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Development and Performance Evaluation of a Low-cost Incinerator for Biomedical Waste Treatment for Rural Areas in Rajasthan

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Abstract

Biomedical waste management in rural areas presents significant challenges due to the high costs of transportation and the lack of on-site treatment facilities. To address these issues, a low-cost incinerator specifically designed for biomedical waste management and disposal in rural settings has been developed. This incinerator is engineered to minimize air pollution, employing a series of advanced filter media that convert airborne pollutants into water. Water samples derived from the most effective filter media were analyzed which revealed a substantial reduction in heavy metal content. These findings contribute valuable insights to the field of environmental engineering, particularly in the sustainable management of biomedical waste in underserved regions.

Keywords: *Biomedical Waste, Heavy Metals, Incinerator.*

Introduction

Biomedical waste management is a pivotal aspect of public health and environmental protection, encompassing any refuse generated from the processes of diagnosing, treating, or immunizing humans and animals, as well as from related research activities [1]. This category of waste includes materials produced within healthcare facilities that possess the potential to adversely affect human health or the environment if not properly disposed of. Typically deemed infectious, such waste can transmit various pathogenic agents, posing significant risks through multiple transmission pathways [1, 2].

Effective management of biomedical waste is essential to mitigate these risks. However, numerous studies have highlighted substantial gaps and challenges in waste-handling practices across different regions and settings. For instance, in developing countries like Tanzania, Botswana, and Turkey, improper handling and disposal practices are prevalent due to inadequate regulations, lack of proper infrastructure, and insufficient training [3–5]. These deficiencies not only elevate public health risks but also contribute to environmental degradation.

Furthermore, the knowledge and awareness among healthcare personnel regarding biomedical waste management are often inadequate. Research indicates that while awareness of biomedical waste segregation exists, comprehensive understanding and proper implementation of handling protocols are lacking [6–8]. Studies emphasize the necessity of continuous education and training initiatives to bridge these gaps and ensure effective waste management practices [9–11].

Additionally, environmental concerns extend beyond direct health risks. The improper disposal of hazardous materials, such as heavy metals and bottom ash from incinerators, poses significant environmental threats, underscoring the need for improved waste treatment and disposal strategies [12, 13].

The Bio-medical Waste Management Rules, 2016 categorize biomedical waste into four distinct colour-coded categories to ensure proper segregation, treatment, and disposal.

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Yellow category waste includes human and animal anatomical waste, soiled waste, expired or discarded medicines, chemical waste, and microbiological waste, requiring incineration or deep burial. Red category waste consists of contaminated recyclable waste such as tubing, bottles, and gloves, which must be autoclaved or microwaved before recycling. White (Translucent) category waste covers waste sharps like needles and scalpels, which should be sterilized and shredded to prevent injury. Lastly, the blue category includes glassware and metallic body implants, which must be disinfected or autoclaved before recycling. These categories ensure that biomedical waste is handled in a manner that minimizes environmental impact and reduces risks to public health [14].

The primary objective of this research is to construct a low-cost incinerator that adheres to the basic requirements for the disposal of yellow-category biomedical waste, as outlined in the Bio-medical Waste Management Rules, 2016. By focusing on essential compliance rather than full adherence to costly standards, the research aims to create an affordable solution for rural areas where high construction and maintenance costs are prohibitive. Additionally, the research seeks to assess the effectiveness of this incinerator in mitigating the risks associated with improper disposal of biomedical waste in these regions. By ensuring that the incinerator can safely handle and reduce the volume of hazardous waste, the study aims to provide a viable waste management solution that addresses the unique challenges faced in rural areas.

Materials and Methods

Commonly available materials like steel drums, PVC pipes, bricks, cow dung, black soil, red soil filter media etc. have been used for the construction of the incinerator.

The low-cost incinerator is an essential tool for managing biomedical waste in rural areas, where traditional waste disposal methods may be limited. This section details the key components of the incinerator—combustion chamber, wet scrubber, and disinfection unit—and explains how they work together to ensure safe and efficient waste disposal in resource-constrained settings as shown in Figure 1.

