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Harnessing Heat: A Conceptual Review and Design Proposal for Sensor-Based Two-Chamber Incinerator for Wet Waste Management

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Abstract

Management of waste is one of the major challenges in the contemporary world. As the demand for various products and forms of energy grows rapidly along with the human population, a lot of waste tends to get accumulated in manufacturing plants. It is of utmost importance to make sure that this waste is burnt in a way that is less harmful to the environment. An incinerator is a widely used method to burn waste materials, as it reduces volume and handles hazardous or biomedical waste safely. Yet, conventional incinerators struggle with two major issues, which are wet waste that burns inefficiently and releases high levels of toxin into the environment, and refractory coatings that wear out quickly and make the incinerator inactive. This review looks at how sensors can make incineration smarter and more efficient. We present the idea of a two-chamber detachable incinerator. In the first chamber, a moisture sensor checks how wet the waste is and dries it accordingly. In the second chamber, a temperature sensor keeps combustion at the right level for complete burning. This setup helps cut down on wasted energy and reduces harmful emissions. To deal with the common problem of wall linings wearing out over time, we suggest using detachable panels that can be removed, recoated, and fitted back in, instead of rebuilding the entire chamber. By combining features like real-time sensing, modular construction, and the option to recover solid pellets from the process, this incinerator is not only more efficient but also easier to maintain and more sustainable in the long run.

Keywords
Smart incineration, Waste management, Moisture and temperature sensors, Modular refractory lining, Sustainable combustion.

1. Introduction
Solid waste management is an integral part of the urban framework as it contributes immensely to the protection of the environment and human health. The quantity of solid waste generation has seen a surge globally and this mainly due to the socio-economic shifts such as population density, industrialization, migration, metropolitanization within India. All these factors together have led to the increase in MSW (Municipal Solid Waste) (Meena et al., 2023). Disposal and management of MSW poses a significant challenge to many nations. Especially in densely populated nations, where land is a limited resource, incineration has become a central and indispensable solution for managing high-volume waste streams(Roy et al., 2022). The sheer volume of global waste is a critical environmental concern. In 2018, the world generated around 2 billion tons of municipal solid waste, a number expected to reach up to 3.4 billion tons by 2050. This dramatic escalation in waste production is intensifying atmospheric pollution and putting serious pressure on environmental and public health systems worldwide (Subedi et al., 2025). The research community is facing challenges to find the most feasible technique to convert the urban waste into usable energy and reduce the amount of toxins released into the atmosphere during the process. Thermal treatment technologies have emerged as a

crucial component to convert waste to energy by advocating efficient techniques(Soni et al., 2025). Among other thermal treatment technologies, Incineration has been widely used in many manufacturing plants. Although the concept of incineration is simple, the system offers significant potential for innovation and improvement(Huang et al., 2022). The growing prominence of incineration technology is driven by its ability to significantly reduce the environmental impact of solid waste disposal, making it a key sustainable alternative(Hamidinasab & Nabavi-Pelesaraei, 2025). A conventional Incinerator is a device that uses high temperature to burn various types of waste materials and eliminate pollutants in them. Firstly, it consists of a primary chamber where the waste is initially treated with heat from the burner. The refractory linings on the walls of the incinerator ensure that the chamber is isolated and the waste burns freely. After that, there is a secondary chamber which is used to burn any unburnt exhaust gases from the previous chamber with the addition of air. Finally, the waste exits from an outlet in the form of ash, gas, or heat(Nafees et al., 2021) Through this process, the solid mass of the waste can be reduced by 80–85% and its volume by 95–96%. The extent of reduction depends on the composition of the waste and the recovery of recyclable materials such as metals from the ash. One of the key advantages of incineration is its ability to destroy clinical and certain hazardous wastes through high-temperature combustion(Jahan Khan, 2020).

