensures compliance with environmental standards.

Economically, sludge incineration reduces fossil fuel dependency and operational costs, supporting carbon reduction targets. Environmentally, it minimizes land use, greenhouse gas emissions, and aligns with circular economy principles. Policy measures, financial incentives, and regulatory frameworks are crucial for adoption.

This study bridges gaps in waste-to-energy strategies, providing a scalable, flexible, sustainable model for industrial sludge management. The integrated BFB-CFB incineration system demonstrates a viable pathway for energy recovery, contributing to Sri Lanka's energy transition and sustainable industrial operations.

Keywords: Sludge Incineration, Thermal Energy, Waste-to-Energy, Bubbling Fluidized Bed (BFB), Circulated Fluidized Bed (CFB), Computational Fluid Dynamics (CFD), Industrial Boiler

1. Introduction

Sludge disposal accounts for a significant global challenge due to the increasing amounts of sludge generated by wastewater treatment process in industries, the stringent environmental regulations on its disposal, efforts aiming at the improvements of existing wastewater treatment plant's performance, implementation of advanced treatment facilities, and the growing scarcity of landfill space. The rising costs associated with sludge handling, treatment, transport, and disposal further exacerbate this issue. Simultaneously, the world faces a pressing energy crisis, primarily driven by the depletion of fossil fuel reserves, the volatile cost of fossil fuel energy, and the massive reliance on fossil fuels, which still account for approximately 70-80% of industrial energy requirements.

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The convergence of these two global challenges highlights a unique opportunity to develop circular economic solutions that simultaneously address waste management and energy recovery, particularly through the recovery of energy from sludge. This approach not only addresses fuel sustainability but also supports innovations in waste-to-energy technologies, with a growing emphasis on enhancing combustion and energy conversion efficiency.

Globally, approximately 75 million tons of dry sludge are generated annually as implied by [1]. The management of sludge is a global challenge due to the high cost of its disposal, which can account 187- 362 USD per ton of dry mass and the tightening laws surrounding its agricultural use [2]. This significant growth in sludge generation and related cost emphasize the need for sustainable and innovative disposal solutions. Sludge is a semi-solid residual generated during industrial wastewater treatment, containing both organic and inorganic materials. The presence of Nitrogen (N) and Phosphorus (P) in sludge presents significant environmental, social, and economic challenges. Conventional disposal methods such as landfilling, agricultural land application, composting, and ocean dumping have raised concerns over issues like Greenhouse Gas emissions (GHGs), groundwater contamination, and land degradation. Additionally, the release of Persistent Organic Pollutants (POPs) such as Polychlorinated Biphenyls (PCBs), polycyclic aromatic hydrocarbons, Dioxins, and Furans, which are resistant to photochemical and biological conversions can adversely affect public health, while pathogens and other microbiological pollutants may contribute unpleasant odours.

Traditional disposal methods suffer from high costs, both in capital investment and operational expenditure, which further hinder their long-term economic viability. Public perception of health and safety, and regulatory pressures on environmental pollution, safety, and health play an important role in determining the public and institutional acceptance and implementation of certain disposal methods. Therefore, there is an urgent need for sustainable, efficient, and cost-effective sludge disposal technologies that can meet the growing demand driven by increased sludge volumes from growing Effluent Treatment Plants (ETPs) due to emerging water-based industries, and enhanced regulatory enforcement by the Board of Investments (BOI) and environmental authorities such as the central and provincial environmental authority of Sri Lanka.

Advanced sludge incineration is increasingly gaining attention as a promising technology as highlighted by [3], [4]. Sludge incineration offers several advantages, including the reduction of sludge volume, pathogen destruction, and the potential for heat recovery as confirmed by a recent study [5]. It has been highlighted by the case study [5] that the solution is considered a viable option for both waste management and energy generation in regions such as Europe (34-58%), Japan (70%), and the USA (15%). Sludge incineration has become a key component of the waste disposal infrastructure. Globally, landfilling remains the dominant method for sludge disposal (40%), with incineration accounting for approximately 20%, while composting and land application make up the remainder as stated by United Nations Environment Programme (UNEP). From an economic perspective, incineration can offer a cost-effective solution, with a treatment cost of approximately 25 USD per ton, including energy recovery as stated in [6]. The energy recovered through advanced incineration can help the thermal and electrical autonomy of operation, while achieving the desired flame temperature in an optimized combustion condition, offset disposal costs, reduce Greenhouse Gas (GHG), and other harmful gas emissions and contribute to environmental sustainability.