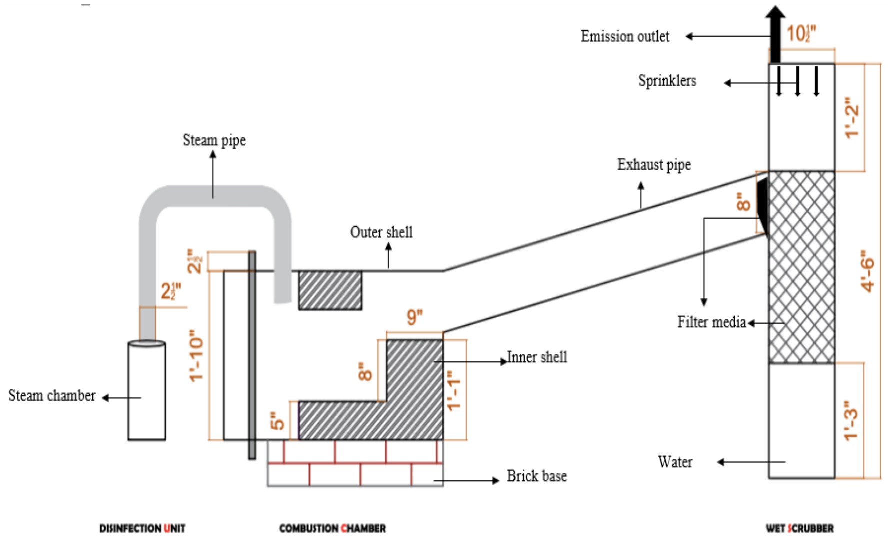

Figure 1. Layout and Components of Incinerator

1. Combustion Chamber: The combustion chamber is the core component of the incinerator, where waste materials undergo thermal degradation. Constructed from a steel drum with reinforced walls for enhanced durability, the chamber's interior is lined with a composite mixture of black soil, red soil, cow dung, and bricks. The black soil, rich in clay, aids in moisture retention and provides fire protection. Red soil contributes additional fire resistance due to its iron oxide content, while cow dung acts as a binding agent and emits gases that help suppress flames. Bricks, known for their high-temperature tolerance, further enhance the fire resistance of the chamber. This construction ensures that the combustion chamber is robust, heat-resistant, and capable of sustaining high-temperature operations during waste incineration.

2. Wet Scrubber: The wet scrubber is essential for the removal of pollutants from the flue gases generated during combustion. It is typically constructed from a steel drum with ribbed outer walls to provide structural rigidity. Inside, brass misting nozzles distribute water uniformly, aiding in the effective capture of particulate matter. The system is equipped with a pressure pump to maintain consistent water flow, ensuring optimal operation. The scrubber incorporates honeycomb filter pads, which provide a large surface area for trapping particles, and grass filter pads, which serve as natural filtration media, absorbing and removing contaminants from the gas stream. The wet scrubber effectively reduces the emission of harmful substances, ensuring cleaner exhaust gases.

3. Disinfection Unit: The disinfection unit is responsible for the neutralization of any remaining hazardous microorganisms in the incinerator's by-products. The unit is constructed with a corrosion-resistant containment structure designed to securely hold chlorine, a common disinfectant. A dosing system ensures precise measurement and controlled release of chlorine, while a mixing mechanism guarantees uniform distribution across the waste stream. To enhance safety, the unit is equipped with ventilation systems and emergency shut-off valves, protecting operators from potential hazards. This disinfection process ensures that all emissions and residuals meet environmental safety standards before being released.

Working Principle: The incinerator operates through a multi-stage process designed to efficiently and safely manage waste. Initially, waste materials are subjected to high temperatures in the combustion chamber, where they are reduced to ash and flue gases. These gases then pass through the wet scrubber, where pollutants are effectively removed. Finally, the disinfection unit neutralizes any residual hazardous microorganisms, ensuring that the incinerator's emissions and by-products are environmentally safe. This systematic approach integrates thermal treatment, pollutant removal, and microbial disinfection, offering a comprehensive solution for waste management. Individual units and combinations of developed incinerators are shown in Figure 2.