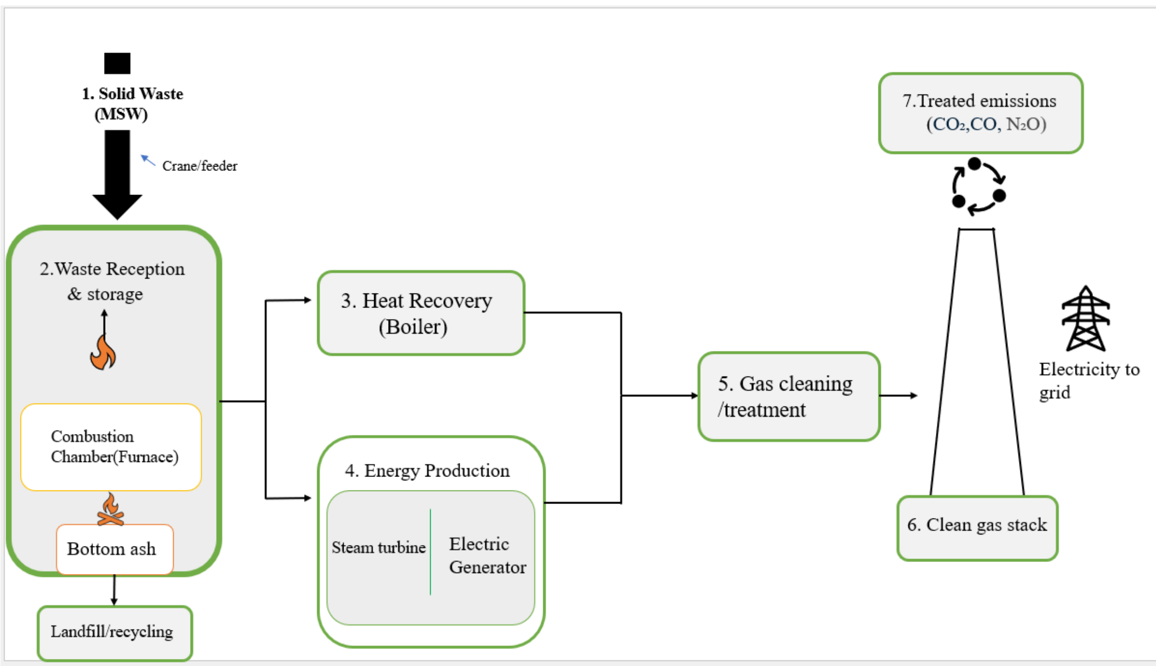

Figure 1. Municipal Solid Waste segregation process

Commercial incineration systems are primarily categorized into rotary kilns, moving grate, and fluidized bed types, all of which operate on the basic principle of thermal combustion to minimize waste. While these technologies can reduce waste volume by up to 90% and effectively neutralize hazardous components, they also present significant drawbacks. The process produces bottom ash and fly ash, often containing toxic substances that require careful handling and disposal in specialized facilities. Additionally, incinerators are expensive to build and operate, contribute to air pollution through CO_2 and other emissions, and generate hazardous by-products. Another critical limitation is their lack of dismantling capability; once the refractory lining deteriorates, the unit becomes unusable, leading to operational and economic challenges.

1.1 Objectives

This is why there is a need for the enhancement of existing incineration technology. This review proposes the idea of developing a modern two-chamber incinerator which is sensor driven and can reduce the amount of hazardous gases that are formed at the end of the process by almost 99.99%. This incinerator will consist of two chambers, the first one equipped with a moisture sensor and the other with a temperature sensor. Once the wet waste enters the first chamber, the moisture sensor checks the level of moisture and sends it to the chamber with the temperature sensor. In this chamber, the temperature sensor adjusts the heat according to the amount of moisture in the waste and it is dried completely. Lastly, the waste exits through an outlet system as a pellet. When burnt, the amount of toxic gases that are emitted from this pellet are close to nil. Additionally, this pellet can be reused as a filter for the next time the incinerator is used. This aspect of the incinerator promotes sustainability and circular economy. One of the main differences in using this incinerator over the conventional one is that this incinerator is designed to be detachable. This is a huge advantage as the refractory coating on the inner walls can be done after the previous one erodes due to continuous usage. This makes the incinerator very efficient and a top prospect to headline the next era of waste management through incineration.

