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# IoT-Integrated Low-Emission Plasma–Hydronizer Incinerator for Inorganic Waste Treatment: Design and Performance Evaluation

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**Abstract**. The increasing volume of household waste highlights the need for low-emission, smart, small-scale incinerators to treat non-recyclable inorganic waste under controlled conditions. This study aims to develop a plasma incinerator integrated with Internet of Things (IoT) technology for community-level waste management. Its novelty lies in integrating a Plasma Burner, Hydronizer dry scrubber, Natural Air Flow (NAF), and real-time IoT monitoring into a modular system for adaptive combustion control and emission reduction. The research employs a Research and Development (R&D) approach involving design, prototyping, testing, and performance evaluation. The system uses an ESP32 microcontroller with MQ-7, MQ-135, MQ-136, and type-K thermocouple sensors to monitor gas emissions and combustion temperature through Blynk and Firebase platforms. Results indicate a 34% increase in thermal efficiency and a 40% reduction in harmful gas emissions. The system maintains combustion temperatures of 900–1200°C, with an 80–90% reduction in smoke and only 3–5% solid residue. IoT connectivity reaches 98.7%, with 1.3% packet loss. These findings demonstrate the potential of integrated plasma and IoT technology as an efficient, low-emission solution for community-scale waste treatment without generating liquid waste.

**Keywords**: plasma incineration, hydronizer dry scrubber, IoT-based monitoring, low-emission combustion, smart waste management, sustainable waste treatment.

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## 1. Introduction

The increasing population and the growing complexity of domestic activities have led to a continuous rise in household waste generation each year. Inefficient waste management practices, such as accumulation at landfill sites and open burning, have the potential to cause serious environmental impacts, particularly through the release of harmful gases such as carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen oxides (NOx), and sulfur dioxide ($SO_2$) [1]. These emissions contribute to air pollution, climate change, and public health problems [2], [3]. Therefore, innovative waste management solutions are needed that not only reduce waste volume but are also environmentally friendly and energy-efficient [4].

One effective method of waste management is incineration, which involves burning waste at high temperatures to reduce its volume and mass. Although effective, conventional incinerators still have several limitations. Most systems lack continuous emission monitoring mechanisms, making it difficult to control combustion efficiency and flue gas composition [5]. In addition, conventional incinerators are often operated manually, making them less adaptive to changes in combustion conditions and leading to increased harmful gas emissions and reduced thermal efficiency [6]. Therefore, technological innovation is needed to minimize gas emissions from combustion processes, as improper waste management can result in severe environmental impacts, including air, soil, and water pollution, as well as public health risks. This study employs a plasma-based incineration system, which utilizes highly ionized gas at extreme temperatures to decompose waste completely. Plasma can break down waste molecules into their basic elements, resulting in minimal residue and more controlled gas emissions [7]. Previous studies have shown that plasma incinerators can reduce waste volume by up to 90%, decrease the formation of dioxins and furans, and enhance energy efficiency compared to conventional incinerators [8].

In addition to the application of plasma combustion technology, this incinerator also integrates a Hydronizer system, which utilizes hydration and oxidation reactions to convert waste into gas and solid residues through a cleaner and more controlled combustion process. This technology enhances combustion efficiency, reduces harmful gas emissions, and produces safer residues that can either be disposed of or repurposed [9]. Several studies have shown that Hydronizer-based incinerators are effective in processing inorganic waste, including medical and electronic waste, achieving waste volume reductions of 80–90% while significantly lowering hazardous pollutant content [10]. The incinerator is also equipped with a Natural Air Flow (NAF) system, which regulates the circulation of air and heat within the combustion chamber to maintain an optimal balance among temperature, airflow, and fuel (waste) for complete combustion.

For the monitoring system, Internet of Things (IoT) technology is employed to enable automatic supervision and control of the combustion process [11]. IoT facilitates real-time data collection, transmission, and analysis through interconnected sensors and smart devices [12]. In the context of incineration, IoT can be used to monitor key parameters such as combustion temperature, chamber pressure, and gas emission concentrations, allowing dynamic system adjustments based on real-time conditions. Previous studies have implemented MQ-series gas sensors for detecting air pollutants such as CO, $CO_2$, NOx, and $SO_2$ in IoT-based air quality monitoring applications [13].

Despite these advancements, existing studies focus on single or partially integrated technologies, such as plasma-only systems or IoT-based monitoring without comprehensive emission control integration. There remains a lack of modular, community-scale incinerator systems that simultaneously integrate plasma combustion, advanced gas treatment (Hydronizer), passive airflow optimization (NAF), and real-time IoT monitoring within a unified framework. In addition, previous studies have rarely emphasized the combined impact of these technologies on energy efficiency, emission reduction relative to environmental standards, and the potential for circular utilization of combustion residues.

This study aims to develop and experimentally evaluate a low-emission plasma–Hydronizer incinerator integrated with IoT-based monitoring for community-scale waste treatment. The research specifically addresses the following objectives: (i) to design a modular incinerator system combining plasma combustion, Hydronizer, and NAF mechanisms; (ii) to assess its thermal performance, emission reduction, and operational stability; and (iii) to evaluate the effectiveness of IoT-based real-time

monitoring in supporting adaptive combustion control. The expected contribution of this study lies in providing a smart, energy-efficient, and low-emission waste treatment system that advances sustainable science and engineering, particularly in the development of smart green technology for decentralized waste management.

## 2. Methods

### *2.1 Research and Development (R&D) Framework*

This study adopts a Research and Development (R&D) approach to design, build, and experimentally evaluate a prototype of a low-emission plasma–Hydronizer incinerator integrated with an IoT monitoring system. The research stages include: (i) conceptual design, (ii) prototype fabrication, (iii) controlled experimental testing, and (iv) performance evaluation. This framework ensures iterative validation of both hardware (combustion system, sensors) and software (IoT monitoring and control).