Figure 2. Different Units of Low-cost Incinerator

Combustion Efficiency: The efficiency can be estimated using the formula:

$$\text{Combustion Efficiency } C.E. = \left(\frac{\%CO_2}{\%CO_2 + \%CO}\right) \times 100$$

High combustion efficiency indicates effective oxidation of waste material, with most carbon being converted to CO_2. According to the Biomedical Waste Management Rules 2016; combustion efficiency should not be less than 99 %.

Sample Collection: Yellow category biomedical waste was collected from a healthcare facility in Kota, Rajasthan, and incinerated using the designed incinerator. The resulting emissions were treated with various wet scrubber configurations, each using different absorbents—plain water, sodium bicarbonate, sodium hydroxide, activated carbon, and a combination of these—to assess their effectiveness in capturing and neutralizing pollutants. Emission samples were then collected post-treatment for analysis, with the primary focus on determining the most effective scrubber configuration for minimizing pollutant levels. The best-performing sample, based on its pollutant reduction capabilities, was further analysed for heavy metal concentrations, providing insights into the environmental impact of the incineration process and the efficacy of the air pollution control measures implemented. Different combination of samples was utilized for analysis and performance evaluation.

Sample Descriptions

Sample A: This represents the baseline scenario where biomedical waste was incinerated in an open environment without any air pollution control measures. This sample serves as a reference point, illustrating the level of emissions when no treatment is applied.

Sample B: Indicates the treatment of emissions using a plain wet scrubber. This setup is designed to assess the basic effectiveness of a wet scrubber in reducing the concentration of pollutants, particularly focusing on the removal of particulate matter and soluble gases.

Sample C: In this sample, the wet scrubber employed sodium bicarbonate as an absorbent. Sodium bicarbonate was chosen for its ability to neutralize acidic components within the emissions, such as sulfur dioxide (SO_2) and hydrogen chloride (HCl), thereby reducing the overall acidity of the emissions.

Sample D: This sample utilized sodium hydroxide as the absorbent in the wet scrubber. Sodium hydroxide, a strong alkaline substance, was selected for its capacity to neutralize a broader range of acidic pollutants, making it an ideal candidate for reducing highly acidic emissions.

Sample E: In this configuration, activated carbon was used as the absorbent within the wet scrubber. Activated carbon is renowned for its high surface area and strong adsorption properties, particularly effective in capturing organic pollutants and volatile organic compounds (VOCs) from the emissions.

Sample F: This sample represents a comprehensive treatment strategy where a mixture of sodium bicarbonate, sodium hydroxide, and activated carbon was used in the wet scrubber. This combination aimed to maximize the capture and neutralization of a wide spectrum of pollutants, leveraging the strengths of each absorbent to achieve superior emission control.

Result and Discussion

This study outlines the subsequent findings, elaborated upon in this section. An evaluation was conducted to compare the extent of gases from the biomedical incinerator. These sectors encompass comparison of different samples from the biomedical incinerator on the bases of carbon dioxide, carbon monoxide and hydrocarbon.

Combustion Efficiency

The combustion efficiency was calculated by the average data of carbon monoxide (CO) and carbon dioxide (CO_2). The average concentration of CO and CO_2 are shown in Table 1.

Table 1. Average Concentration of CO and CO_2 of Various Samples

Sample	**A**	**B**	**C**	**D**	**E**	**F**
CO (in %)	0.06	0.06	0.06	0.03	0.01	0.01
CO_2 (in %)	1.48	1.47	1.03	1.4	0.77	0.5
Combustion efficiency	96	96	94	97	98	98

Table 1 shows that samples E and F have the highest combustion efficiency of 98%, followed by sample D at 97%. Samples A and B both have a combustion efficiency of 96%, while sample C has the lowest 94%.

Pollutant Removal Efficiency

Pollutant removal efficiency in a non-fueled biomedical waste incinerator refers to the capability of the incinerator to effectively capture and reduce harmful emissions and pollutants generated during the combustion process. This efficiency is crucial for ensuring that the incinerator operates within environmental standards and minimizes its impact on air quality.

