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Design and development of an IoT-based burner-wet scrubber system for mitigating emissions from agricultural waste combustion

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ABSTRACT
Background: This study is situated in the context of increasing agricultural waste generation and the continued reliance on open burning practices in rural farming areas, which contribute to air pollution, greenhouse gas emissions, and occupational exposure risks. The aim of this study is to design and examine a transitional engineering solution in the form of an Internet of Things (IoT)-based Burner-Wet Scrubber system to support controlled biomass combustion and emission mitigation in agricultural waste processing. Previous studies have primarily focused on composting and agricultural waste reuse, with limited attention to practical solutions for small-scale farming. **Methods:** This study applies an engineering-experimental approach consisting of reverse engineering analysis, system design, prototype development, and pilot testing under controlled biomass combustion conditions. Data were collected through IoT sensor monitoring of combustion temperature and exhaust flow behavior, accompanied by observational assessment of particulate dispersion and functional performance of the wet scrubber unit. **Findings:** The proposed system is capable of processing 100 to 875 kg of agricultural waste per cycle while producing a char yield of 25 to 35% under controlled pyrolysis with an electrical power consumption of approximately 1200 W. The results show that the system operates effectively as an integrated combustion and filtration unit, characterized by more stable combustion conditions inside the burner chamber and a visible reduction in particulate dispersion compared to open burning conditions, while the monitoring interface facilitates transparent process observation and operational evaluation. These findings support the theoretical position of the system as an engineering intervention that aligns environmental mitigation objectives with practical field conditions. **Conclusion:** The study concludes that an IoT-based Burner-Wet Scrubber system has the potential to serve as a feasible, adaptive, and community-scale emission mitigation alternative for agricultural waste combustion. **Novelty/Originality of this article:** The novelty of this study lies in integrating a controlled burner, wet scrubber, and real-time IoT monitoring for smallholder agricultural applications.

KEYWORDS: agricultural waste; emission mitigation; IoT.

1. Introduction

Indonesia is an agrarian country, a condition in which the economic and social structure is strongly supported by the agricultural sector, both in terms of its economic contribution, employment absorption, as well as its role in food security and commodity

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trade (Kusumaningrum, 2019). Economically, the agricultural sector contributes approximately 12.4–14.3% to the national Gross Domestic Product (GDP), indicating that agriculture remains an essential pillar in Indonesia's economy (Bagus et al., 2024). From a land-use perspective, based on IndexMundi survey data, around 30% of Indonesia's total land area is used for agricultural activities. Furthermore, data from the 2023 Agricultural Census show that agricultural landowners are distributed across all provinces in Indonesia, consisting of 28.42 million Agricultural Household Enterprises/*Rumah Tangga Usaha Pertanian* (RTUP) and 29.34 million Individual Agricultural Enterprises/*Usaha Pertanian Perorangan* (UTP), with the majority of farmers engaged in food crops and plantation commodities. This condition illustrates that agricultural land in Indonesia is not only extensive, but also intensively utilized by millions of agricultural actors across different regions.

The agricultural sector in Indonesia, particularly the food-crop subsector which includes rice, maize, and tuber crops and the plantation subsector such as oil palm, rubber, and coffee, constitutes the dominant components within the national agrarian structure (Dina, 2024). This is reflected in the extensive distribution of agricultural land for rice cultivation across nearly all regions of Indonesia, both on Java Island and in several provinces outside Java that serve as national food production centers (Rachman et al., 2022). This statement is supported by Statistics Indonesia/*Badan Pusat Statistik* (BPS) 2024 data, which shows that East Java ranks as the province with the largest harvested rice area in Indonesia, reaching 1.87 million hectares, followed by Central Java with 1.8 million hectares and West Java with 1.55 million hectares. Other provinces outside Java also demonstrate significant agricultural land dominance, namely North Sumatra and South Sulawesi, with harvested rice areas of 956.7 thousand hectares and 882.4 thousand hectares, respectively.