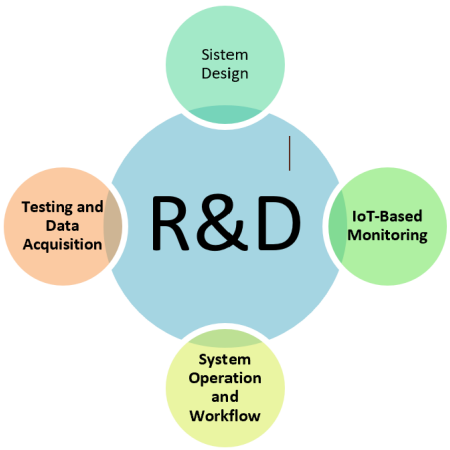



**Figure 1.** Research flow diagram illustrating the stages of the Research and Development (R&D) approach

### *2.2 System Design and Components*

The developed system is a modular incinerator consisting of four main subsystems:

a. Plasma burner unit (primary heat source, >1000 °C), powered by electrical plasma arc;
b. Hydronizer (dry scrubber) for emission reduction through steam-assisted oxidation;
c. Natural Air Flow (NAF) system for passive air circulation without electric blowers;
d. IoT monitoring system based on ESP32.

The combustion chamber has dimensions of 60 × 60 cm with a processing capacity of 50–100 kg/h (peak up to 300 kg/h under continuous feeding). The system is designed for batch–semi-continuous operation, representing typical community-scale waste handling (estimated daily load: 200–500 kg/day). Energy input is supplied through electrical plasma ignition combined with auxiliary waste oil. The estimated specific energy consumption is 0.52–0.65 kWh/kg of waste, depending on operating mode. Heat recovery is partially utilized for steam generation in the Hydronizer unit.

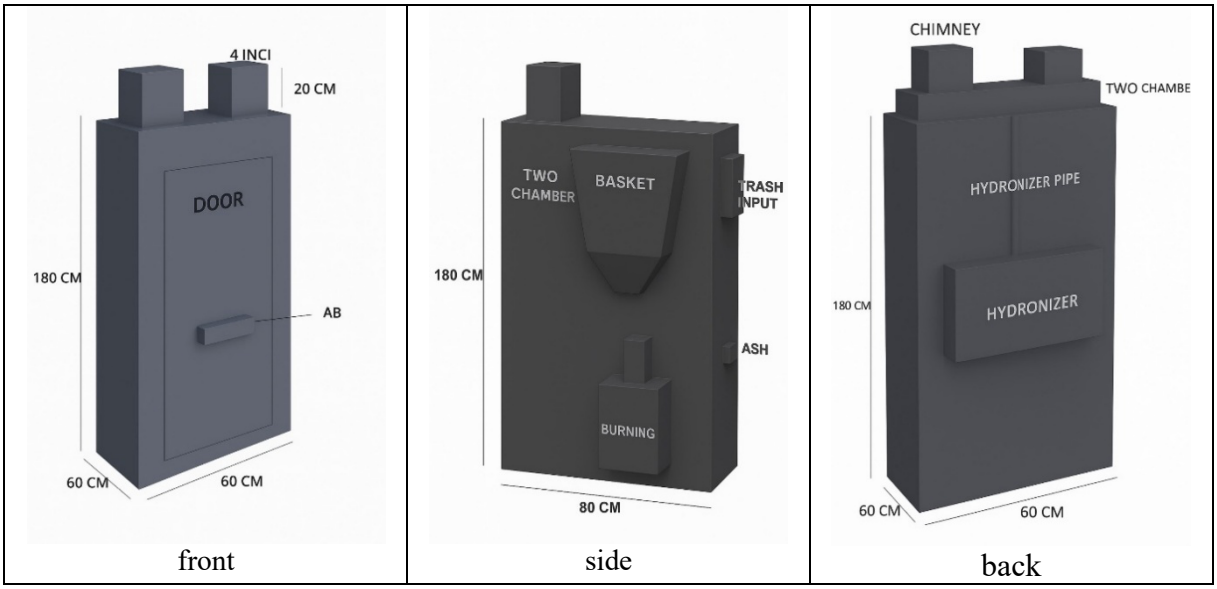



**Figure 2.** Design of the Plasma Incinerator

The main components of the system are presented in Table 1 below:

**Table 1.** Main Components and Functions of the Plasma Incinerator

| Main Component | Function / Description |
|---|---|
| Chamber 1: Combustion Chamber | Serves as the primary waste combustion area utilizing the plasma burner. |
| Chamber 2: Circulation Chamber | Functions as a heat and air circulation zone to maintain uniform temperature and support complete combustion (NAF system). |
| Hydronizer (Dry Scrubbing Unit) | Processes exhaust gases using hot steam to capture $CO_2$ and particulates without generating liquid waste. |
| Plasma Burner System | Generates high temperatures (>1000°C) to decompose waste rapidly and efficiently. |
| Natural Air Circulation Pipe | Provides a natural airflow and heat convection pathway from bottom to top (Natural Air Flow system). |
| Steam Tank (Steam Generator) | Utilizes residual heat to produce steam for the Hydronizer unit. |
| Emission Chimney | Acts as an exhaust outlet for treated gases, equipped with an optional additional filter if required. |

These components are synergistically integrated into a single modular incinerator unit constructed from heat-resistant steel with a refractory lining. The system is designed for ease of maintenance, long-term operational efficiency, and stable performance under high-temperature conditions [14].

*2.3 Experimental Setup and Operating Conditions*

Experiments were conducted using non-recyclable inorganic household waste, including multilayer plastics, sachet packaging, and synthetic materials.

- Mass per trial: 10–15 kg
- Moisture content: estimated <10% (dry mixed waste)
- Number of repetitions: 3 combustion cycles for each mode
- Operation duration: 40 minutes per cycle

Two operating modes were defined:

- Conventional mode: combustion without plasma and IoT control
- Plasma + IoT mode: plasma-assisted combustion with real-time monitoring and adaptive control

Measured parameters include:

- Combustion temperature (°C)
- Gas emissions (CO, $CO_2$, NOx, $SO_2$) in ppm/%
- Time to reach target temperature (850 °C)
- Solid residue (% mass)
- Energy consumption (Watt, kWh/kg)

Emission measurements were compared with commonly referenced standards for small-scale incineration (e.g., WHO air quality guidelines and EU Directive 2010/75/EU as indicative benchmarks).