A graph shown in Figure 3**,** illustrates the concentration of CO_2 over time in seconds for all the samples. This graph clearly shows a visual comparison of how the different absorbents (sodium bicarbonate, sodium hydroxide, activated carbon and their mixture) impact CO_2 emissions during the scrubbing process. By plotting the CO_2 concentration on the y-axis and time on the x-axis, the graph shows the effectiveness of each sample in reducing CO_2 emissions over the specified period, highlighting the superior performance of sample F with consistent performance.

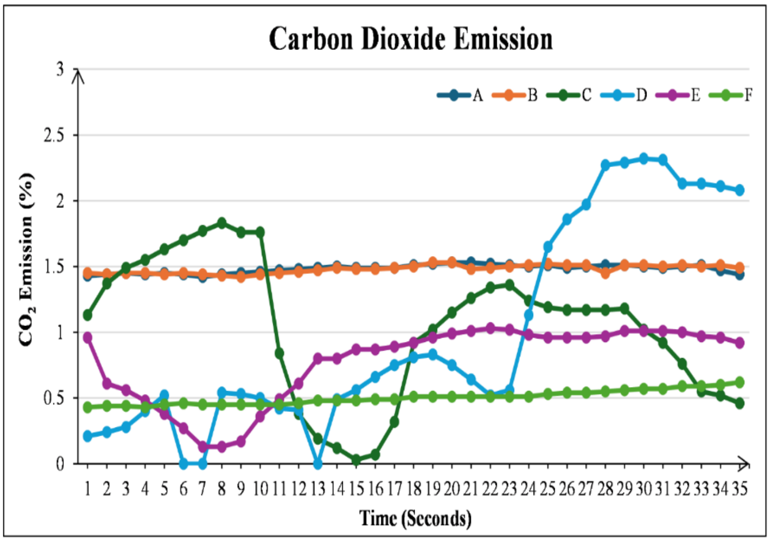

Figure 3. Time Graph of Monitoring of CO_2 of Different Samples

Figure 3 describes that the concentration of *CO_2* gradually decreases as the wet scrubber is introduced, showcasing the efficacy of different absorbents in the scrubbing process. The effectiveness of the CO_2 treatments across different samples can be evaluated by calculating the average CO_2 concentration for each sample. Sample F exhibits the lowest average CO_2 concentration, with an average value of approximately 0.49, indicating that this sample underwent the most effective treatment for reducing CO_2 levels. Following sample F, sample D has an average CO_2 concentration of around 0.89, suggesting it was also treated effectively, though not as efficiently as sample F.

Sample A and sample B show moderately low average CO_2 values of approximately 1.48 and 1.48, respectively, reflecting a decent level of treatment effectiveness. However, Samples C and E exhibit higher average CO_2 concentrations, with averages of approximately 1.17 and 0.82, respectively, indicating that the treatments applied to these samples were less effective in reducing CO_2 compared to the others.

As shown in Figure 4, sample F, with the lowest average CO_2 value of 0.49, underwent the most effective treatment, followed by sample D with an average of 0.89. Samples C and E, with higher averages of 1.17 and 0.82, respectively, appear to have been treated less effectively. It can be concluded that sample F demonstrates the highest efficiency among all the samples.

The data indicates that the wet scrubber using a mixture of sodium bicarbonate, sodium hydroxide, and activated carbon (sample F) is more effective in reducing CO_2 emissions compared to the scrubbers using each chemical individually (samples C, D, and E). This suggests that the combination of these absorbents enhances the overall scrubbing performance, resulting in significantly lower CO_2 emissions and more efficient pollution control.

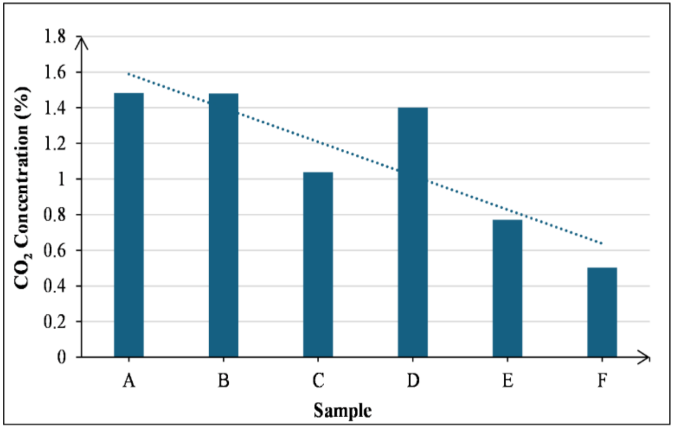

Figure 4. Average of CO_2 Effluent from the Different Samples

The presence of CO_2 (carbon dioxide) in the fumes from a biomedical incinerator primarily indicates the combustion of carbon-containing materials. CO_2 is a natural byproduct of the complete oxidation of organic compounds present in biomedical waste, such as plastics, paper and other carbon-based substances.