Thermochemical conversion, such as incineration, generally yields a higher energy output compared to biochemical conversion processes like anaerobic digestion. This is primarily due to the fact that at high temperatures, thermochemical processes can convert all of the chemical energy present in the waste into heat, regardless of whether it is biodegradable or non-biodegradable. In contrast, anaerobic digestion is limited by its ability to digest only biodegradable organic matter, escaping a significant portion of non-biodegradable and refractory materials that cannot be converted into biogas. The report [7] stated that, as a result, thermochemical conversion can generate approximately twice the energy of anaerobic digestion, as the biodegradability of the organic content does not limit it and can utilize the full energy potential of the waste.

However, despite its potential, sludge incineration possesses its inherent challenges. The combustion behaviour of sludge is highly complex, driven by factors such as heat transfer, chemical reaction kinetics and equilibrium limitations, fluid dynamics, and the heterogeneous nature of sludge. Variations in sludge composition, moisture content, and organic material presence can significantly impact the efficiency and consistency of the incineration process. Moreover, the technical complexity of the incineration process, including the need to manage issues like material handling, odour control, corrosion, and emissions, complicates both the design and operation of incineration systems. Additionally, current incineration designs often lack scalability and adaptability, limiting their ability to address the increasing volumes of sludge generated. This gap highlights the need for innovative solutions in the design, operation, monitoring, control, and optimization of sludge incinerators.

Recent advancements in incineration technology, particularly fluidized bed combustion modular systems, offer promising solutions to these challenges. The development of advanced incinerators with features such as fluidized beds, single chamber design with disengagement, hot cyclones, heat exchangers, continuous monitoring, and automatic feedback control mechanisms have improved heat recovery efficiencies by up to 80%. These systems are designed to be scalable, allowing for capacity adjustments based on the varying sludge feed and enabling co-incineration with alternative fuels such as crushed saw dust briquettes or wood chips. However, despite these advancements, there remains a need for further research to optimize the operation of these systems, particularly in terms of energy recovery efficiency, emission control, and the integration of waste characterization processes to ensure optimal performance.

Furthermore, several knowledge gaps exist in the current literature on sludge incineration. These include the need for better energy recovery and valorisation strategies, challenges related to waste characterization and dynamic process control in high-temperature environments, and the lack of comprehensive data on the economic and environmental feasibility of different incineration technologies and alternative sludge management systems. Detailed assessments using a consistent and thorough methodology than existing Life Cycle Analysis (LCA) reports in the literature [8], are needed to assess the economic, environmental, and social feasibility. Therefore, it is also a need for critical application of methodologies, such as advanced Computational Fluid Dynamics (CFD), comprehensive Life Cycle Analysis (LCA), full-scale Techno-economic Analysis (TEA), and integrated Multi-criteria Decision Analysis (MCDA), to assess the social, techno-economic, and environmental impacts of sludge incineration more effectively.

2. Objectives

The primary objective of this paper is to explore sustainable industrial waste management through the optimization of sludge incineration for thermal energy recovery. The paper [9] aims to propose innovative approaches to enhance incinerator design and operation, focusing on key performance parameters such as sludge volume reduction, thermal energy recovery, and emission profile. The optimization of sludge incineration conditions, based on detailed sludge characteristics and dynamic operational parameters, will be examined in this study. Advanced numerical models will be used to predict and optimize the combustion behaviour and energy recovery potential of advanced incinerators.

3. Methods

A comprehensive literature survey was conducted to review existing research on waste management technologies, sludge incineration, and energy recovery technologies. This survey helped identify key gaps in the current body of knowledge, particularly in the optimization of sludge incineration units for energy recovery. Additionally, an evaluation of existing operational units was carried out to understand their performance, challenges, and potential for scaling up.