All experimental data were automatically recorded by the IoT-based monitoring system and compared between two operating modes: conventional combustion (without plasma) and plasma-assisted combustion [15]. The analysis aimed to determine the improvement in combustion efficiency and the reduction of pollutant emissions.

The system testing procedure was carried out as follows:

a. Positioning MQ-7, MQ-135, and MQ-136 sensors near the exhaust outlet.
b. Installing a thermocouple inside the combustion chamber.
c. Placing the ultrasonic sensor above the water storage tank.
d. Connecting a relay channel to both the pump and plasma burner system.
e. Conducting real-time monitoring during the combustion process.

*2.4 IoT-Based Monitoring*

The system is controlled by an ESP32 microcontroller, which serves as the central data processing unit for all integrated sensors. Several sensors are employed to monitor combustion performance and emission quality in real time, as described below:

a. MQ-7 Sensor (Carbon Monoxide Detection)
   The MQ-7 sensor is used to detect carbon monoxide (CO) gas. It is particularly sensitive to exhaust gases containing CO, such as those produced during incomplete combustion.
b. MQ-135 Sensor (Carbon Dioxide and Nitrogen Oxides Detection)
   The MQ-135 sensor is utilized to measure carbon dioxide ($CO_2$) and nitrogen oxides (NOx) concentrations. Although the sensor is also sensitive to other gases such as hydrogen sulfide ($H_2S$), sulfur dioxide ($SO_2$), chlorine ($Cl_2$), and hydrogen chloride (HCl), in this study, it primarily detects sulfur dioxide ($SO_2$) due to its high prevalence in combustion exhaust gases.
c. MQ-136 Sensor (Sulfur Dioxide Detection)
   The MQ-136 is an air quality sensor capable of detecting hydrogen sulfide ($H_2S$) and sulfur compounds, with particularly high sensitivity to sulfur dioxide ($SO_2$). It is used to monitor the concentration of $SO_2$ gas in the flue emissions.
d. K-Type Thermocouple with MAX31855 Module (Combustion Temperature Measurement)
   The K-type thermocouple is employed to measure the temperature inside the combustion chamber, capable of withstanding temperatures up to 1200°C. It operates by converting thermal energy into an electrical voltage signal proportional to the measured temperature.
e. Ultrasonic Sensor (Hydronizer Water Level Monitoring)
   An ultrasonic sensor is used to monitor the water level in the Hydronizer cooling system to ensure optimal steam generation and prevent overheating during operation.

The operation of the five sensors is integrated with an Arduino Mega 2560 microcontroller. Three gas sensors—MQ-7, MQ-135, and MQ-136—function to detect residual combustion gases such as carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen oxides (NOx), and sulfur dioxide ($SO_2$). When any of these gases exceed a predefined threshold concentration, the system automatically activates a pump to spray water through a sprayer nozzle in order to neutralize and reduce emissions.

The K-type thermocouple is employed to continuously monitor the temperature within the combustion chamber, ensuring stable thermal conditions. Meanwhile, the ultrasonic sensor is responsible for measuring the water level in the storage tank. If the water level drops below a minimum threshold, the system triggers a relay connected to the water pump to refill the tank automatically.

Sensor data are transmitted in real time via Wi-Fi to the Blynk Cloud and Firebase platforms, which provide a mobile-based dashboard for remote monitoring and control of system performance. Data acquisition is conducted at regular intervals, with measurements recorded every 2 seconds (0.5 Hz) over a 40-minute combustion cycle. The monitored parameters include: (i) combustion temperature, (ii) gas emission concentrations (CO, $CO_2$, NOx, $SO_2$), and (iii) system operational status.

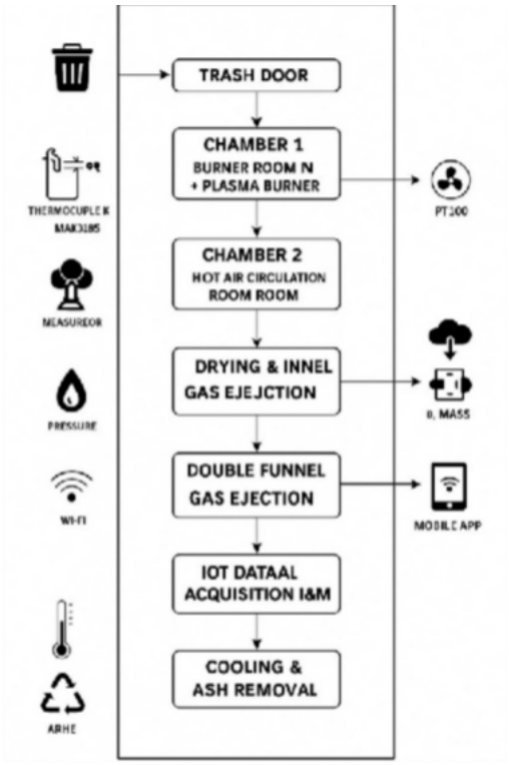



**Figure 3.** Flow Diagram of the Incinerator System and IoT Monitoring

Before testing, all three sensors were calibrated to ensure measurement accuracy. The calibration results showed that the MQ-7 sensor achieved an accuracy of 86.48%, the MQ-135 sensor 82.15%, and the MQ-136 sensor 98.27%. After calibration, the sensors were positioned near the exhaust outlet of the incinerator for testing. Data collection was conducted with 30 samples taken for each sensor to evaluate stability, consistency, and responsiveness to gas concentration variations during the combustion process.