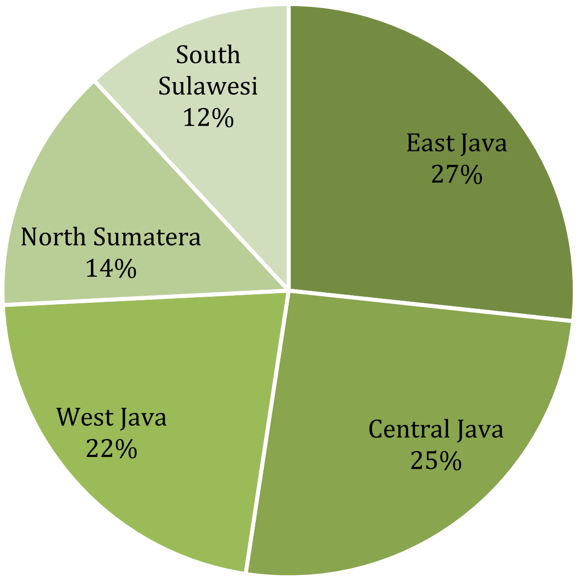

Fig. 1. Provinces with the largest agricultural land areas in Indonesia (BPS, 2024)

Overall, the total harvested rice area in Indonesia in 2024 reached approximately 10.05 million hectares, producing 52.66 million tons of milled dry unhusked rice (GKG), which is one of the primary food commodities forming the basis of national rice supply. In addition to rice, other commodities such as maize also have significant production scale and land coverage. In 2024, the harvested maize area reached around 2.55 million hectares, with a production volume of more than 15 million tons of dried maize kernels (BPS, 2024).

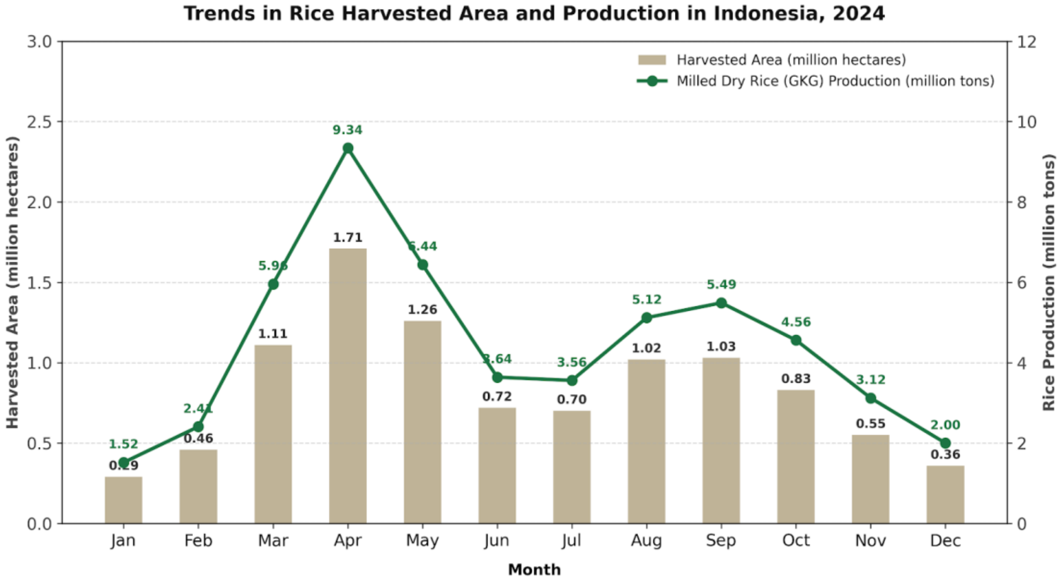

Fig. 2. Harvested area of rice in Indonesia
(BPS, 2024)

The agricultural sector in Indonesia not only encompasses food crop production, but also the plantation subsector, which is widely developed and distributed across almost all regions of the country (Faoziyah et al., 2024). According to the Agricultural Mechanization and Modernization Agency/*Balai Penerapan Modernisasi Pertanian* (BPMP) in 2025, the total plantation area in Indonesia has reached 27 million hectares, managed by approximately 17 million plantation farmers operating at both small and large scales throughout Indonesia. One of the key plantation commodities is oil palm, with a total oil palm plantation area reaching 16 thousand hectares in 2024. The dominance of the plantation subsector particularly oil palm is also reflected in the distribution of its land area across various provinces. Based on Statistics Indonesia (BPS) 2024 data, Riau Province is recorded as the region with the largest oil palm plantation area in Indonesia, reaching 3.4 thousand hectares, followed by Central Kalimantan with 2.16 thousand hectares, West Kalimantan with 2.15 thousand hectares, and East Kalimantan with 1.48 thousand hectares. The total oil palm plantation area continues to increase from year to year and is even projected to reach around 17 thousand hectares based on expansion trends over the past decade (Murphy et al., 2021). In addition to land area, oil palm also shows strong production potential. Based on Statistics Indonesia data for 2023 and 2024 on national oil palm production, there has been a consistent increase over time. In 2023, Indonesia produced 47.08 tons of oil palm, and this figure rose to 47.47 tons in 2024.