The presence of CO_2 in the fumes is a key indicator of the combustion process's efficiency and completeness, as well as a factor in evaluating the environmental footprint of biomedical waste incineration.

Figure 5 describes as the wet scrubber is introduced into the system, there is a gradual decrease in the concentration of *CO*. This decline is facilitated by the incorporation of various chemical agents. Specifically, sodium bicarbonate (sample C), sodium hydroxide (sample D), activated carbon (sample E), and a combination of all these substances (sample F) play crucial roles in the mitigation process.

Based on the observed data for carbon monoxide (CO) concentrations across various samples, the effectiveness of the treatments can be evaluated by calculating the average CO concentration for each sample. Lower average CO values indicate more effective treatment.

Sample F exhibits the lowest average CO concentration, with an average value of approximately 0.015, suggesting that this sample underwent the most effective treatment for reducing CO levels. Following sample F, sample E shows an average CO concentration of approximately 0.017, indicating that it was also treated effectively, though not as efficiently as sample F.

Samples A, B, and C have slightly higher average CO values of around 0.067 each, reflecting a moderate level of treatment effectiveness. Sample D, however, shows a relatively higher average CO concentration of approximately 0.031, particularly rising towards the later periods, suggesting that the treatment applied to sample D was less effective in reducing CO compared to the others.

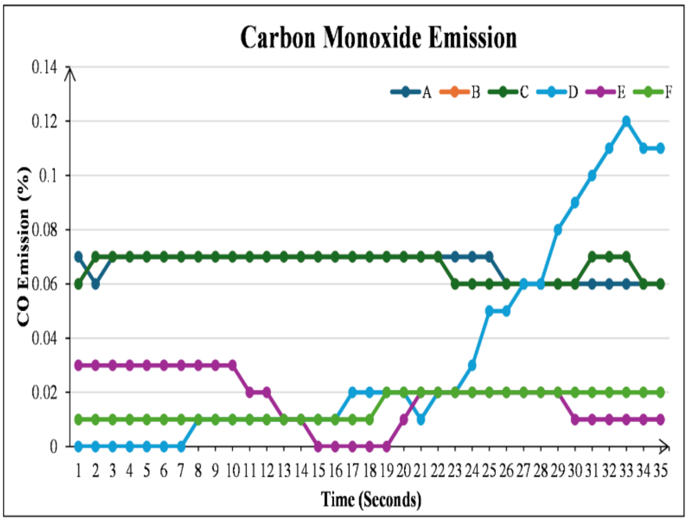

Figure 5. Time Graph of Monitoring of CO of Different Samples

As shown in Figure 6, sample F, with the lowest average CO value of 0.015, underwent the most effective treatment, followed by sample E with an average of 0.017. Samples A, B, and C show moderate treatment effectiveness with averages of 0.067 each, while sample D appears to have been treated less effectively, with an average CO concentration of 0.031.