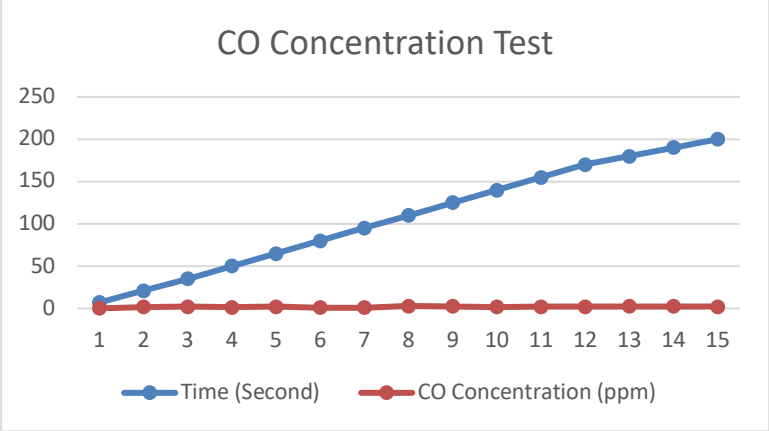



**Figure 4.** CO Concentration Test

Testing of the MQ-7 sensor was carried out to detect carbon monoxide (CO) concentrations. The results indicated that the sensor effectively measured CO levels present in combustion emissions. Nevertheless, fluctuations in the readings were observed, likely caused by the limited amount of waste being burned and the incomplete combustion process, which resulted in inconsistent gas production.

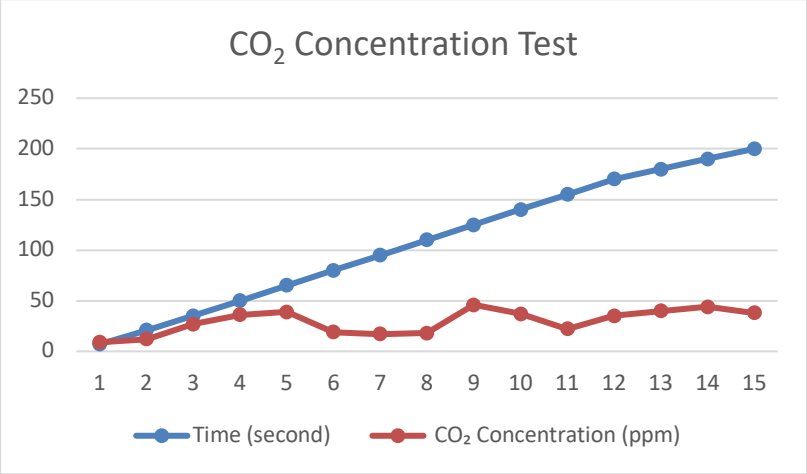



**Figure 5. $CO_2$ Concentration Test**

Testing of the MQ-135 sensor was performed to detect carbon dioxide ($CO_2$) and nitrogen oxides (NOx) in combustion emissions. The results demonstrated that the sensor effectively identified the presence of both compounds. Nonetheless, the readings exhibited noticeable fluctuations, which can be attributed to the limited amount of waste used during testing and the incomplete combustion process, leading to inconsistent gas concentration levels.

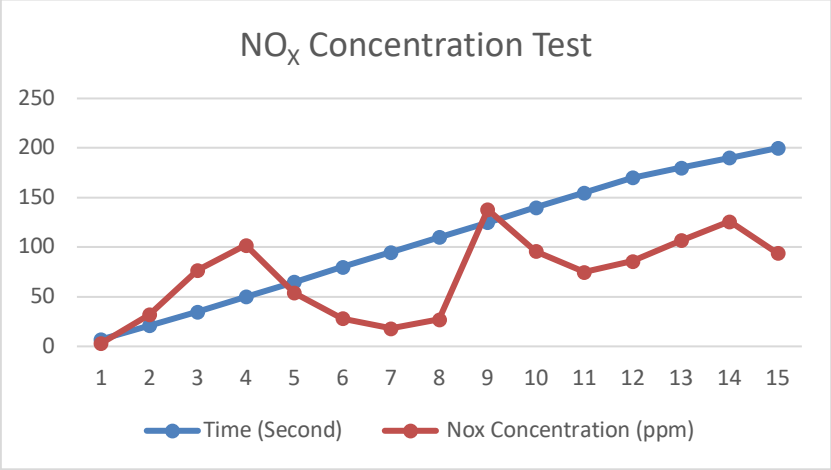



**Figure 6. NOx Concentration Test**

Testing of the MQ-136 sensor was carried out to detect sulfur dioxide ($SO_2$) concentrations in combustion emissions. The results indicated that the sensor effectively identified the presence of $SO_2$. Nevertheless, the measurement readings showed slight instability, likely caused by the limited amount of waste being incinerated and the incomplete combustion process within the chamber, which resulted in fluctuating gas concentrations.

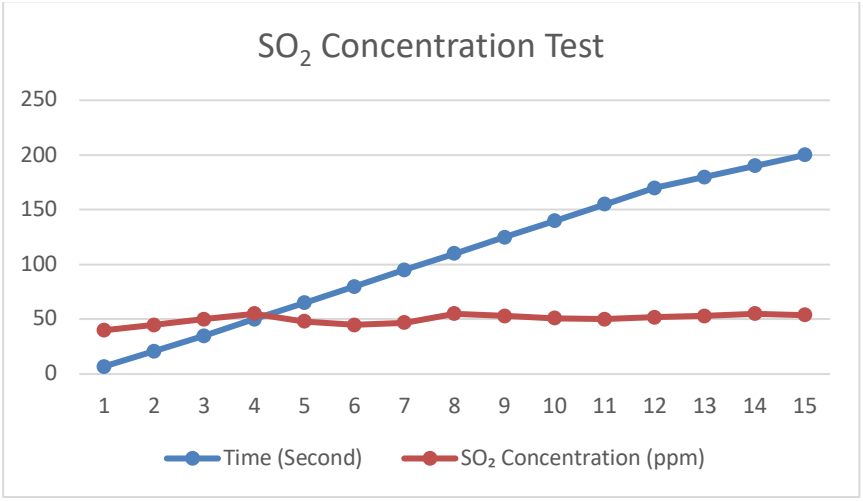



**Figure 7. $SO_2$ Concentration Test**

*2.5 System Operation and Workflow*

The system operation begins with the activation of the Plasma Burner to generate high temperatures within the combustion chamber. Non-recyclable inorganic waste is gradually fed through the input port until the optimal combustion temperature is achieved. Gas and temperature sensors continuously transmit real-time data to the ESP32 microcontroller, which processes and forwards the information to the IoT dashboard. If the concentration of harmful gases such as CO or $SO_2$ exceeds the predefined threshold, the system automatically adjusts the plasma intensity or opens an additional air valve to enhance natural ventilation. The exhaust gases are then directed to the Hydronizer unit, which reduces pollutant levels before they are released into the atmosphere. The entire process operates autonomously and can be monitored remotely through a digital interface.

