Design and performance analysis of IoT-based portable waste incinerator for environmental efficiency and marketing

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ABSTRACT

The increasing volume of waste in urban areas such as Yogyakarta is not supported by adequate public awareness or effective waste management systems. This study aims to design and evaluate the performance of an IoT-based portable waste incinerator as an efficient and feasible solution for household and community use. The prototype was developed using an iterative design approach with recycled materials and low-cost IoT components. Test results show that the device maintains a stable combustion temperature of 600–800 °C and achieves an average waste volume reduction of 85%. SO_2 emission levels remain below 120 ppm, meeting environmental safety standards. The IoT monitoring system, using an ESP8266 module and DHT22 sensor, enables real-time tracking of temperature and ash accumulation and provides automatic alerts for maintenance. Financial analysis indicates that production costs can be reduced by approximately 40%, resulting in an estimated unit price below IDR 4,000,000. Market validation across five locations in Yogyakarta shows an 85% interest rate and a satisfaction score of 4.2/5. Overall, the IoT-based portable waste incinerator demonstrates technical reliability, environmental efficiency, and market viability.

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1. INTRODUCTION

The current waste problem is a concern for all stakeholders, including both local governments and individuals. In the regulations of Law No. 18 of 2008 concerning waste management, everyone is obliged to manage waste in a directed and integrated manner, both household waste and similar household waste, with a mutually sustainable and comprehensive management system that has an impact on the environment [1].

In terms of waste management governance, the government has an important role in managing its area by making an agreement to manage a well-organized green environment in a structured and conceptual manner from upstream to downstream, including the impacts that will be caused [2], [3].

Based on data from the Ministry of Environment and Forestry, Directorate General of Waste Management, Waste and B3, Directorate of Waste Management, Special Region of Yogyakarta Province. In tourist cities like Yogyakarta, population growth directly contributes to an increase in waste volume that is disproportionate to available management capacity, according to a study [4]. However, household waste management systems still prioritize collection and disposal over reduction or processing at source, as demonstrated [5]. Therefore, technological solutions that can be used independently by people at the household and community levels are urgently needed [6]. Figure 1 presents the volume of waste production in the Special Region of Yogyakarta Province over a five-year period, while Figure 2 shows the corresponding amount of waste that has been handled.