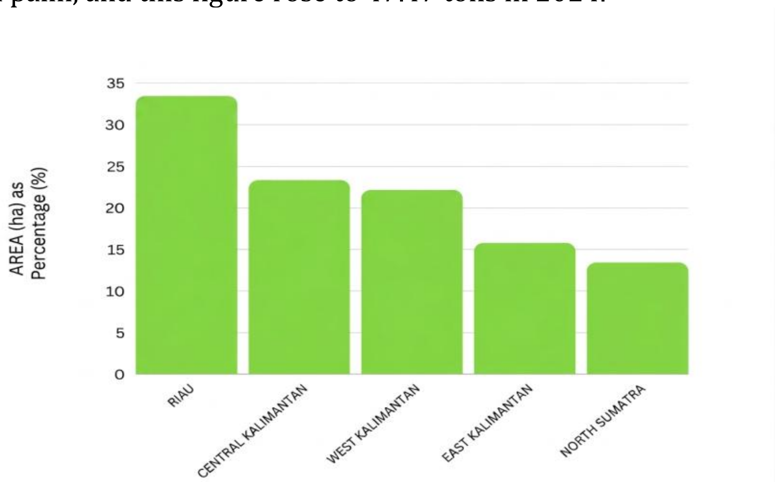

Fig. 3. Provinces with the largest oil palm plantation areas in Indonesia
(BPS, 2024)

The data above demonstrate that the scale of land allocated for agricultural activities in Indonesia includes not only rice fields, but also dryland farms, plantations, and productive upland areas distributed across Sumatra, Kalimantan, Java, Sulawesi, and the eastern regions of Indonesia. Thus, the wide spatial distribution of agricultural land serves as empirical evidence that agriculture occupies a substantial portion of Indonesia's national land-use structure (Juniyanti et al., 2021). This further reinforces the characterization of Indonesia as an agrarian country whose geographic and demographic conditions are strongly supported by agriculture as the socio-economic foundation of its society (Yulianda & Harini, 2020). However, behind this strategic contribution, the agricultural sector also generates agricultural waste in very large quantities as a direct consequence of production and post-harvest processes (Wijaya & Syam, 2021). Agricultural residues such as rice straw, rice husks, corn stalks, corn cobs, sugarcane bagasse, coconut husks, and other biomass residues continue to increase in volume in line with the intensification and modernization of agricultural production (Gupta et al., 2022).

On the other hand, the Paris Agreement, ratified on December 12, 2015, represents a significant milestone in global climate policy. The agreement establishes a comprehensive framework for addressing climate change in pursuit of a low-carbon and sustainable future. It requires countries to enhance and update their Nationally Determined Contributions every five years and encourages a dynamic and progressive approach to climate action (Sihotang, 2025). At the same time, global warming has emerged as a critical international issue due to its substantial impacts on climate change. Biodiversity, human survival, and ecosystems are all threatened by global warming driven by everyday human activities (Ariska et al., 2022). Countries with large populations and high levels of industrialization including Indonesia tend to have high carbon footprints, meaning they are responsible for a considerable share of carbon emissions contributing to global warming (Dian, 2024). Producing more than 704.4 million tons of carbon in 2023, Indonesia is the sixth-largest carbon emitter in the Asia-Pacific region.