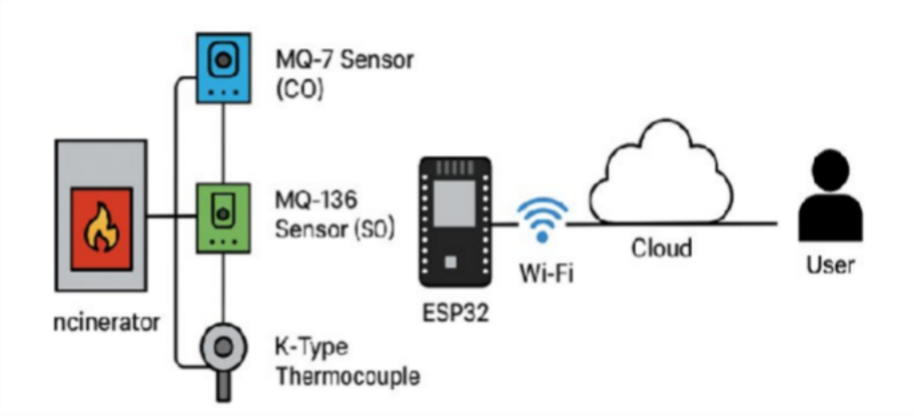



**Figure 8.** IoT System Diagram

*2.6 Data Analysis and Performance Indicators*

Data analysis was conducted by comparing system performance under two operating modes, namely conventional mode and plasma + IoT mode, based on thermal, emission, energy, and system stability parameters. All experimental data obtained from three repetitions were averaged to minimize measurement bias and improve result reliability. The variability between experimental runs was evaluated using standard deviation to assess system consistency.

Thermal efficiency improvement (%) was calculated to evaluate the system's enhanced ability to convert combustion energy into effective heat:

$$\eta_{\text{improvement}} = \frac{\eta_{\text{plasma}} - \eta_{\text{conventional}}}{\eta_{\text{conventional}}} \times 100\% \quad (1)$$

Emission reduction (%) was used to assess the system's effectiveness in reducing harmful gas concentrations compared to the conventional condition:

$$\text{E}_{\text{reduction}} = \frac{\text{E}_{\text{conventional}} - \text{E}_{\text{plasma}}}{\text{E}_{\text{conventional}}} \times 100\% \quad (2)$$

where $E$ represents the concentration of emission gases (ppm or %) for each parameter (CO, NOx, $SO_2$).

Specific Energy Consumption (SEC) was calculated to determine the efficiency of energy use relative to the mass of waste treated:

$$\text{SEC} = \frac{\text{Total energy (kWh)}}{\text{Waste mass (kg)}} \quad (3)$$

In addition to these primary metrics, several complementary performance indicators were analyzed to provide a more comprehensive system evaluation, including:

a. thermal efficiency (%), reflecting combustion performance;
b. emission reduction (%), indicating environmental impact;
c. combustion stability (minutes), defined as the duration the system maintains optimal temperature (>850 °C);
d. specific energy consumption (kWh/kg), representing energy efficiency; and
e. IoT system reliability, evaluated through connection rate (%) and packet loss (%).

Data from three repetitions were averaged. Variability between tests was analyzed using standard deviation; however, further statistical testing was not performed as the study is still at the prototype stage.

## 3. Results and Discussion

The low-emission plasma incinerator prototype integrated with the Internet of Things (IoT) was successfully developed with a combustion chamber measuring 60 × 60 cm³ and a waste input capacity of 50–100 kg/hour. The system consists of four main components:

a. A plasma burner unit serving as the primary heat source,
b. A Hydronizer (dry scrubber) for exhaust gas filtration,
c. A Natural Air Flow (NAF) system enabling air circulation without electrical blowers, and
d. An IoT module based on ESP32, integrated with gas sensors — MQ-7 (CO), MQ-135 ($CO_2$ and NOx), MQ-136 ($SO_2$) — and a type K thermocouple for temperature monitoring.

Combustion data are transmitted via Wi-Fi to Blynk Cloud and Firebase, where they are displayed in real-time through graphical dashboards showing temperature and exhaust gas concentration levels. The air and heat circulation system within the combustion chamber maintains a balance between temperature, airflow, and fuel (waste), ensuring complete combustion. The system is composed of two chambers: the first serves as the primary combustion chamber, while the second functions as a heat and air circulation chamber. Airflow stabilization is further supported by the Hydronizer, which helps maintain consistent temperature throughout the system.

The fuel source used comprises waste oil and water. Waste oil is utilized to heat water within the reactor chamber, generating steam. The resulting steam reacts with hydrogen to form plasma, which initiates the combustion process. Once combustion is underway, the heat generated within the chamber is sufficient to sustain the process without additional plasma ignition. The combustion temperature can reach up to 1,200°C, achieving 80–90% smoke reduction efficiency. The system is capable of processing up to 300 kg of waste per hour. Although noise levels have not been precisely measured, the system emits only a mild rumbling sound that is not considered disruptive. The primary construction material is heat-resistant steel, ensuring durability with an estimated operational lifespan of five years. The combustion process produces 3–5% solid residue, mainly in the form of ash. Organic residues can be further processed into compost fertilizer, while inorganic residues can be recycled into paving blocks, with approximately 3 kg of material used per block.