The predictions of the CFD model developed by [14] for the hydrodynamic of Bubbling Fluidized Bed (BFB) filled with spherical solid particles and subsequent empirical model derived from experimental data show a reasonable agreement with the numerical simulation results of this study. The integrated BFB-CFB reactor developed through CFD modelling is similarly validated, supporting the design of full-scale sludge incineration systems for Sri Lankan ETPs to recover energy from wastewater treatment sludge. Once upgraded, this sludge is considered a viable waste fuel for thermal energy generation. The pilot unit was designed to simulate conditions of full-scale incineration while facilitating the optimization of key parameters for energy recovery.

Thermochemical analysis is performed on representative composite sludge samples collected from the effluent treatment plant to assess the combustion characteristics and potential energy content of the sludge. The analysis included both proximate and ultimate analyses, which provided important data on the chemical composition, moisture content, volatile matter, ash, and carbon content of the sludge. The ash ultimate analysis under oxidative and oxygen-deficient environments is also performed to identify ash elemental composition and ash fusion temperature, which is a critical parameter for the design of the incinerator. The results of these tests were essential for understanding the fuel properties of the sludge and refining the combustion process.

Table 1 presents the proximity analysis of the composite sludge sample, which represents the average composition of the collected sludge, on which this study is based on.

Table 1 - Proximity Analysis of Sludge

Parameter	Value	Unit
Ash	13.8	% by mass
Fixed carbon	17.3	% by mass
Volatile matter	68.9	% by mass
Gross Calorific Value (GCV)	18.5	MJ//kg
Moisture content	67.0	% by mass

Based on this data, the initial dry matter (DM_1) content and final dry matter (DM_2) content of the sludge were determined to be 30% and 90%, respectively. Using these values, the energy recovery efficiency of the proposed incineration model was calculated at 80%. The energy recovery calculations were performed manually using Eq. (1) - (3) below to calculate drying energy (Q_{DE}) in MJ/kg dry matter, energy generation from incineration (Q_{HR}) in MJ/kg dry matter, and balance of energy recovery (Q_{EB}) in MJ/kg dry matter at the steam boiler, respectively. The recovered waste heat depends on the heat recovery efficiency (η), and the Lower Heating Value (LHV) of sludge, which can be predicted from Organic Dry Matter (ODM) and final dry matter (DM_2) as shown in Eq. (2) by case study [10].

$$Q_{DE} = 3.24.(1/DM_1 - 1/DM_2) \quad \ldots(1)$$

$$Q_{HR} = \eta.LHV = \eta.\ [21.6.ODM-17.64.\ (1-DM_2)] \quad \ldots(2)$$

$$Q_{EB} = Q_{HR} - Q_{DE} \quad \ldots(3)$$

The results were used to estimate the average monthly drying energy, energy generation, and the balance of energy recovery through the steam boiler. These calculations also enabled a comparison of the incineration system's performance with conventional coal-based energy generation methods.

Furthermore, the Greenhouse Gas (GHG) emission reductions achieved by the proposed energy recovery system were evaluated. The emissions from the sludge incineration process were compared to those of a coal-based Combined Heat and Power (CHP) plant, which has an average daily coal consumption of 55-65 metric tons. The data shows a significant reduction in GHG emissions from the sludge incineration system, contributing to the management's goal of phasing out coal use by 2026. This aligns with their commitment to the Science-Based Targets Initiative (SBTi) and the broader objective of achieving net-zero carbon emissions by 2050. The sustainability goals of the company, which are also in line with the United Nations' Sustainable Development Goals (SDGs), emphasize reducing the carbon footprint through energy recovery and transitioning away from fossil fuel-based systems.

4. Methodology and Analysis

This study develops a numerical model for sludge incineration enabling optimized analysis, instant, and accurate energy and emission predictions based on sludge characterization and model definition. It is validated either using pilot-scale incinerator measured data, long-term operational records, or other validated model data supported by experts and manufacturers, and statistical analysis.

The model employs a Circulated Fluidized Bed (CFB) combustion system intergraded to a bubbling bed drying with the dual-path mechanism comprising a hot cyclone, return air, and condensate fluidized bed. The combined effects of modular design and CFB enable scalability and waste flexibility based on variations in feed quality. It provides provision for direct combustion and co-combustion with wood chips, wood briquettes, or Refused Derived Fuel (RDF) in the combustion chamber designed for sludge incineration. It ensures self-sustained combustion with consistent flame temperature while energy recovery in a water-wall steam boiler.