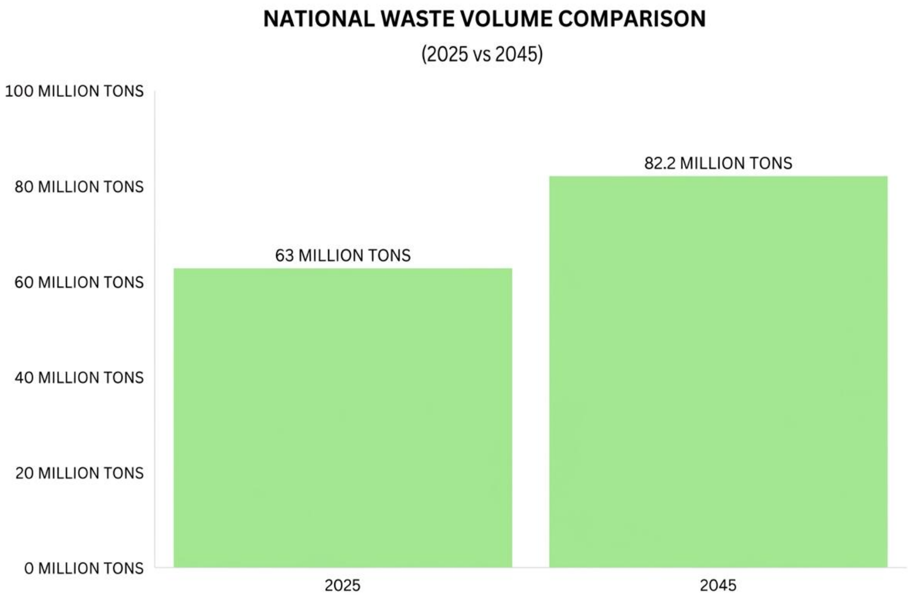

Fig. 4. National waste volume comparison 2025 vs 2045
(Yonatan, 2025)

The main challenge in agricultural waste management in Indonesia lies in the imbalance between the massive scale of agricultural waste generated and the limited availability of adequate waste-management systems (Arista, 2024). This condition emerges when the increasing volume of agricultural residues is not accompanied by proper management capacity, despite extensive agricultural land and high production intensity. The agricultural sector in Indonesia produces a substantial amount of waste every year (Dewi et al., 2024). According to the Long-Term National Development Plan (2025–2045)

Strategic Environmental Assessment Report issued by the National Development Planning Agency/*Badan Perencanaan Pembangunan Nasional* (Bappenas), Indonesia's waste volume in 2025 is projected to reach 63 million tons and is estimated to increase to 82.2 million tons by 2045 with agricultural waste identified as one of the major contributing sectors.

Indonesia is currently facing a severe waste management problem. Based on data from the Ministry of Environment, the total volume of waste generated in Indonesia has reached 73 million tons per year, or the equivalent of 200 thousand tons per day. This figure is dominated by organic waste, a large proportion of which originates from agricultural waste, amounting to approximately 150 million tons per year. These agricultural residues come from food crop and plantation activities, including rice straw, rice husks, corn cobs, sugarcane stalks, and empty fruit bunches of oil palm. In the food crop subsector, rice straw contributes around 80 million tons per year, while the plantation subsector, particularly oil palm, produces more than 40 million tons per year in the form of empty fruit bunches, fibers, and shells (Irawan et al., 2023). The magnitude of this volume indicates that agricultural waste is not a peripheral issue, but rather a structural consequence of the national agricultural production system (Chen et al., 2022).

The large volume of agricultural waste generated is not matched by adequate post-harvest recycling efforts. In Indonesia, the percentage of agricultural waste that is processed remains very low, with the post-harvest agricultural waste recycling rate currently below 10%, meaning that around 90% of agricultural residues are not managed properly or in an integrated manner (Arista, 2024). In many rural areas, more than 60% of agricultural waste is still managed through open burning practices, particularly during the post-harvest phase. This method is often chosen because it is considered the fastest, cheapest, and most practical way to clear land and prepare it for the next planting season (Judijanto, 2025). However, behind this convenience lies a serious and cumulative environmental consequence. Open burning of agricultural waste without emission control produces various harmful pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), sulfur dioxide (SO_2), as well as fine particulate matter $PM_{2.5}$ and black carbon (Kirasamutranon et al., 2025).

Within the context of national emission inventories, the agricultural sector was recorded as generating approximately 53.93 million tons of CO_2-eq in 2022, originating from several activities including paddy field management, fertilizer use, and agricultural waste burning (Hidayat, 2025). In the long term, the accumulation of emissions from agricultural residues that are burned openly without proper management may accelerate global warming and exacerbate climate change (Harahap et al., 2024). According to data from the World Resources Institute (2021), there are five major sectors contributing to global greenhouse gas emissions, with the energy sector being the largest contributor at 75.7%, followed by the agricultural sector as one of the next largest contributors. Although its contribution is still below that of the energy and forestry sectors, emission trends from agriculture continue to increase in line with production intensification and land expansion (Raihan et al., 2022). Among agricultural by-products, rice husk a residue from rice cultivation in the food crop subsector is often neglected and simply burned, making rice cultivation one of the second-largest contributors to greenhouse gas emissions within the agricultural sector (Fathia et al., 2024).

Based on these conditions, it can be projected that, without effective mitigation interventions, emissions from agricultural burning will continue to increase over the coming decades, thereby intensifying pressure on national emission-reduction efforts and Indonesia's commitments to the global climate agenda. Ironically, a sector that should serve as a pillar of environmental sustainability has the potential to become a source of environmental degradation when its waste is not managed responsibly (Bansal et al., 2025). Furthermore, the issue of agricultural waste burning cannot be reduced merely to behavioral factors or low environmental awareness among farmers, as such a perspective risks placing the blame on farmers without addressing the deeper structural roots of the problem (Suswandi, 2022).