2. Literature Review

2.1 Conventional Incineration Technologies

Incineration has been one of the most widely adopted methods for reducing the bulk amount of municipal solid waste (MSW), especially in cities where land is limited. Systems such as rotary kilns, moving grate furnaces, and fluidized beds are commonly used in practice. Each of these has its own strengths: rotary kilns can handle mixed waste streams, moving grates are reliable for large-scale municipal waste treatment, and fluidized beds provide efficient mixing and stable combustion(Nafees et al., 2021). Despite these advantages, all three suffer from recurring challenges. They are expensive to build and maintain, generate fly ash that requires safe disposal, and struggle to deal effectively with waste that has high moisture content.

2.2 Sensor-assisted Waste Management

With the rise of digital technologies, sensors are beginning to play a major role in waste management practices. In a few energy plants that focus on converting waste to energy, temperature sensors are already being used to track combustion conditions, while moisture sensors are helping to determine how wet the incoming waste is(Vishnu et al., 2022). By feeding this data into control systems, the combustion process can be adjusted in real time, improving efficiency, and reducing emissions. Some modern plants are experimenting with sensor-driven automation, where airflow and burner intensity are fine-tuned automatically as waste properties change(Bayu Wahyudi et al., 2025). Even though widespread adoption is still limited, these efforts show that real-time monitoring can help solve operational drawbacks and environmental impacts.

2.3 Challenges in Handling Wet Waste

Moisture is one of the most difficult obstacles to deal within waste management. Studies have shown that wet waste consumes more energy during combustion because a part of the heat is utilized in evaporating water instead of burning the material itself. This makes the process less efficient and often results in incomplete burning. The consequences for this are higher emissions of harmful gases such as carbon monoxide and dioxins. Conventional incinerators do not have systems that can adapt to these variations, and that is why pre-drying or active moisture monitoring is seen as a promising improvement(Wang et al., 2025).

2.4 Refractory Lining Limitations

The refractory lining is another area where conventional incinerators fall short. These linings are essential to withstand high operating temperatures and protect the outer shell, but they tend to degrade over time due to heat stress, abrasion, and chemical attack. When the lining corrodes, the incinerator must be shut down completely or expensive repairs must be done on it. Most of the current systems are built as fixed units and there is no option to replace only the worn sections (Chen et al., 2015). Therefore, an incinerator with modular or detachable refractory linings which would allow selective replacement of damaged sections and make maintenance much easier.

3. Proposed Conceptual Design: Two-Chamber Detachable Incinerator

3.1 Design Overview

The proposed system comprises of mainly two primary, sequentially connected chambers designed to optimize the waste treatment into a usable form of energy. The first chamber acts as a dedicated pre-processing unit that does the basic function, while the second is optimized for high-temperature combustion. Both the chambers are constructed with detachable refractory panels, allowing for simplified system, cost-effective maintenance. The inner lining of the incinerator is coated with a refractory material to withstand high temperatures and harsh conditions during several critical functions. The entire system is being controlled as a single integrated unit, featuring a continuous sensor-based network for real-time monitoring and control. The proposed design of the **Two-Chamber Detachable Incinerator** addresses common drawbacks by ensuring waste is in the dry state for combustion and simplifying the maintenance of the detachable components. Hence, this design approach enhances the system's adaptability and long-term economic viability.

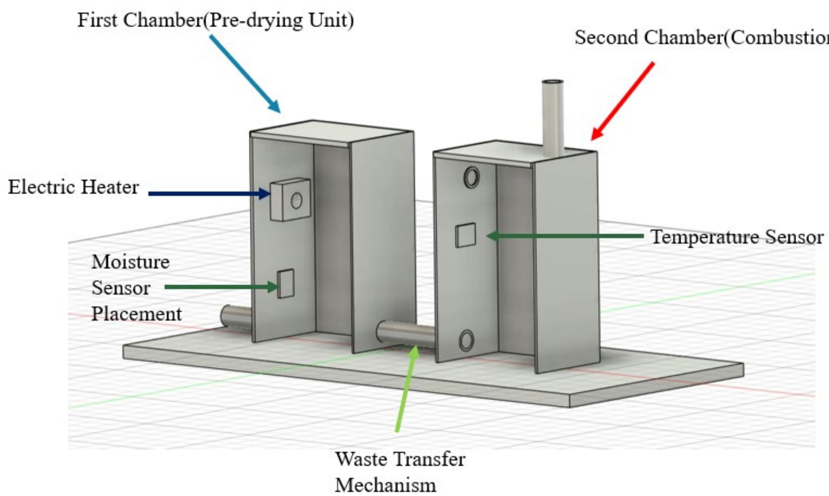

Figure 2. Conceptual 3-D Sectional View of the Two-Chamber Detachable Incinerator