It minimizes Particulate Matter (PM), metal, opacity, and gaseous emissions such as CO, NO_x, SO_2, Dioxins, and Furans by optimizing combustion conditions such as time, residence time, and mixing.

Its techno-economics and sustainability are ensured through sludge drying, optimized design, careful material selection, a long lifespan, continuous monitoring, automatic control, and reducing operation costs of incinerator system. Figure 1 presents the feeding, incorporated drying, combustion, energy recovery, and gas cleaning units. The economic feasibility is accessed through cost benefit, capital recovery analysis, and aromatization strategies. The environmental sustainability is accessed through LCA.

4.1 Boundary Conditions, Assumptions, and Numerical Setup

The computational domain represents the integrated BFB-CFB reactor having 0.6 m diameter and 14 m height with inlet and outlet zones considering no-slip wall boundaries. Superficial gas velocity was assigned based on fluidization regimes. Minimum fluidization velocity (~0.06 m/s) and superficial gas velocity (~0.6 m/s) are assigned within the BFB-CFB reactor. Operating pressure was set at 103.3 kPa, and at initial void fraction of 0.6 was assumed for the packed bed zone.

The initial bed height to total CFB height ratio was taken as 1:4. The simulation domain was discretised using a structural mesh with 5×10^{-3} m grid resolution, resulting in approximately