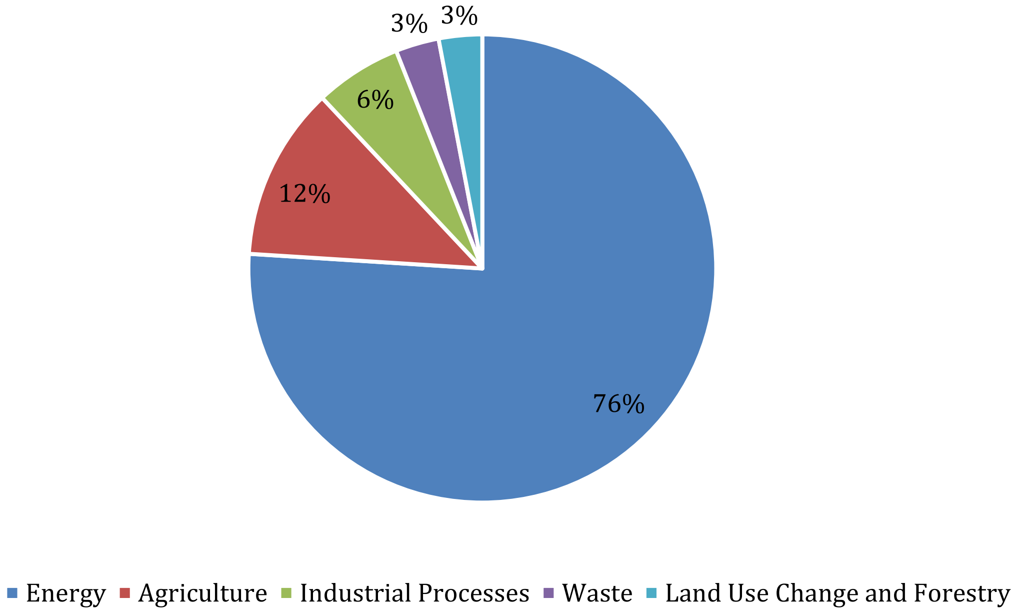

Fig. 5. Global greenhouse gas emissions diagram
(World Resources Institute, 2021)

Limited access to waste-processing technology, inadequate supporting infrastructure, and the absence of incentive systems that encourage productive waste utilization make open burning the dominant option that farmers find difficult to avoid. In other words, open burning represents a manifestation of systemic failure in providing appropriate technology that is compatible with the social, economic, and geographical context of rural areas (Suryani et al., 2025). This condition reflects a clear gap between global sustainability agendas and field realities in Indonesia's agricultural sector. On one hand, the world demands large-scale carbon reduction and ecosystem protection; on the other hand, the primary actors in the field are not yet equipped with the technical means necessary to meaningfully contribute to these agendas. Without technological interventions that are both applicable and adaptive, sustainability demands risk becoming an additional burden for communities rather than a shared solution.

The challenge of agricultural waste in Indonesia does not lie solely in the prevalence of open burning, but also in the absence of waste-management solutions that are truly effective, innovative, and capable of generating added value both for agricultural residues and for local communities in economic terms (Kusumastuti et al., 2025). Previous approaches to agricultural waste utilization have often focused on reuse as compost or animal feed. However, these solutions still face managerial and technical constraints (Judijanto, 2025). One of the main challenges is processing time, as the microbial decomposition needed to reduce organic carbon and nitrogen requires a relatively long period, sometimes months depending on climatic conditions, humidity levels, and processing techniques. In agricultural systems that depend on rapid crop rotation, long decomposition cycles are often perceived as an obstacle to land preparation (Al-Musawi et al., 2025).

In addition, manual waste-processing activities involve repetitive physical tasks such as carrying, turning, mixing, and arranging waste piles, which may increase physical workload, fatigue risk, and non-ergonomic working postures, particularly among elderly farmers and informal rural laborers (Silvia et al., 2024). From an engineering ergonomics perspective, most existing agricultural waste-management solutions have not been designed with adequate consideration of user comfort and operability. Moreover, many agricultural waste-management initiatives still emphasize waste reduction without integrating value-added utilization (Muzdalifah & Ruqayyah, 2025). In fact, agricultural residues hold potential to be integrated into biomass industries, bioenergy systems, alternative materials, or advanced land-processing technologies. As a result, agricultural residues are still positioned as low-value surplus materials often limited to composting rather than recognized as potential resource inputs (Ramirez et al., 2021). This condition highlights a technological innovation gap in developing engineering solutions that transform agricultural waste into value-added materials.