3.2 First Chamber (Pre-drying Unit with Moisture Sensors)

The waste that is collected from the Municipal Solid Waste (MSW) is usually wet, which often leads to incomplete combustion and wasted energy during the incineration process. The chamber is designed in a way to overcome this challenge by undergoing a dedicated pre-drying process with the help of the moisture sensors. By removing the moisture content present in the waste before combustion ensuring a much more complete and stable burn of the waste(Xing et al., 2021). An array of moisture sensors is embedded within the chamber to provide continuous and real-time data on the waste's moisture content. The data that is collected is fed to a central control system, that dynamically adjusts the drying duration and intensity. This pre-treatment step is critical for ensuring consistent furnace performance and complete moisture removal process for the wet waste.

3.3 Second Chamber (Combustion Chamber with Temperature Control)

Following the pre-treatment stage, the dry waste has been obtained and is automatically fed into the second chamber for the thermal treatment. This chamber is specifically optimized to maintain stable, high-precision temperature for a complete and efficient combustion. High-precision temperature sensors are used to provide continuous feedback to the automated control system. This system seamlessly manages the airflow and the waste feed rate ensuring the temperature remains is above its critical threshold temperature in the range of 700 to 850°C. The complete combustion process maintains an optimal temperature for the thermal destruction of volatile organic compounds and other hazardous substances by reducing the formation of pollutants such as carbon monoxide (CO), dioxins, and furans. This systematic approach of the separation and precise control of the combustion process resulting in a cleaner and more reliable system with much better environmental performance comparative to the single-chamber designs(Matee & Manyele, 2015).

3.4 Detachable Refractory Panels

Conventional incinerators face one of the most significant operational and economic drawbacks such as the extensive downtime and increased costs associated with the refractory lining maintenance. The two-chamber design proposal utilizes a modular refractory lining composed of easily detachable panels rather than a single, fixed panel. This efficient design offers a paradigm shift in maintenance practices by allowing us to individually replace any specific panel that shows any sign of failure or wear, it can be replaced easily without requiring to completely shut down the complete system. This kind of specific repairs significantly contribute to reducing the time required for maintenance by minimizing the operational downtime(Obuka, 2018). The cost of making detachable panels is lower than the cost of replacing an individual panel. This design innovation improves the economic viability by reducing the maintenance costs and lost revenue from non-operation.

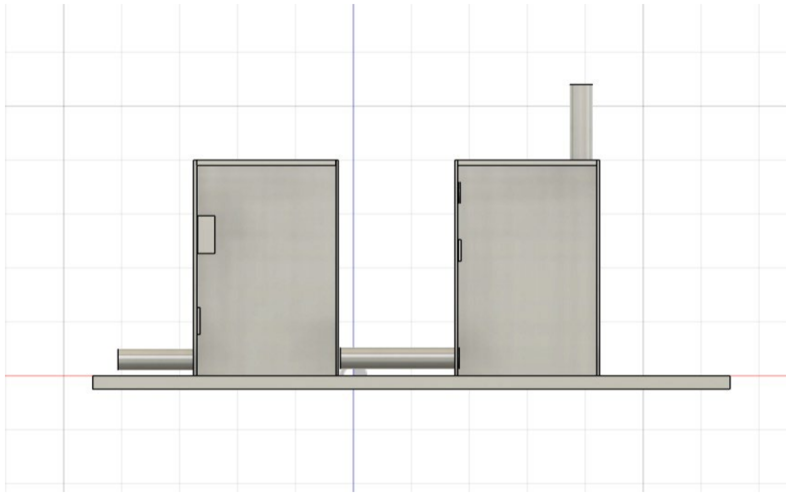

Figure 3. External View of the Proposed Two-Chamber System with Interconnecting Pipe

3.5 Energy Recovery and By-product Utilization

An important aspect of the proposed two-chamber detachable incinerator is its ability to not only reduce waste volume but also to recover useful by-products that can be fed back into the energy cycle or other industrial applications. Conventional systems often let this potential go unused, but the proposed design aims to extract additional value through two main pathways: solid pellet recovery and heat recovery.