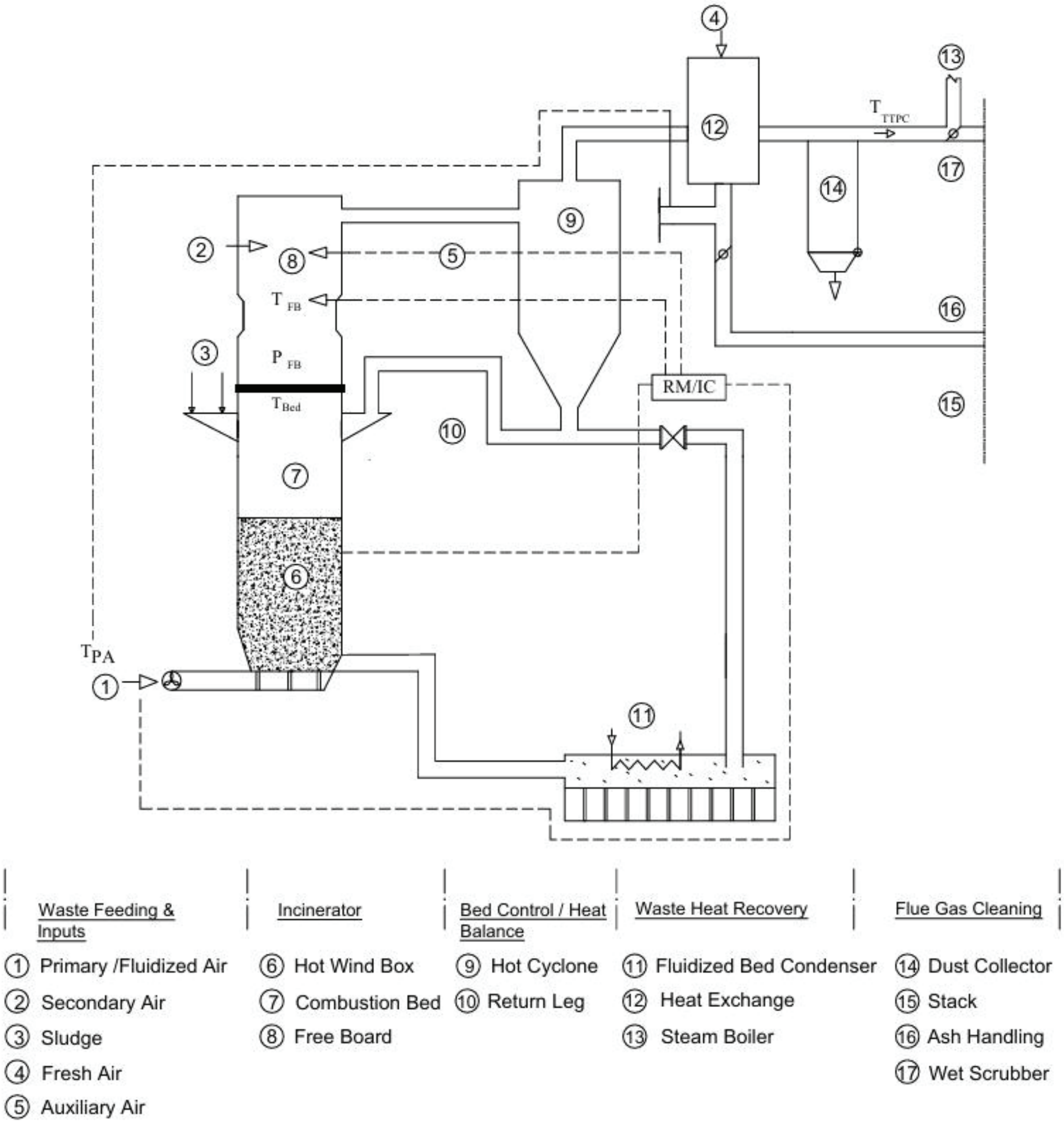

Figure 1 - Schematic Diagram of CFB Incinerator

100,000 control volumes. The two-dimensional (2D) simulations of the fluidized bed during quasi-steady-state conditions were performed. A time step of 0.001 s with 20 iterations per time step was used. The governing equations such as mass conservation and momentum, energy, and species transport were solved at solid and gas phases.

The convergence criteria were set to 0.0001 residual value. Finally, the hydrodynamic behaviour of gas-solid flow was used to estimate energy recovery potential and volume reduction of sludge in the integrated BFB-CFB reactor filled with particle 275 µm in size and 2600 kg/m^3 in density. Temperature boundary conditions include preheated primary air at 300-350^{0}C and incinerator operating within 850-950^{0}C combustion window. A residence time of 2-3 s at 1200^{0}C in the free board zone was ensured to meet complete combustion and Dioxins destruction in line with Sri Lanka's regulatory standards. A schematic flow chart outlining the overall simulation framework is presented in Figure 2.

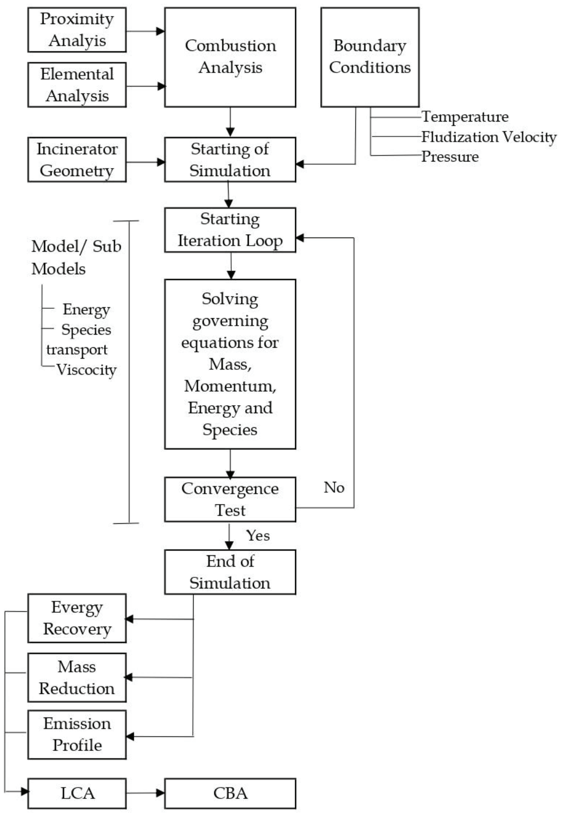

Figure 2 - A Schematic Flow Chart Outlining the Overall Simulation

The Euler-Euler multiphase model assumes spherical, mono sized sludge and bed material within interpenetrating continua. Syamlal-O'Brien model is employed to represent Interphase momentum exchange. The system was treated as adiabatic, and local thermal equilibrium between gas and solid phase was assumed. Turbulence was modelled using k- ε model, and radiation was considered using the Discrete Ordinates (DO) method.