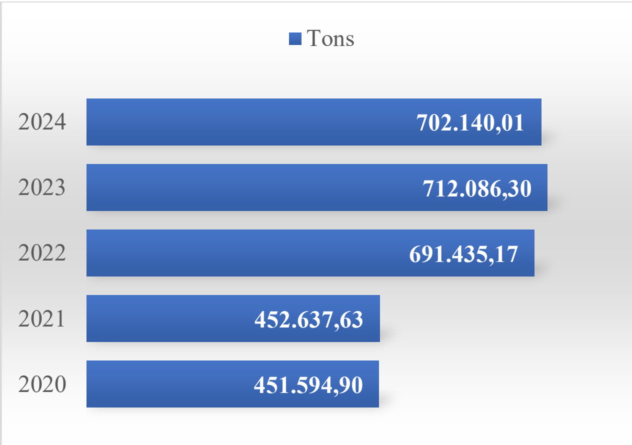

Figure 1. Volume of waste production in the Special Region of Yogyakarta

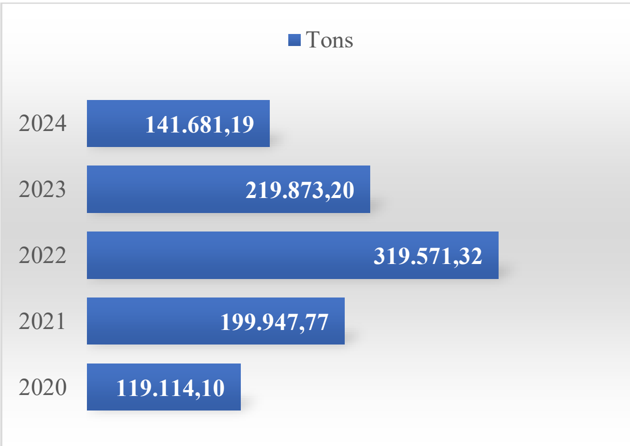

Figure 2. Volume of waste handled in the Special Region of Yogyakarta

Based on the volume of waste production from year to year, it shows Figure 2. that the volume of waste that cannot be handled is still hundreds of tons. This has resulted in confusion among the public regarding appropriate waste disposal, leading to actions such as dumping waste in rivers or on streets, or open burning without consideration of the consequences. The global increase in waste generation is exacerbating problems of pollution, inadequate waste management, and limited recycling capacity, underscoring the urgent need for innovative approaches to enhance the efficiency and resilience of the waste ecosystem. Waste management that does not consider transportation and distribution factors to the appropriate final disposal location will result in waste being abandoned, causing negative impacts on health and will also seriously disrupt the sustainability of environmental functions and aesthetics [7], [8]. The increase in the volume of waste that occurs is not accompanied by an increase in understanding or awareness of the community to make the environment cleaner [9], [10]. Many people still have low awareness of waste management and dispose of waste in the wrong place [11]. Waste streams that are non-recyclable or cannot be managed safely pose serious environmental and public-health concerns, highlighting critical gaps in current waste-management practices. This results in many waste problems that accumulate, so that its implementation has not achieved maximum results [12]. Although policies related to plastic and marine waste management are currently in place, there remain no specific regulations governing the conversion of waste into value-added products. Therefore, this waste problem, if not handled seriously, will become an ongoing problem, such as an increase in population, socio-economic conditions, and technological advances that are increasingly developing significantly [13]. The restricted landfill capacity and the pervasive open burning without emission controls are two of Yogyakarta's biggest waste management issues [14]. When paired with a hazardous gas filtration system, controlled burning (incinerators) can minimise waste volume by 80–90% and lower the danger of environmental pollution, making it a practical alternative [15]. An intermediate option that can be used locally in this situation without requiring significant infrastructure is the use of IoT-based portable waste incineration technology. The availability of organic waste supplies constitutes the highest priority factor in determining the feasibility of community-based waste management systems, whereas technological innovation and the application of appropriate technology rank as the lowest priorities due to limited awareness, adoption readiness, and resource constraints at the local level [16].

The development of technology also has an impact on the transition to the era of digitalization. Various kinds of technology that were initially done manually are now starting to be digitally based. The development of technology, such as the Internet of Things (IoT), makes it easy to access. This garbage burner is one of the innovations that has been used to reduce waste and neutralize exhaust emissions by applying the IoT. Environmental concern is also thought to be a factor driving the use of environmentally friendly products. Organic waste management strategies in urban areas should aim to create added value from waste streams [17], [18]. The socioeconomic features of the Yogyakarta Special Region (DIY) include a high urban population density and comparatively high levels of digital literacy. Because users can remotely manage the temperature and combustion state, IoT technology is relevant as an automated monitoring system for garbage incinerators. Yogyakarta's Smart City policy, which promotes the use of technology for environmental efficiency, is also in line with this strategy [19], [20]. This tool works by applying the IoT with a sensor connected to a reminder remote alarm, so if the temperature gets higher and the garbage ash accumulates, this tool will send an alarm signal to the remote to immediately clean/remove the ash from the burner [21]. If the ash is not removed immediately, it will become an obstacle during the combustion process. This tool has a diameter of 60 cm and a height of less than 1.5 m, so that this portable garbage burner can be moved according to the wishes of its users.

The existing design of low-cost waste incinerators in Indonesia often neglects ergonomic and safety considerations, resulting in devices that are difficult to operate, unsafe for non-technical users, and misaligned with the anthropometric characteristics of the local population. This problem is particularly critical for household and community-scale waste management in urban and semi-urban areas, where users require compact, safe, and easy-to-operate technologies. Therefore, this study aims to develop an IoT-based portable waste incinerator that integrates anthropometric design principles and automated monitoring to enhance user safety, operational comfort, and environmental efficiency. To achieve this objective, the prototype incorporates ergonomic features derived from the Indonesian National Standard (SNI 6389:2019) and the Indonesian Anthropometric Database (2020). The device height (<1.5 m) and loading-opening height (95–100 cm) align with the average standing elbow height of Indonesian adults (96–110 cm), enabling waste insertion or removal without excessive bending or arm elevation. The 60 cm chamber diameter also accommodates the average arm reach (70–80 cm), supporting natural movement and reducing postural strain.