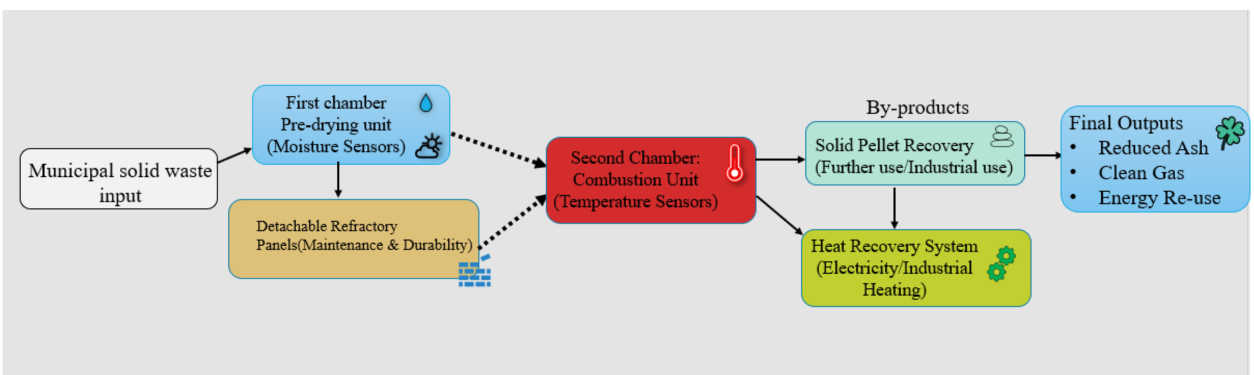

Figure 3. Process Flow Diagram of the Proposed Two-Chamber Detachable Incinerator

3.5.1 Solid Pellet Recovery

During the drying and combustion stages, a fraction of the waste can be processed into dense, carbon-rich pellets rather than being released solely as ash. These pellets formed under high-temperature conditions; hence they are structurally stable and possess adsorptive properties that allow them to be reused within the system. Specifically, they can serve as a filtration medium during consecutive combustion cycles and help in capturing residual particulates and toxins. Apart from internal reuse, such pellets have potential applications as absorbents in wastewater treatment, as fillers in construction materials, or even as a fuel source in compatible systems. This reuse not only enhances sustainability but also contributes to a circular economy model by turning waste into a secondary resource.

3.5.2 Heat Recovery

The incineration process essentially generates large amounts of thermal energy. In the proposed design, this heat is captured through integrated heat exchangers located along the gas outlet stream. The recovered thermal energy can be utilized in two ways:

- Electricity Generation: By driving a steam turbine or an organic Rankine cycle (ORC) system, the recovered heat can be converted into electricity. This makes the incinerator partially self-sustaining and reduces its external energy requirements.

- Industrial or District Heating Applications: The captured heat can also be utilized in nearby industrial processes like pre-heating in manufacturing plants or in urban heating networks. This maximizes the overall energy efficiency of the system and minimizes dependence on conventional fossil fuels(Yuan et al., 2025).

The proposed incinerator design transforms waste treatment from a purely destructive process into an energy-recovery system by combining solid by-product reuse with thermal energy recovery. This dual focus not only reduces environmental impact but also improves the economic status of the system by cost savings.

4. Comparative Analysis

4.1 Conventional vs Proposed System

To clearly understand the improvements offered by our design, it's helpful to look at how it compares with a conventional incinerator. Traditional systems have been around for many years and work well, but they come with issues like poor handling of wet waste, incomplete burning, high emissions, and high repair costs when the refractory lining wears out. Our proposed two-chamber incinerator takes a different approach by adding sensors for moisture and temperature control, detachable panels for easier maintenance, and using methods to recover both heat and useful by-products. The table below shows a comparison of the two incinerator systems. This makes it easier to see the differences in performance, efficiency, and sustainability.