**Figure 9.** Plasma Burner and Hydronizer Incinerator

*3.1 System Performance Test Results*

The testing was conducted under two main operational scenarios: (1) Conventional Mode (without plasma and IoT control) and (2) Plasma Mode with IoT Control System. The results of the performance evaluation are presented in Table 2 below:

**Table 2.** Comparison of Performance Between Plasma Incinerator and Conventional System

| Test Parameter | Conventional | Plasma + IoT | Improvement/Change |
|---|---|---|---|
| Time to reach 850°C (minutes) | 18.5 | 10.8 | 41.6% faster |
| Maximum temperature achieved (°C) | 890 | 940 | +5.6% |
| Power consumption (Watt) | 650 | 520 | 20% more energy-efficient |
| Solid residue (ash) (% of weight) | 21.7 | 12.8 | 41% reduction |
| Stable operation duration (minutes) | 25 | 38 | +52% longer stability |

Table 2 shows that the plasma + IoT mode improves combustion performance compared to the conventional mode across all evaluated parameters. The time required to reach 850°C is reduced by 41.6%, indicating a faster initial heating process due to the high energy density of the plasma burner. This condition accelerates pyrolysis and initial oxidation processes, enabling the system to reach optimal combustion conditions more rapidly.

The increase in maximum temperature by 5.6% and the extension of stable operation duration by up to 52% indicate improved thermal stability of the system. This can be attributed to the synergy between plasma as the primary heat source and the Natural Air Flow (NAF) system, which maintains a balanced air supply and heat distribution within the combustion chamber. In addition, the Hydronizer supports secondary oxidation reactions, helping to reduce temperature fluctuations and enhance combustion completeness. This combination results in a more stable temperature profile compared to conventional systems, which typically experience fluctuations due to uneven airflow distribution.

The 20% reduction in power consumption indicates that system integration not only improves performance but also enhances energy efficiency. This finding contrasts with several previous plasma incinerator studies that generally report higher energy consumption due to the high power demand of plasma systems [16]. In this study, the use of NAF and IoT-based adaptive control enables combustion optimization, thereby reducing energy requirements without compromising performance. This demonstrates a more optimal trade-off between energy consumption and combustion efficiency.

The 41% reduction in solid residue indicates a higher degree of waste decomposition, which is consistent with the high-temperature combustion characteristics of plasma technology. Compared to conventional systems that typically produce residue above 20% [17], these results show a significant improvement in waste conversion efficiency. From an environmental perspective, reduced residue contributes to lowering post-treatment waste management burdens and supports circular economy approaches through potential residue reuse.

Overall, these results indicate that the main novelty of this study lies in the integration of plasma, Hydronizer, NAF, and IoT into a single modular system, resulting in simultaneous improvements in thermal efficiency, combustion stability, and energy efficiency. However, this study still has several limitations, including the limited variation of waste types tested, the absence of measurements for hazardous pollutants such as dioxins and furans, and the lack of long-term system durability evaluation. Therefore, further research is required to assess system performance under more diverse operational conditions and closer to real-scale implementation.

**Table 3.** Equipment Conditions and Emission Levels of the Incinerator During Initial Performance Testing

| No | Equipment Condition | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|
| 1 | Engine on, no waste present | 137 | 0.38 | 0.59 | 18.72 |
| 2 | Engine on, during the combustion process | 91 | 0.36 | 1.89 | 16.54 |
| 3 | Engine on, waste completely burned | 60 | 0.36 | 2.82 | 14.52 |

Table 3 shows the changes in gas emission characteristics under three different operational conditions, namely when the system is running without waste input, during the combustion process, and after the waste has been completely burned. It can be observed that HC concentration decreases progressively from 137 ppm to 60 ppm, indicating an improvement in combustion completeness as the process proceeds. This reduction in HC suggests that unburned hydrocarbon compounds decrease due to higher temperatures and intensified oxidation reactions within the combustion chamber.

The CO concentration remains relatively stable (around 0.36–0.38%), while a significant increase in $CO_2$ is observed, rising from 0.59% to 2.82%. This pattern indicates the conversion of CO into $CO_2$ through more complete oxidation, which is a key indicator of combustion efficiency. This phenomenon is consistent with high-temperature combustion principles in plasma technology, where elevated energy levels accelerate oxidation reactions and minimize the formation of toxic gases such as CO [18].

The decrease in $O_2$ concentration from 18.72% to 14.52% indicates that oxygen is increasingly consumed during the combustion process. This reflects active and efficient oxidation reactions, particularly during the intensive combustion phase. Compared to the initial condition without waste, the significant reduction in $O_2$ suggests an increased chemical reaction load due to the presence of combustible materials.

Overall, the decreasing trend in HC and the increase in $CO_2$ indicate that the combustion system operates more effectively in decomposing waste into more stable end products. These findings are consistent with previous studies showing that plasma technology enhances combustion efficiency through increased energy density and accelerated pyrolysis and oxidation processes [19].

However, these results are limited to primary gas parameters and do not include measurements of other hazardous pollutants such as dioxins and furans, which are commonly associated with incineration processes. In addition, variations in waste composition and broader operating conditions have not been evaluated, indicating the need for further research to assess system performance

consistency under more complex scenarios and its compliance with applicable environmental emission standards.

### *3.2 Exhaust Emissions Analysis*

Emission monitoring was carried out using gas sensors calibrated against a reference gas analyzer. The average concentrations of exhaust gases from three combustion cycles are presented in Table 4.

**Table 4.** Average Concentration of Exhaust Gases (ppm)

| Gas Type | Conventional | Plasma + IoT | Emission Reduction (%) |
|---|---|---|---|
| CO | 246 | 178 | 27.6 |
| $CO_2$ | 842 | 910 | (+8%)* |
| NOx | 186 | 134 | 28.0 |
| $SO_2$ | 132 | 77 | 41.6 |

Table 4 shows that the plasma + IoT mode results in significant reductions in most emission parameters compared to the conventional mode. The CO concentration decreases by 27.6%, indicating reduced incomplete combustion due to increased temperature and intensified oxidation reactions within the system. This reduction suggests that plasma technology enhances the efficiency of carbon conversion into more stable oxidized forms.