From a safety standpoint, the combustion chamber is equipped with double-layer steel and ceramic insulation to maintain external temperatures below 40°C, while the ash collection port positioned at ~40 cm meets the 5th–95th percentile comfort range, enabling residue removal with minimal stooping effort. These anthropometric and ergonomic considerations ensure that the device can be safely and comfortably operated by both male and female users across typical Indonesian body-size variations.

The contribution of this study lies not only in ergonomic integration but also in the adoption of IoT-based monitoring—addressing the lack of responsive safety features in low-cost incinerators [22]. Temperature sensors and automated ash-accumulation alarms provide real-time feedback, allowing users to supervise the combustion process remotely. This automated system supports communities with limited technical backgrounds and aligns with the increasing need for space-efficient, safe, and digitally supported waste management solutions. Ultimately, the proposed design advances household-scale waste management by combining ergonomic suitability, user safety, and smart monitoring technology within an affordable portable device.

2. MATERIALS AND METHODS

2.1. Material

The design development method used in this study refers to the prototype-based iterative design approach, which emphasizes the design, manufacture, and refinement of the tool iteratively based on user feedback. The process begins with exploring user needs through observation and interviews, followed by creating sketches and initial 3D models. The initial design is evaluated in terms of functionality and comfort, then a functional prototype is made using recycled materials. The materials used include recycled components such as used drums, hollow iron, and buckets. The reason for using used materials is to utilize used goods that are still suitable for use and reduce carbon gas emissions. Apart from that, this tool controls dangerous emissions from smoke emitted using Sulfur Dioxide (SO_2) and Sodium Oxide (Na_2O), reacting with acid gas to form a harmless compound, namely Sodium Sulfate Na_2SO_4). Technical and budgetary considerations were the two primary factors taken into account while choosing a way for creating a prototype of an IoT-based portable waste incinerator. Technically speaking, the prototype design places a high value on portability, simplicity of use, and combustion process efficiency. Utilised drums, hollow iron, and metal buckets were among the materials utilised because they are readily available, easily modified, and have good heat resistance.

To improve user safety and comfort, the combustion system has a temperature sensor that is connected to an Internet of Things module. This sensor detects ash buildup and triggers a remote alarm automatically. The tool's comparatively compact size (diameter of 60 cm and height of less than 1.5 m) makes it portable and suitable for usage in a variety of settings. Using recycled parts and inexpensive but dependable electrical modules, such temperature sensors and ESP8266-based microcontrollers, is a cost-effective strategy from a financial standpoint. Technical evaluations were carried out by testing combustion temperature, emissions, and the reliability of the sensor system. Financial aspects were also analyzed using a cost-performance optimization approach, so that the selling price can be affordable for lower-middle class people without sacrificing the quality and safety of the device.

This method is considered the most appropriate because it is able to bridge technological innovation and social adaptation in the context of community-based waste management. This approach also supports the principles of sustainability and reducing industrial waste through the use of recycled materials. Technical and budgetary factors were the two main factors taken into account when choosing the prototype design technique. Technically speaking, portability, usability, and combustion efficiency were given top priority in the device's design [23]. Iterative prototype design was used in this design, and each prototype version was evaluated according to three main criteria: (1) stability of the combustion temperature, (2) efficacy of the sensor in identifying ash accumulation, and (3) operational safety for non-technical users. Financially speaking, a cost-performance optimisation strategy was employed to guarantee that the gadget could be manufactured at a reasonable cost without compromising essential technical features. The ESP8266 IoT module and the DHT22 temperature sensor are two examples of electronic components that were chosen because to their excellent reliability, open source nature, and ease of local availability. Additionally, using recycled materials like hollow iron and repurposed drums lowers production costs by about 40% while simultaneously promoting the circular economy and industrial waste reduction ideas.