Table 1: Comparative Analysis of Conventional vs. Proposed Two-Chamber Detachable Incinerator

Feature	Conventional Incinerators	Proposed Two-Chamber Detachable Incinerator
Waste Handling	Limited ability to process wet waste; requires pre-segregation.	Moisture sensor & pre-drying chamber enable effective handling of wet waste.
Combustion Control	Fixed combustion process; inefficient with variable waste.	Real-time temperature sensors ensure complete combustion.
Energy Efficiency	High fuel consumption due to wet waste and incomplete burning.	Pre-drying and optimized combustion reduce energy loss.
Emission Levels	Produces toxic gases (CO, dioxins, furans).	Controlled combustion reduces harmful emissions up to 99.99%.
Maintenance	Fixed refractory lining; once corroded, unit must be shut down.	Detachable refractory panels allow quick replacement and reduced downtime.
By-product Recovery	Minimal resource recovery; ash disposal is challenging.	Solid pellet recovery for reuse as filters or secondary fuel.
Heat Recovery	Limited; not optimized for reuse.	Integrated heat recovery for electricity or industrial heating.
Sustainability	Linear use (burn → ash disposal).	Circular economy approach: reusable pellets + modular design.

Economic Viability	High operational and maintenance costs.	Cost-effective due to modularity, reduced downtime, and energy recovery.

4.2 Integration of AI and IoT

The proposed two-chamber incinerator can be made even more efficient by adding Artificial Intelligence (AI) and Internet of Things (IoT) features. At present, the system uses moisture and temperature sensors mainly for monitoring and control. If these sensors are connected through an IoT network, the data they collect can be shared in real time to a computer or cloud-based dashboard. This would allow operators to see what is happening inside both chambers, such as temperature changes, gas flow, or drying rates. This will not need anyone to be physically near the incinerator. Having this kind of feature helps to react quickly if something unusual happens during combustion or drying.

AI can take this one step further. When the data from the sensors are stored and analyzed, AI algorithms can start learning patterns over time. For example, how different types of waste burn or how the system behaves under certain moisture levels. Based on that learning, AI can automatically adjust parameters such as air supply, burner intensity, and drying duration. This would make the combustion process smoother and more balanced, even if the waste varies in composition. It would also reduce human error and the need for constant supervision.

Another important advantage is predictive maintenance. Normally, operators find out about problems like refractory wear or uneven heat only after they become serious. With AI and IoT, the system could detect small changes in sensor readings that signal early signs of damage or clogging. It can then alert the operator before the issue grows, saving time and repair costs. These alerts can also help plan maintenance schedules more efficiently and keep the incinerator running longer without interruptions.

Overall, connecting the incinerator through IoT and adding AI control would turn it from a semi-automatic setup into a smart, self-learning system. It would not only help maintain ideal combustion conditions but also improve safety and reliability. In the long run, this kind of digital integration fits perfectly with the ideas of Industry 4.0 and smart waste management, where technology is used to make systems more sustainable and less dependent on manual control.

4.3 Comparative Case Study: Handling of Wet Biomedical Cotton

To see how the two systems work in practice, let us take a simple but common example: blood-soaked cotton waste coming out of a hospital. This type of waste is classified as biomedical and is usually sent to treatment plants for incineration. The cotton is highly infectious and since it is wet, it is one of the most difficult wastes to burn properly.

1) Conventional Incinerator

If this wet cotton is put straight into a standard incinerator, the first problem is the moisture. A large part of the heat goes into drying the cotton instead of burning it. As a result, the cotton does not burn completely, and thick smoke with a strong odor is released. Harmful gases like carbon monoxide and other toxic compounds also escape. To keep the chamber hot enough, more fuel has to be used and this adds to the running cost. The end result is half-burnt ash mixed with residues that still need to be handled carefully. Over time, this kind of waste also damages the refractory lining inside the chamber, which will lead to more frequent and expensive repairs.

2) Proposed Incinerator

Now, if the same cotton goes into the proposed two-chamber incinerator, the process is different. The waste first enters the drying chamber. Sensors check the level of moisture and make sure enough heat is applied to remove most of the water. Once dried, the cotton is moved into the main burning chamber. Here, the temperature is kept steady with the help of sensors and the waste burns fully and cleanly. Instead of heavy smoke, the exhaust gases are lighter and safer. The burning process produces uniform pellets, which can be collected and reused for energy recovery. If the lining inside the chamber wears out, only the damaged panel needs to be changed, instead of repairing the entire unit.