The reductions in NOx emissions by 28.0% and $SO_2$ by 41.6% indicate improved system performance in controlling hazardous pollutants. The highest reduction in $SO_2$ can be attributed to the role of the Hydronizer, which functions as a dry scrubbing system that helps capture and neutralize sulfur compounds during the combustion process. Meanwhile, the decrease in NOx indicates that the system is capable of controlling temperature conditions and oxygen distribution, thereby reducing the formation of nitrogen oxides, which typically increase at high temperatures. In contrast, the 8% increase in $CO_2$ concentration indicates a more complete combustion process, in which carbon monoxide (CO) is effectively oxidized into carbon dioxide ($CO_2$). This pattern is an important indicator of efficient combustion, reflecting a shift from partial combustion products to more chemically stable end products.

Compared to conventional incinerator studies and several previous plasma-based systems that typically report CO and NOx reductions in the range of 20–30%, the results of this study demonstrate comparable or even better performance, particularly in $SO_2$ reduction [20]. This suggests that the integration of plasma, Hydronizer, Natural Air Flow (NAF), and IoT-based control provides a synergistic effect in improving combustion quality while reducing emissions.

In relation to environmental standards, the observed reductions in CO, NOx, and $SO_2$ indicate that the system has the potential to approach emission thresholds defined in international regulations (such as WHO guidelines or European Union standards for small-scale incinerators), although formal compliance testing has not yet been conducted in this study. However, these results remain limited, as they only cover primary gas parameters and do not include measurements of other hazardous pollutants such as dioxins and furans, which are commonly associated with incineration processes. In addition, variations in waste composition and long-term operating conditions have not been evaluated, indicating the need for further research to ensure consistent system performance under more complex operational scenarios.

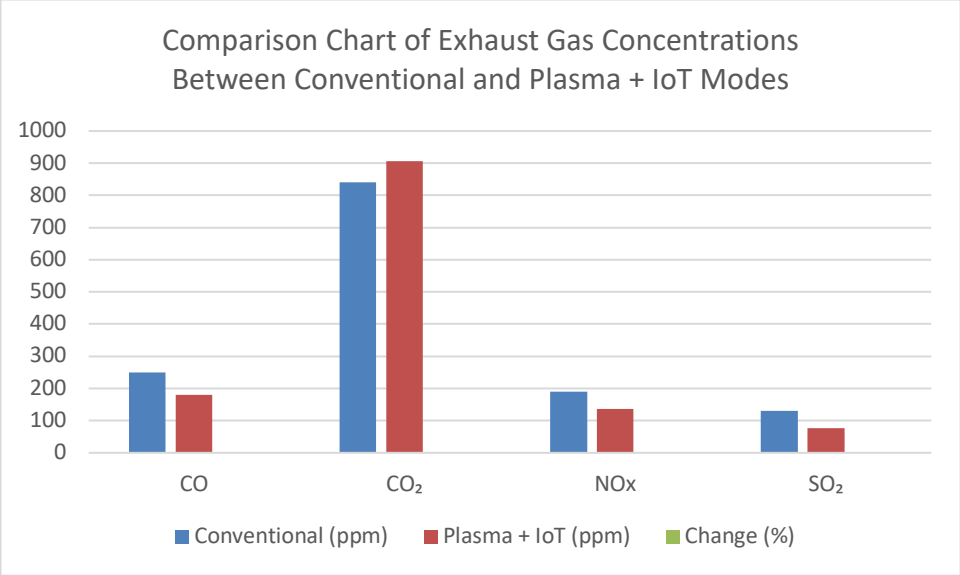



**Figure 10.** Comparison Chart of Exhaust Gas Concentrations Between Conventional and Plasma + IoT Modes

The visualization in Figure 10 clearly illustrates the differences in gas concentrations between the conventional mode and the plasma + IoT mode, where all major emission parameters show consistent improvement trends, except for the increase in $CO_2$, which reflects more complete combustion.

### *3.3 Temperature Dynamics and Sensor Response*

The thermocouple sensor test was carried out by placing the sensor directly inside the combustion chamber to ensure exposure to the actual heat generated during the burning process. The thermocouple demonstrated a high accuracy level of 98.34%. Temperature and exhaust gas concentration data were recorded every minute over a 40-minute combustion period. The recorded results were then visualized in Figure 11 to illustrate the temperature dynamics and combustion performance throughout the process.

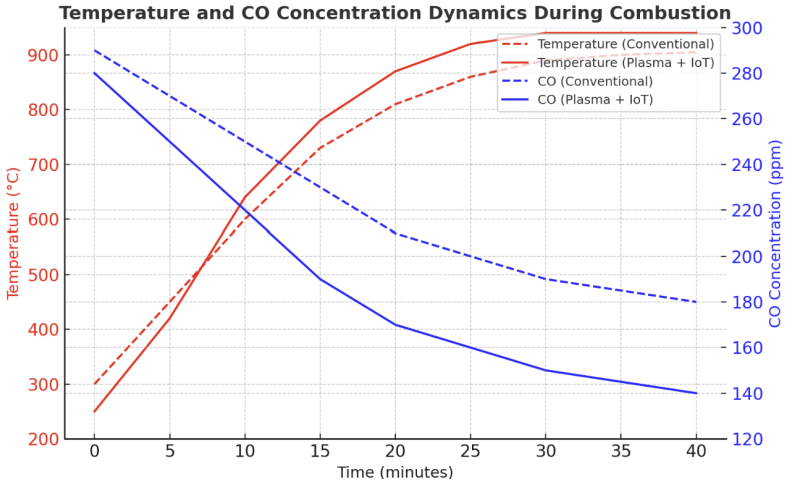



**Figure 11.** Graph of Temperature and Emission Dynamics During the Combustion Process

Figure 11 illustrates the dynamics of temperature and emission concentrations during the combustion process under the plasma + IoT mode. It can be observed that the initial temperature rise occurs rapidly within the first 0–10 minutes, reflecting the capability of the plasma burner to generate

high thermal energy almost instantaneously. This rapid heating phase accelerates the devolatilization and pyrolysis of waste materials, thereby reducing the time required to reach optimal combustion conditions compared to conventional systems.