2.2. Methods

The methodology in this research uses qualitative data with a literature study approach. Data collection methods included surveys, interviews with residents in densely populated areas, and a literature review. From the data obtained through this, researchers process data that makes a tool for managing waste that can be used on a home scale [24].

This portable waste burner is also a market need, because of the emergency needs of waste management [25]. Market needs analysis, according to Serrat [26] needs the market to be based on the customer's wants and needs, as the basis for marketing, based on market segmentation, targeting, and positioning [27], [28]. Segmentation, targeting, and positioning (STP) analysis is a model approach in the development of a marketing strategy for portable waste burning equipment. The subjects in this study are the local government and the public [29], [30]. To make sure the prototype design was both technically possible and embraced by the end-user community, a validation process for market acceptance was carried out. Among the validation phases were:

1. Testing of technical functionality, such as emissions, combustion temperature, and the reaction of IoT sensors to ash buildup.
2. Surveys and interviews with prospective customers from households, neighbourhood associations (RT/RW), and waste management MSMEs are used to test market perception and interest.
3. Economic feasibility testing determined the equilibrium between local producers' profit margin, market-acceptable selling price, and manufacturing costs.

A systematic approach was applied to ensure that the prototype design and performance evaluation were conducted in a structured, comprehensive, and replicable manner. This approach consists of four main stages:

1. Needs Exploration and Requirement Definition.
   The process began with identifying functional, safety, and economic requirements through field observations, literature review, and interviews with residents in densely populated areas of Yogyakarta. The requirements were categorized into: (a) technical needs (temperature control, ash monitoring, combustion stability), (b) ergonomic needs (comfortable loading height and safe handling), and (c) financial constraints (cost ceiling < IDR 4,000,000).
2. Systematic Prototype Engineering.
   The prototype was developed using an iterative design cycle, consisting of conceptual modeling, visualization, material selection, and fabrication. Each iteration evaluated three key aspects:
   (a) Thermal performance (ability to reach and maintain 600–800°C),
   (b) IoT responsiveness (sensor accuracy and latency of alarm activation), and
   (c) Operational safety (external temperature < 40°C and stable combustion airflow).
   Material selection utilized a cost-performance optimization framework that compared thermal resistance, ease of fabrication, and cost efficiency of recycled components.
3. Comprehensive Performance Testing.
   Performance testing was conducted in controlled and real-use scenarios. The following quantitative tests were performed:
   (a) Combustion Temperature Stability Test: continuous monitoring for 40–60 minutes using DHT22 sensors; stable operation achieved at 600–800°C.
   (b) Waste Reduction Efficiency Test: measurement of mass and volume before and after combustion, showing average 85% volume reduction.
   (c) Emission Measurement: SO_2 concentration measured using a portable gas analyzer, remaining below 120 ppm, following environmental safety thresholds.
   (d) IoT Alert Responsiveness: latency measurement of ESP8266–sensor communication; alarm activation occurred within ≤ 1.2 seconds after ash accumulation reached threshold.
   These tests ensured that the device met functional criteria for safety, efficiency, and environmental compliance.
4. Market Feasibility and Social Acceptance Validation.
   Market validation was carried out using the Segmentation, Targeting, and Positioning (STP) framework. Surveys and interviews were conducted in five different demographic clusters to assess usability, price acceptance, and perceived safety. The prototype achieved 85% user interest and a 4.2/5 satisfaction score, confirming alignment between technical performance and market expectations.

Overall, this systematic approach integrates engineering design, ergonomic consideration, IoT-based monitoring, and market strategy into a comprehensive methodology. It ensures that the prototype is not only technically robust but also economically viable and socially acceptable for household and community-scale waste management.