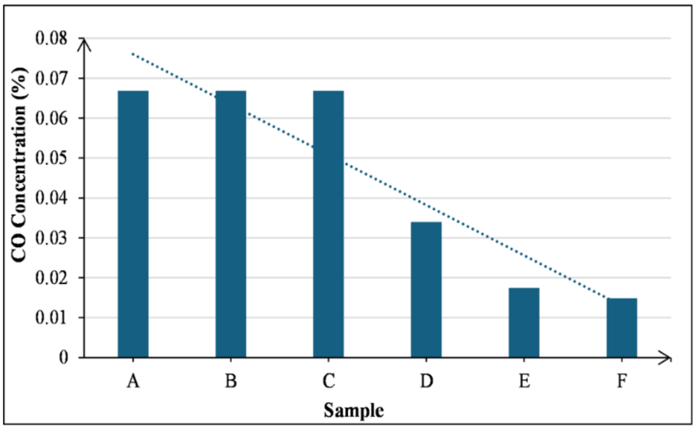

Figure 6. Average of CO Effluent from the Different Samples

Figure 7 describes the concentration of *HC* gradually decreases as the wet scrubber is introduced, showcasing the efficacy of different absorbents in the scrubbing process. Based on the observed data for hydrocarbon concentrations across various samples, the effectiveness of the treatments can be evaluated by calculating the average hydrocarbon concentration for each sample. Sample F exhibits the lowest average hydrocarbon concentration at approximately 0.143, indicating that it underwent the most effective treatment for reducing hydrocarbon levels. Following sample F, sample E shows a slightly higher average concentration of around 0.218, suggesting that it was also treated effectively but not as efficiently as sample F. Sample D has an average hydrocarbon value of approximately 0.266, reflecting moderate treatment effectiveness. In contrast, samples C, B, and A have higher average concentrations of approximately 0.742, 0.747, and 0.953, respectively, indicating that these samples received less effective treatments.

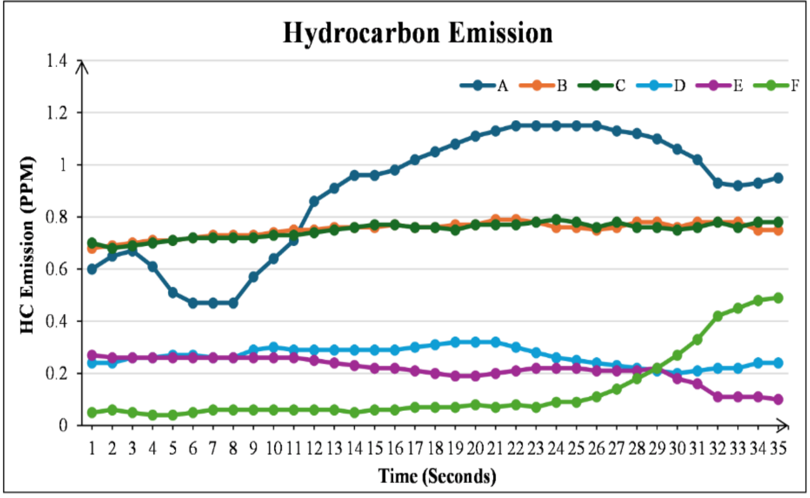

Figure 7. Time Graph of Monitoring of HC of Different Samples

Overall, sample F, with the lowest average hydrocarbon concentration, demonstrates the best treatment efficacy, while samples C, B, and A show less effective treatment as shown in Figure 8.

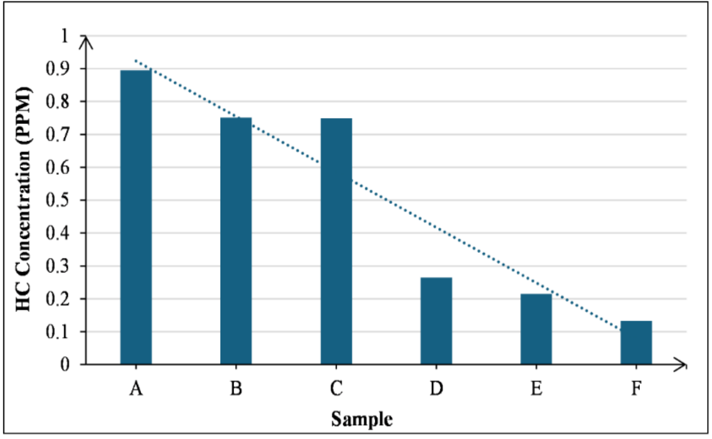

Figure 8. Average of HC Effluent from the Different Samples

Analysis of Wastewater Obtained from Sample F

In this study, the focus is on evaluating the effectiveness of a biomedical incinerator. For this purpose, a single, specially prepared sample was used, consisting of a blend of activated carbon, sodium bicarbonate, and sodium hydroxide. This sample was processed through a two-filter wet scrubber system designed to maximize its efficiency in treating the incinerator's emissions. The specific combination of chemicals and the specialized filtration setup highlights the complexity and high cost involved in achieving precise analytical results.