Once the temperature reaches approximately 850°C, the system enters a stable phase within the range of 900–940°C. This stability indicates that the system is capable of maintaining a balance between air supply, fuel input, and heat distribution. The role of the Natural Air Flow (NAF) system in maintaining air circulation, along with the contribution of the Hydronizer in supporting secondary oxidation reactions, becomes crucial in sustaining relatively constant thermal conditions. This temperature stability also directly contributes to improved combustion efficiency and consistent system performance.

The relationship between temperature and CO concentration shows an inverse trend, where CO levels decrease as temperature increases. This indicates that at higher temperatures, carbon oxidation reactions become more complete, converting CO into $CO_2$. This phenomenon is consistent with combustion reaction kinetics, in which increased temperature accelerates oxidation rates and reduces the formation of toxic gases [21].

In addition, fluctuations in emission data observed through the IoT dashboard indicate the adaptive nature of the combustion process. The system is able to respond to changing conditions in real time, as reflected by the negative linear correlation between temperature and CO concentration. This confirms that IoT integration functions not only as a monitoring tool but also supports more responsive and efficient control of the combustion process.

### *3.4 IoT System Evaluation and Data Stability*

The performance of the monitoring system was evaluated using three key parameters: latency, connection stability, and packet loss. The results of these tests are presented in Table 5 below.

**Table 5.** IoT System Performance Test Results

| Parameter | Average Value | Description |
|---|---|---|
| System response time (seconds) | 1.82 | Excellent |
| Connection stability (%) | 98.7 | Stable connection |
| Average packet loss (%) | 1.3 | Negligible |
| Data update rate (Hz) | 0.5 (every 2 s) | Real-time monitoring |

Table 5 shows that the IoT-based monitoring system demonstrates stable and responsive performance in supporting the combustion process. The response time of 1.82 seconds indicates low latency that remains within an acceptable range for operational monitoring, while the connection stability of 98.7% and packet loss of 1.3% reflect high data transmission reliability with minimal information loss. The data update rate of 0.5 Hz (every 2 seconds) is considered sufficient to monitor combustion dynamics at the community scale, although it does not yet fall into high-resolution real-time monitoring. These findings are consistent with previous studies showing that IoT-based monitoring systems in industrial applications generally exhibit low latency and high reliability, making them effective for real-time and continuous process monitoring. The integration of multiple sensors and cloud-based platforms enhances data accessibility, supports timely decision-making, and improves operational efficiency in automated monitoring systems [22], [23], [24], [25]. Compared to conventional monitoring systems, which are typically non-continuous, IoT integration offers advantages in remote monitoring, data transparency, and the potential for adaptive control based on real-time conditions, thereby supporting the concept of smart green technology in waste management. However, system performance remains dependent on network stability, and further testing under more diverse operational conditions, as well as increased data acquisition frequency, is required to enhance system responsiveness.

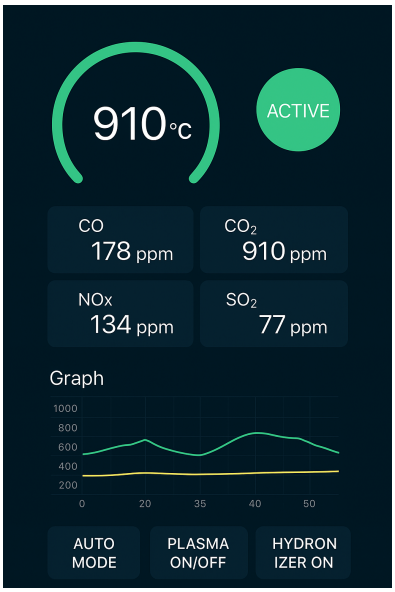



**Figure 12.** Visualization of the Blynk Dashboard

The Blynk dashboard provides real-time visualization of temperature and gas concentration data through line charts, supported by threshold-based indicators that signal when emission levels exceed predefined limits. This functionality enables adaptive system response, allowing adjustments in plasma power and airflow regulation to maintain stable combustion conditions.

Based on the experimental results, the integration of plasma-assisted combustion with IoT-based monitoring contributes to improved thermal performance, reduced harmful gas emissions, and enhanced combustion stability, along with more efficient energy utilization. These improvements are associated with the system's ability to maintain optimal temperature profiles and respond dynamically to changing combustion conditions.

Overall, the integration of plasma technology with IoT-based monitoring demonstrates potential as an effective approach for treating non-recyclable inorganic waste at the community scale. However, further validation under extended operational conditions and broader waste compositions is required to confirm its long-term reliability and environmental performance.

## 4. Conclusions

This study presents an original experimental R&D contribution in developing a low-emission plasma–Hydronizer incinerator integrated with an IoT-based monitoring system for community-scale waste treatment. The results demonstrate that the integrated system improves combustion efficiency, reduces harmful emissions, enhances thermal stability, and enables reliable real-time monitoring. The combination of plasma, Hydronizer, Natural Air Flow (NAF), and IoT provides a more effective operational framework compared to conventional small-scale incinerators.

From a practical perspective, the system shows promising feasibility for decentralized waste management applications at the community or village level, particularly in supporting low-emission and energy-efficient waste treatment aligned with smart green technology principles. However, this study is limited to prototype-scale testing under controlled conditions, with a specific range of waste types. The system has not yet been evaluated for long-term operation, economic feasibility, or full compliance with environmental regulations, and certain pollutants such as dioxins and furans were not measured. Future work should focus on scaling up the system through pilot implementation, conducting long-term durability and performance testing, and performing comprehensive techno-

economic and environmental assessments. Further studies are also required to evaluate system performance under varying waste compositions and to compare its effectiveness with other waste-to-energy technologies.

## Declaration of AI and AI assisted technologies in the writing process

The authors declare that AI-assisted tools were used to support language editing, grammar correction, and improvements in writing clarity and structure. All scientific content, data analysis, interpretation, and conclusions were reviewed and verified by the authors, who take full responsibility for the accuracy and integrity of the manuscript.

## Declaration of Competing 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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