3. RESULTS AND DISCUSSION

3.1. Flow of IoT implementation

The development of a portable garbage burning device that implements the IoT system, namely by providing a device connected to a remote that is connected to the internet, so the principle of the tool is that if during the combustion process the ash has collected under the ash filter, the sensor will activate when ash accumulates and reduces available space in the combustion chamber. From this sensor, it is forwarded using the principle of the IoT, so that if, during the combustion process, it is left behind, it will provide a sense of security to the user and comfort when the tool is on.

3.2. Market Needs Analysis

Market needs analysis is important in understanding the needs, wants, and demands of customers. The general public, particularly those in densely populated areas, clearly requires an effective, workable, and reasonably priced waste management solution, according to the findings of the market needs analysis gathered through surveys and interviews [31]. From a technological and budgetary standpoint, the prototype design process was directly based on this discovery. Technically speaking, the prototype was made to be portable, simple for non-technical individuals to operate, and capable of autonomously controlling temperature and ash accumulation using IoT technology [32]. This satisfies the community's demand for a waste-burning device that is safe, eco-friendly, and efficient [33]. The following is something that is achieved in analyzing the market needs of this portable garbage burner:

1. Identifying customer needs through direct surveys about complaints in the community, which shows that basic needs can be met by building a portable garbage burner.
2. Focus on customer needs, not only in the product, so that customer expectations can be fulfilled in accordance with the problems that exist in the community environment.
3. Local governments and neighborhoods can measure consumers' desires by assessing the level of demand in an effort to achieve Long-term waste management that is structured and can reach all elements of society so that there is no accumulation of waste.

Financially speaking, the analysis's findings indicate that the community's purchasing power falls between low and medium. Therefore, the key tactics for cutting manufacturing costs without compromising tool functioning are the adoption of affordable and open-source IoT components and the selection of used materials that are still usable.

In addition to being utilised to comprehend customer characteristics, the outcomes of the market needs study and the STP (Segmentation, Targeting, and Positioning) model form the foundation for the technical and financial design of the prototype. According to the findings of surveys and interviews, residents in Yogyakarta's urban and semi-urban areas choose waste management equipment that is inexpensive, portable, energy-efficient, and safe to use. The product engineering process then uses this data as a guide, with technical design concentrating on:

1. Portability and safety, through the use of lightweight materials such as used drums and hollow iron with a heat-insulating system.
2. Combustion efficiency, by maintaining an optimal temperature of 600–800°C using an IoT-based temperature sensor to maintain low energy consumption.
3. Monitoring system reliability, with the integration to send warning signals if the temperature or ash accumulation exceeds optimal limits.

Meanwhile, segment and target market analysis results indicate that primary users are from the productive age group (25–50 years old) with intermediate to high digital literacy levels. Therefore, the IoT system interface design was kept as simple as possible, with an automatic indicator display on the remote alert, without the need for complex additional applications. This approach reinforces the practical value and suitability of the device for the socio-technical context of Yogyakarta residents, who generally have limited space and require a household-scale waste management solution.

3.3. Segmentation, Targeting, and Positioning (STP) Analysis

Segmentation, targeting, and positioning (STP) analysis is an important process in marketing that helps companies to target the right market segments and make optimal products. The following is a segmentation, targeting, and positioning (STP) analysis [34]:

1. Market segmentation is the process of dividing a market into smaller subgroups with similar levels of characteristics, needs, or behavior. Segmentation constitutes the initial step in the STP analysis to identify groups of potential users with distinct characteristics that influence the adoption of an IoT-based portable waste incinerator. Table 1 presents a structured summary of the key segmentation variables relevant to this study, covering geographic, demographic, socioeconomic, behavioral, and technographic factors.

This table serves as the analytical foundation for determining the most appropriate target market and positioning strategy for the proposed prototype.