5. Results

The estimated sludge generation on a received basis at 10% Dry Matter (DM) was 3.5 million kg from TJ Lanka ETP in a full-scale study in the year 2024. This sludge undergoes thickening and dewatering processes, including screw pressing, centrifugation, and steam drying, which achieves a final dry matter content of 90% (DM_2). The energy requirements for this sludge drying process are significant, with a total energy consumption of 10,370 GJ for drying and 520 GJ for electricity, respectively. These values are subject to variation depending on the specific drying technology and operational efficiency employed. The specific energy consumption for drying and electricity is 7.2 MJ/kg and 0.36 MJ/kg of dried sludge, respectively. Figure 3 represents the energy balance of incineration.

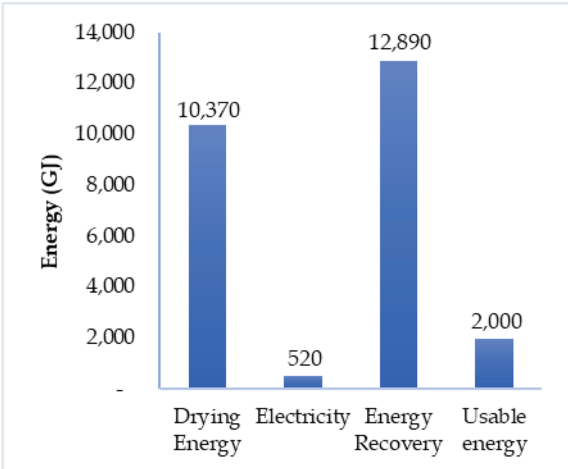

Figure 3 - Energy Consumption and Recovery

The energy recovery potential of the proposed incinerator model is evaluated and found to be 12,890 GJ on an annual basis having an energy value of 8.96 MJ/kg dried sludge. This recovery allows for the generation of 2,000 GJ of usable energy with a net energy value of 1.4 MJ/kg of dried sludge for steam generation, which corresponds to a monthly production of 52,000 kg of steam, assuming a 75% boiler efficiency. This steam generation represents a significant cost-saving opportunity in terms of fuel replacement. Table 2 summarizes the energy recovery potential and steam generation output.

Table 2 - Energy Recovery and Steam Generation

Parameter	Value	Unit
Energy Recovery Potential	12,890	GJ/year
Energy Value of Dried Sludge	8.96	MJ/kg
Usable Energy Generation	2,000	GJ/year
Net Energy for Steam Generation	1.40	MJ/kg dried Sludge
Steam Generation at 1000 kg/hr Sludge Feed Rate	550	kg/h
Boiler Efficiency	75	%

Specifically, the estimated monthly fuel cost saving against coal consumption is approximately 1800 USD.

The simulation results of coupled Euler-Euler multiphase model integrated with Kinetic Theory of Granular Flow (KTGF) at the optimal operating window of 850-950^{0}C were validated against pilot-scale data, including an error analysis, based on average data collection of sludge incineration studies as shown in Table 3 [11] [12].

Table 3 - Simulation Results with Pilot-Scale Experiment Data

Parameter	Simulation Results	Exp./Lit. [1] Data	Error (%)
GCV[2] of Dried Sludge (MJ/kg)	18.5	18.0 ± 2.0	2.70
Recovery Heat Energy (MJ/kg)	8.96	9.0	0.40
Net Usable Energy (MJ/kg)	1.4	1.5	7.10
Boiler Efficiency (%)	75	75	0
Steam Generation(kg/h)	550	589	13.50

Exp./Lit.[1] refers to the Experimental and Literature
GCV[2] refers to Gross Calorific Value

It exhibits good agreement with published data, with relative errors generally below 10%. The recovered heat energy and net usable energy were predicted within 0.4% and 7.1% error, respectively. The steam generation showed a slightly higher deviation, attributed to operational limitations in pilot-plant. These results confirm the robustness and predictive accuracy of the simulation model for sludge incineration systems.

In terms of environmental impact, the proposed incineration system results in a notable reduction in Greenhouse Gas (GHG) emissions. The estimated annual GHG emission reduction is 1.1 million kg of CO_2 equivalent. This reduction aligns with the sustainability objectives of the project, contributing to the reduction of the carbon footprint associated with conventional sludge disposal methods.