Without engineering innovations that can accelerate processing time, enhance functional utility, and remain ergonomically feasible for users, farmers ultimately return to open burning as the fastest, cheapest, and least labor-intensive option. Referring to one of the mandates of the Republic of Indonesia as stated in Law No. 18 of 2008 concerning sustainable waste management, all forms of waste produced represent a form of responsibility arising from patterns of consumption and production. Furthermore, the issue of agricultural waste management in Indonesia has direct implications for the achievement of sustainable development targets, particularly SDG 9: Industry, Innovation and Infrastructure, and SDG 13: Climate Action.

Within the context of SDG 9, continued reliance on conventional waste-handling methods such as open burning reflects a technological and infrastructural gap in small-scale agricultural systems. SDG 9 emphasizes the importance of strengthening industrial engineering capacity, adopting appropriate technology, and developing inclusive infrastructure to improve production efficiency while reducing environmental impact. Meanwhile, agricultural waste burning is closely related to SDG 13: Climate Action, as open biomass combustion releases multiple greenhouse gas emissions, particularly CO_2, CH_4, and black carbon, which contribute to global warming. These emissions not only have local-scale impacts in the form of air-quality degradation and health risks, but also contribute to the accumulation of atmospheric greenhouse gas concentrations (Sokhi et al., 2021). This condition calls for engineering solutions that are not only capable of reducing emissions, but also adaptive to the practical constraints faced by farmers.

2. Methods

2.1 Overview

This study was conducted in the context of agricultural waste management practices in rural farming areas where open burning of biomass remains widely applied due to the absence of low-cost and appropriate emission-control technologies. The research was carried out over a period of several months, covering the stages of conceptualization, system design, prototyping, and experimental testing of the BERIKLIM system, a Burner–Wet Scrubber integrated with Internet of Things (IoT) monitoring for controlled biomass combustion. The study focuses on agricultural residues such as rice husks, corn cobs, and dried agricultural biomass which are commonly burned openly during the post-harvest season. This practice contributes to smoke formation and greenhouse gas emissions, particularly carbon monoxide (CO) and particulate matter. The development of BERIKLIM is positioned as a transitional environmental technology, aiming to reduce the negative environmental impacts of biomass burning while remaining feasible for community-scale agricultural use.

The selection of the study context and testing environment was based on the prevalence of open burning as a dominant disposal method for agricultural residues, the absence of affordable emission-control alternatives, and the relevance of introducing a semi-technical system capable of stabilizing combustion and filtering exhaust gas prior to release. From an ontological perspective, this research acknowledges that biomass burning persists as a necessary practice in rural areas due to economic and accessibility constraints. Epistemologically, the research applies engineering-based experimental inquiry, where system design decisions are validated through prototyping, field-aligned testing, and quantitative sensor-based measurements.

2.2 Identification of needs and field-based problem mapping

The initial stage of the research was conducted through a literature review, field observation of existing practices, and discussions with local stakeholders to understand the characteristics of biomass burning in real-field conditions, the risks of smoke exposure to operators, the limitations of available emission-control facilities, and the need for simple and easy-to-operate technological solutions. From this process, several key technical requirements were identified, namely: a combustion system capable of maintaining temperature and airflow stability; an exhaust-gas filtration mechanism to reduce particulate dispersion and emissions; a data-based monitoring system to support operational evaluation; and a design that is easy to maintain and suitable for community-scale agricultural use. Agricultural biomass residues were selected as the test material because they are commonly burned after the harvest period. This stage ensured that the technology developed was not only laboratory-based, but also relevant to field conditions and user needs.