Table 1. Market segmentation

Segmentation Type	Key Variables	Relevance to Product
Geographic	Urban and semi-urban areas (Yogyakarta and similar regions)	High waste volume, limited land, high need for compact waste solutions
Demographic	Age 20–55 years (productive users) - Household decision-makers	Likely to operate the device, financially capable, familiar with basic technology
Socioeconomic	Middle-income households - Small community groups (RT/RW)	Able to purchase low-cost technology (< IDR 4,000,000) for shared use
Behavioral	Concern for cleanliness - Preference for simple, practical tools - Awareness of waste issues	Motivates adoption of a portable, easy-to-operate incinerator
Technographic	Basic digital literacy - Familiarity with mobile phones/alerts	Required to operate IoT-based temperature and ash alerts

The Table 1 shows that the selection of market segmentation aspects is in accordance with the grouping of consumers in Indonesia based on the criteria that have been selected and adjusted.

2. Try not to put market targeting, which is a process of selecting one or more market segments, and an evaluation process to determine which market segments to serve [19]. This is an important consideration in selecting the most profitable segment, aligned with the company's objectives. In this case, the target selection is rural communities, cities, and areas with densely populated and rural demographics, as well as people who want a healthy life and smooth and energetic activities. Therefore, the innovation of making portable waste can reach all targets with the assumption that the tool can be moved, is environmentally friendly, low in emissions, and does not take up much space, which makes the tool useful for all groups and can work effectively and efficiently.
3. Positioning is a process of placing products that can adapt to the community environment and make the desires of consumers themselves compared to competing products [5]. This portable trash burner is designed with the concept of affordable prices, using environmentally friendly technology, and making products with superior safety, so that this tool can become a friendly customer need among the community.

The primary target market is the productive age group in urban and semi-urban areas, according to the demographic and geographic parameters used for segmentation. Households and RT/RW communities are among the categories that are the focus of the targeting process since they have a greater demand for autonomous waste management solutions. In order to align with the values desired by the target market, the product is positioned as a useful, cost-effective, and ecologically friendly waste management solution. Validation that the prototype will be accepted by the market is carried out with two approaches: first, through qualitative and quantitative feedback from respondents on the initial prototype, and second, through direct trials in several locations with different market characteristics. The interest rate of 85% and a user satisfaction score of 4.2 out of 5.0 indicate that the prototype design has met market expectations, both technically and financially. From a financial standpoint, cost and price strategies are also determined by the findings of the STP study. Setting a maximum acceptable price limit without sacrificing device quality is based on the market categories identified as middle-income households and MSMEs. By (a) employing recycled materials to cut production costs by 35–40% and (b) choosing open-source hardware-based IoT modules to reduce reliance on imported components, this strategy is put into practice utilising the cost-performance optimisation concept.

The validation process also identified several important user feedbacks, such as the need for a backup battery and ease of maintenance, which will be the focus of further development. Overall, the prototype proved to be both technically and financially feasible and has strong potential for market adoption, especially in environments with limited access to centralized waste management systems.

3.4. Attention

Technical validation was conducted through direct testing of the device under real conditions, including monitoring the temperature during the combustion process, the speed of ash accumulation, and the effectiveness of the IoT sensor in providing warnings to users. Technically, the device is able to maintain a stable temperature in the range of 600–800°C with an accurate alarm sensor response. From a financial perspective, the calculation results show that production costs can be reduced to below IDR 4,000,000, including the ESP8266-based IoT module, DHT22 temperature sensor, and recycled materials. This makes the prototype feasible for mass production with a reasonable profit margin for local manufacturers. Trials at five locations with different market characteristics showed a user interest rate of 85% and a satisfaction score of 4.2 out of 5. This indicates that the prototype has market feasibility both technically and economically. Prototype Specifications with the Concept of IoT as shown in Figure 3.