In addition to energy recovery and GHG reductions, the proposed system offers substantial financial benefits through avoided costs. These include savings on sludge transportation fees to co-processing plants, such as cement kilns, as well as gate fees. The annual savings from these avoidable costs are estimated at 0.7 million USD, further enhancing the financial feasibility of the proposed incineration system. The cost-benefit analysis shows that the Cost-to-Benefit Ratio (CBR) is greater than 1, and the Net Present Value (NPV) is positive, considering cash flow over the 10-year lifespan of the incinerator. The financial analysis incorporates a discount factor of 12%, Chemical Engineering Plant escalation/De-escalation Cost Index (CEPCI), an exchange rate of 1 USD = LKR 300, and considers 2024 as the base year for monetary evaluations. The financial benefits of the system are summarized in Table 4.

Table 4 - Financial Benefits

Parameter	Value	Unit
Annual Fuel Cost Savings	21,600	USD
Annual savings from Avoided Costs (Transportation and Gate Fees)	700,000	USD
Cost-to-Benefit Ratio (CBR)	2.72	-
Net Present Value (NPV)	2,579,040	USD

The model also predicts a significant reduction in sludge volume, with an anticipated volume reduction of 90-95%, corresponding to a 70-75% mass reduction. This volume reduction is achieved when operating with 40% excess air and a fuel-to-air ratio of 1:8. This result highlights the efficiency of the system in both reducing waste volume and enhancing energy recovery, further demonstrating the sustainability and efficiency of the proposed incineration model. Table 5 illustrates the environmental impact and the system's contribution to waste disposal.

Table 5 - Environmental Impact and Waste Reduction

Parameter	Value	Unit
Annual GHG Emission Reduction	1.1	million kg CO_2-eq
Volume Reduction	90-95	%
Mass Reduction	70-75	%

6. Conclusion

This study demonstrates that sludge incineration for thermal energy recovery can be an effective and sustainable approach for industrial waste management, particularly when the energy transfer requirements and waste generation are located in close proximity. The proposed incineration model, which incorporates a modular and scalable design, offers significant potential for energy recovery and waste reduction in industries with substantial sludge generation, such as wastewater treatment plants and other industrial effluent treatment facilities.

The performance of the proposed system has been validated through various scales of operation, including a pilot-scale unit, laboratory-scale tests, and simulations based on Computational Fluid Dynamics (CFD) predictions. These evaluations, alongside expert opinions from industry practitioners and a comprehensive review of relevant literature, confirm the feasibility of extrapolating the model for industrial application, particularly in systems focused on steam generation. The validation process indicates that the proposed model is capable of delivering consistent performance in terms of energy recovery and emission reduction across different operational scenarios.

However, the achievement of predicted performance levels hinges on continuous monitoring and control of critical operational parameters, such as combustion temperature, airflow rates, and energy output. These factors are essential to ensure optimal energy recovery and minimizing of harmful emissions. The incorporation of advanced monitoring and automated control systems is, therefore, essential for the reliable operation of the incineration unit. By enabling real-time adjustments based on performance data, these systems can enhance the efficiency of both combustion and heat recovery, ensuring that the unit operates at peak efficiency throughout its lifecycle.

In conclusion, the proposed sludge incineration system presents a promising solution for addressing both the challenges of industrial waste disposal and the growing demand for renewable energy sources. By optimizing thermal energy recovery and minimizing environmental impacts, this model contributes to the broader goals of sustainable industrial practices, carbon footprint reduction, and the circular economy.

6.1 Key Takeaways

Key takeaways could be summarised as follows:

- Sludge incineration is a viable solution for industrial waste management, particularly when the waste generation and energy needs are co-located.
- The proposed model, supported by pilot-scale and CFD-based predictions, can be tailored for full-scale industrial applications with a focus on steam generation.
- Continuous monitoring and automatic control of key operational parameters are crucial to achieving the predicted energy recovery and emission reductions.
- The system offers significant environmental and economic benefits, including reduced greenhouse gas emissions and cost savings, by providing an alternative to coal-based energy generation.

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