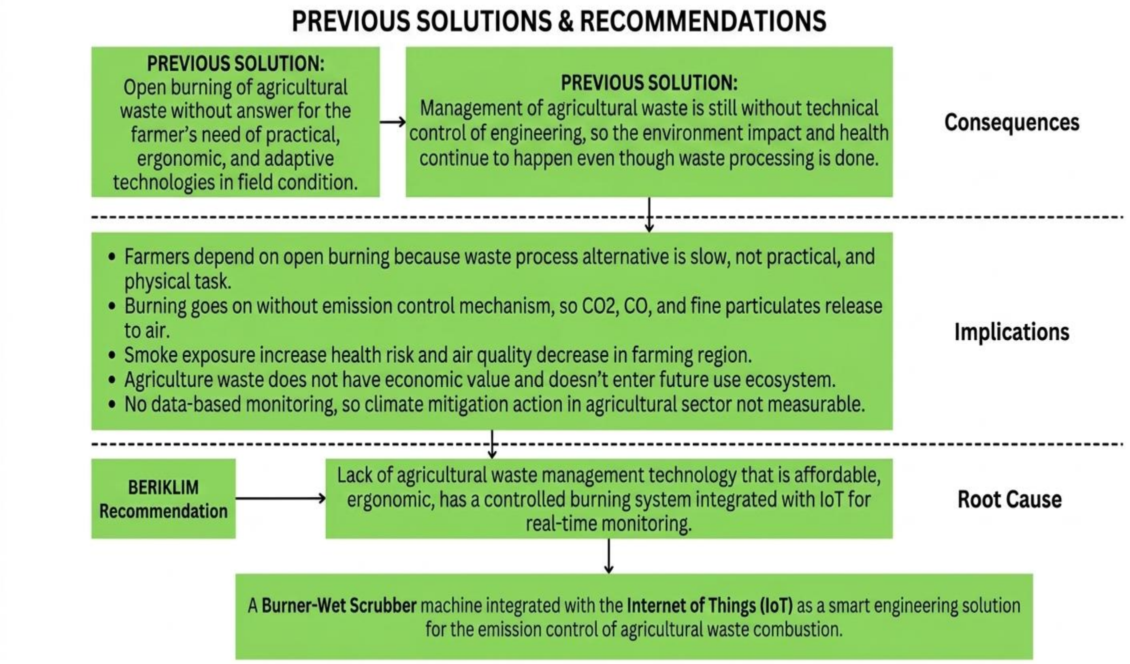

Fig. 6. Problem analysis tree of pre-BERIKLIM solutions

2.3 Reverse engineering

The design of the BERIKLIM system employed a reverse-engineering approach, in which existing small-scale biomass burning practices were analyzed to derive the most critical functional components, which were then reconstructed into a new system that is safer and more measurable in its operation. The stages of the reverse-engineering process included the analysis of flame behavior and exhaust-gas flow pathways, identification of points of smoke and particulate formation, determination of key design parameters (temperature, airflow, and exhaust-gas direction), functional modeling of the burner and wet scrubber components, and evaluation of material affordability and ease of assembly. This approach was selected to ensure that the technology developed remains contextually relevant and simple in construction, while still demonstrating improved environmental performance. At this stage, the integration of an IoT-based monitoring system was also established as a means of ensuring process transparency and systematic recording of operational data.

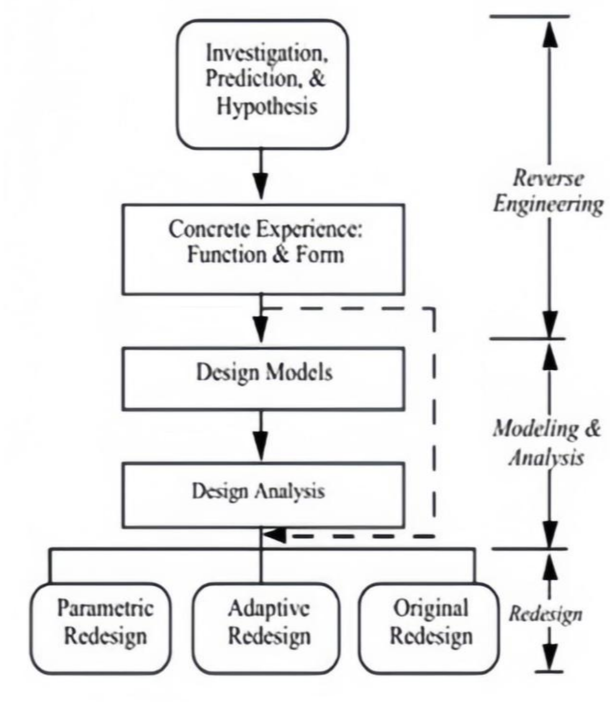

Fig. 7. Reverse engineering processes

2.4 System design and component configuration

The BERIKLIM prototype consists of three main subsystems, namely the burner unit, wet scrubber unit and IoT-Baset Real-Time Monitoring System. The Burner Unit functions as a controlled combustion chamber to reduce incomplete combustion and uncontrolled smoke formation. Meanwhile, The Wet Scrubber Unit is designed to filter exhaust gas through contact with a liquid medium to reduce particulate concentration and absorb gaseous emissions. In addition, IoT-Based Real-Time Monitoring System: comprising microcontroller modules, temperature sensors, gas concentration indicators, and a digital dashboard for recording operational data. The design considered airflow direction, exhaust pathway routing, thermal distribution, and operator access. The configuration was arranged so that exhaust gases produced from combustion first pass through the connecting duct, then enter the wet scrubber prior to atmospheric release. A simple structural frame was selected to support ease of assembly, maintenance, and potential replication in similar agricultural environments.