From this example, it becomes clear that the old system struggles with wet waste as it gives poor results and higher costs. The proposed system, on the other hand, manages the same waste in a cleaner and more controlled way. For hospitals and treatment plants, this will ensure safer handling of biomedical waste, lower fuel use, and less trouble with maintenance.

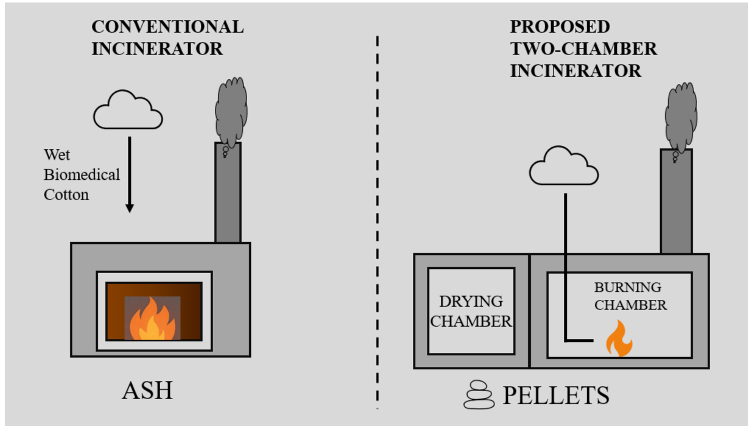

Figure 4. Comparative Schematic of Single-Stage Combustion (Conventional) vs. Optimized Two-Chamber System for Resource Recovery

5. Challenges and Future Scope

The proposed two-chamber, sensor-assisted incinerator offers a promising approach to improving waste drying and combustion efficiency, but several challenges remain. One of the main hurdles is the initial setup cost. Installing moisture and temperature sensors, along with modular refractory linings, can make the system more expensive than conventional incinerators. Operationally, handling waste with varying moisture content and composition can be challenging. Very wet or heterogeneous waste may require longer drying times and this can affect the overall efficiency of the system. Additionally, sensors must remain accurate under high temperatures, humidity, and dusty conditions, which will require regular calibration and maintenance. The modular linings and movable components also need routine inspection to prevent downtime and ensure safe operation.

Despite these challenges, the system has considerable potential for further development. The first chamber already benefits from the heat generated in the second chamber, which reduces energy consumption, but there is room for optimization. Advanced automation could allow the system to adjust drying time and combustion parameters in real-time based on sensor feedback. This will improve efficiency and consistency. The modular design also offers flexibility, making it possible to scale the system for different types of waste such as waste from municipal, hospital, and industrial sources. Incorporating improved emission-control technologies, such as scrubbers or catalytic converters could further reduce pollutants and make the system safer for the environment. Moreover, IoT-based monitoring and predictive maintenance could allow operators to track performance remotely and anticipate issues before they become critical. Overall, though the system is not without its challenges, its design provides ample opportunities for future research and technological enhancement, potentially making waste management safer, more efficient, and more sustainable.

6. Conclusion

Waste management remains a pressing challenge in urban development, with incineration still playing a crucial role in reducing the volume of municipal and hazardous waste. Despite its widespread use, conventional incineration systems exhibit several limitations that hinder efficiency and sustainability. High moisture content in waste streams reduces combustion efficiency and increases pollutant emissions, while degradation of refractory linings necessitates costly shutdowns for repair or replacement. These operational drawbacks compromise both environmental performance and economic viability.

This review examines a conceptual design for a dual-chamber incinerator that integrates modular construction with sensor-driven process control. The primary chamber incorporates moisture sensors to facilitate pre-drying of incoming waste, thereby enhancing combustion readiness. The secondary chamber employs temperature sensors to maintain optimal thermal conditions for complete and efficient burning. Together, these features aim to achieve cleaner combustion, lower emissions, and improved energy recovery. In addition, the proposed use of detachable

refractory panels enables targeted maintenance, allowing selective replacement of damaged components rather than full structural overhauls, thereby minimizing downtime and operational costs.
Although the proposed design remains at the conceptual stage and requires experimental validation, it demonstrates the potential of combining sensor technologies with modular engineering to overcome persistent challenges in incineration. With further development, such systems could advance waste-to-energy applications by offering greater reliability, operational flexibility, and long-term sustainability.

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