The following results are obtained from the analysis of Sample F and are shown in Table 2.

Table 2. Removal of Heavy Metals from Wastewater

S. No.	Test Parameter	Result (ppm)
1	*Hg*	0
2	*Ni*	175.45
3	*Cd*	2.661
4	*Pb*	1.4
5	*Cr*	396.23
6	*Mn*	0.77
7	*As*	19.77
8	*Zn*	18.25

The analysis of the wastewater sample obtained from the wet scrubber section of a low-cost incinerator reveals varying concentrations of several heavy metals, indicating the composition of the waste being incinerated and the effectiveness of the pollution control measures in place. Notably, mercury (Hg) was undetectable in the sample, suggesting either its absence in the incinerated material or effective mitigation by the scrubber system. However, significant concentrations of other toxic metals were present, including nickel (Ni) at 175.45 ppm, chromium (Cr) at 396.23 ppm, arsenic (As) at 19.77 ppm, cadmium (Cd) at 2.661 ppm, lead (Pb) at 1.4 ppm, and zinc (Zn) at 18.25 ppm as shown in table 2. These elevated levels indicate that the waste processed by the incinerator contained substantial amounts of these hazardous substances, which were subsequently captured by the wet scrubber and transferred into the wastewater stream. Manganese (Mn) was detected at a lower concentration of 0.77 ppm, which is less alarming but still warrants monitoring due to potential environmental impacts. The presence of these heavy metals in the wastewater underscores the necessity for comprehensive treatment processes before discharge or reuse, to prevent environmental contamination and protect public health. Proper management and remediation strategies must be implemented to ensure that the effluent meets regulatory standards and minimizes ecological risks associated with heavy metal pollution.

The heavy metal concentrations observed in the wastewater sample from the wet scrubber of the low-cost incinerator show distinct differences compared to previous studies [15,16]. Notably, mercury was undetectable in this study, while nickel and chromium levels were higher than in earlier findings. In contrast, cadmium, lead, arsenic, and zinc concentrations were generally lower. These variations highlight the influence of factors such as the composition of incinerated materials, scrubber design, and operational conditions on pollutant capture efficiency, underscoring the need for context-specific evaluations in pollution control.

The results demonstrate the effectiveness of the newly designed biomedical waste incinerator in achieving high combustion efficiency and reducing pollutant emissions. The combination of sodium bicarbonate, sodium hydroxide, and activated carbon as absorbents significantly enhances pollution control. These findings underscore the potential of the incinerator design to improve waste management practices in rural areas, thereby safeguarding environmental and public health.

Conclusion

This study effectively evaluated the combustion efficiency and pollutant removal performance of a low-cost biomedical waste incinerator, with a particular focus on the emissions of carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (HC). The results revealed that the combination of sodium bicarbonate, sodium hydroxide, and activated carbon in the wet scrubber (sample F) significantly enhanced the incinerator's efficiency in capturing and reducing harmful pollutants. Sample F demonstrated superior combustion efficiency (98%) and the lowest average concentrations of CO_2 (0.49), CO (0.015), and HC (0.143), indicating its effectiveness in pollution control. In contrast, other samples with individual absorbents displayed lower efficiencies, confirming the advantage of a combined treatment approach.

The analysis of wastewater from the wet scrubber system indicated substantial heavy metal concentrations, with significant levels of nickel (175.45 ppm), chromium (396.23 ppm), and arsenic (19.77 ppm). The absence of detectable mercury and lower concentrations of cadmium, lead, and zinc compared to previous studies suggest that the specific composition of incinerated materials and the design of the wet scrubber play critical roles in pollutant mitigation. These findings emphasize the importance of tailored pollution control strategies and robust treatment systems to minimize environmental and public health risks.

Overall, the study demonstrates that optimizing the chemical composition and design of the wet scrubber can significantly improve the performance of low-cost biomedical waste incinerators, making them more effective in reducing emissions and capturing toxic pollutants. Further research is recommended to refine these systems and to develop context-specific solutions for different waste types and operational conditions.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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