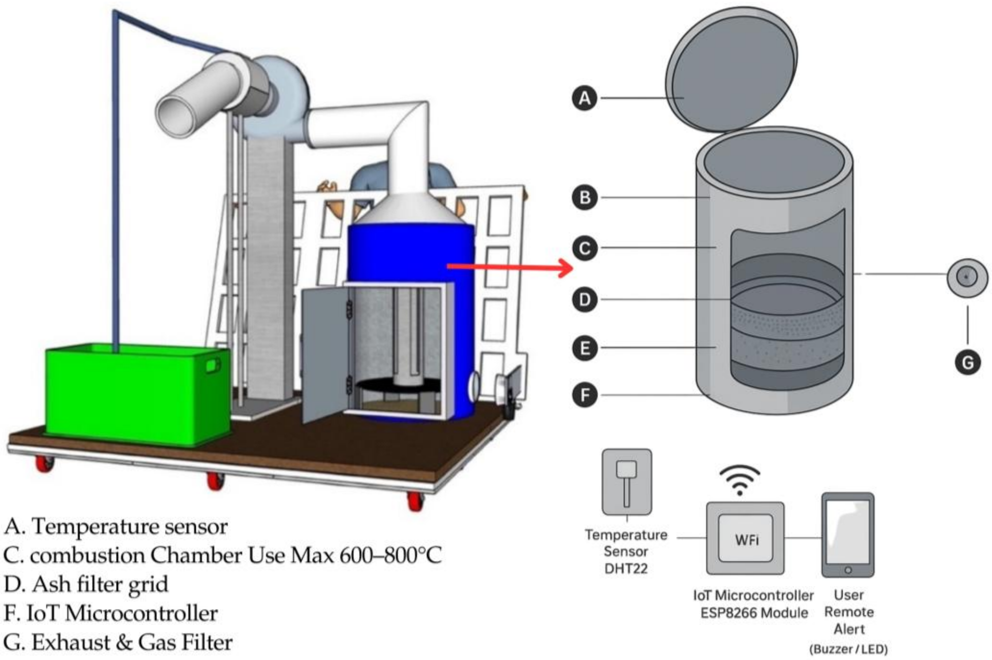

Figure 3. Prototype Specifications with the Concept of IoT

Prototype testing was conducted under two conditions:

1. Controlled testing at a laboratory/open-air test site to continuously monitor thermal and emission parameters.
2. Field testing (real-use) at different locations in the Yogyakarta region to test operational performance, user comfort, and market acceptance. Each technical test was run at least 3 times for each representative waste material loading scenario (organic-dominant, plastic-dominant, and mixed household). Each combustion cycle was observed for 40–60 minutes to check combustion stability and IoT system response. The instruments and measured parameters used in this study are described as follows:

1. Sensors & IoT: The ESP8266 module is connected to a DHT22 temperature sensor for real-time combustion chamber temperature monitoring and determination of the ash accumulation threshold.
2. Emissions measurement: A portable gas analyzer is used to measure SO_2 concentration during operation. (Please list the brand/type of instrument in the final draft if available.)
3. Waste reduction measurement: The mass and/or volume of waste is measured before and after combustion to calculate the percentage volume and mass reduction. Precision digital scales and simple volumetric measurements are used.

4. IoT response time: Alarm latency is measured from the occurrence of the ash accumulation threshold to the warning signal sent by the ESP8266 module.
5. User data collection: Surveys and short interviews with field test users (n at each site) are conducted to assess acceptability, ease of operation, and satisfaction (scale of 1–5).

4. CONCLUSION

Based on the research results above In order to solve the problems associated with household waste management in urban and semi-urban locations such as Yogyakarta, this study successfully produced the design and performance analysis of a portable garbage incinerator based on the IoT whose technical performance, cost structure, and safety profile demonstrate significant improvements over existing low-cost designs. The prototype's production cost remains below IDR 4,000,000, positioning it as a more economical alternative to commercially available small incinerators. In terms of environmental performance, the device maintains SO_2 emissions below 120 ppm, supported by stable combustion temperatures of 600–800°C, indicating higher combustion efficiency relative to comparable prototypes. The incorporation of real-time IoT monitoring, automated temperature and ash accumulation alerts, and external thermal insulation below 40°C provides additional safety features that are rarely found in low-budget systems. These elements strengthen operational reliability while reducing user risk.The ergonomic configuration, informed by Indonesian anthropometric data, and the positive market validation results affirm that the prototype is not only technically sound but also socially acceptable and commercially viable. The device offers distinct comparative advantages in cost, emission safety, and technological integration, highlighting its novelty and reinforcing its contribution as a practical, scalable solution for household and community waste management.

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