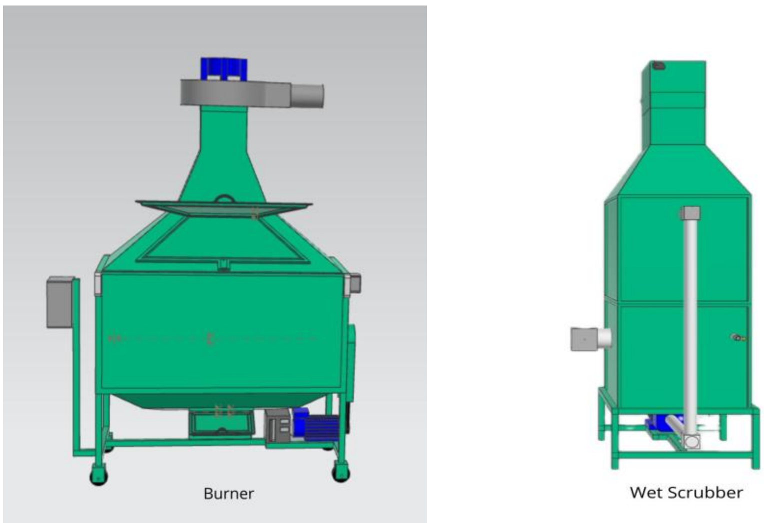

Fig. 8. Burner-Wet scrubber design

2.5 Prototype development and assembly

Following the completion of the design process, a prototype was constructed using a welded steel frame to support the burner chamber, gas pathway, and wet scrubber unit. A drum was used as the combustion chamber structure, supported by an air supply system to stabilize combustion during operation. The wet scrubber system was constructed as a compact filtration unit designed for compatibility with the burner exhaust flow. The IoT monitoring modules were installed to collect combustion-related parameters, and wiring integration was carried out to enable synchronized data logging. The prototype development stage served as both a technical implementation phase and a design validation process, ensuring that the constructed system was aligned with the initial engineering objectives.

3. Results and Discussion

3.1 Solutions

Results Based on the previously discussed issues in agricultural waste management, it can be concluded that open burning remains the dominant practice among farmers in many rural areas. This condition is primarily driven by limited access to appropriate technologies, inadequate supporting infrastructure, and the absence of practical and economically feasible alternatives for waste management. These findings indicate that the core problem does not lie in the existence of biomass burning itself, but rather in the lack of an engineering-based system capable of controlling and mitigating the environmental impacts of a practice that remains difficult to avoid in current field conditions.

In response to this challenge, this study proposes a transitional solution that is realistic, adaptable to the socio-economic conditions of smallholder farmers, and capable of significantly reducing harmful exhaust gas emissions and particulate matter. The proposed approach focuses on the application of an engineered combustion system integrated with emission control mechanisms, serving as a technical mitigation strategy for agricultural waste burning practices. This approach is not intended to legitimize open burning practices, but rather to provide an interim mitigation framework for emissions arising from activities that continue to occur in practice. By adopting this perspective, environmental sustainability efforts are not placed solely on behavioral changes among farmers, but are instead supported by technological interventions that enable a more controlled, measurable, and environmentally responsible combustion process.

Conceptually, the proposed system integrates a controlled combustion unit with a wet-based emission control device within a single operational framework that can be monitored in real time through Internet of Things (IoT) technology. This integration is designed to ensure that agricultural waste combustion does not occur in an uncontrolled manner, as observed in conventional open burning, but instead operates under monitored, safer, and more environmentally accountable conditions.

3.2 System architecture diagram

As illustrated in Figure 8, the proposed Internet of Things (IoT) system architecture is designed with the ESP32-S3 microcontroller as the main control and processing unit. The ESP32-S3 functions as the central node that acquires sensor data, executes control logic, and coordinates actuator operations, while simultaneously enabling real-time data communication through a cloud-based platform. This centralized architecture allows integrated monitoring, control, and data logging within a single embedded system framework. During the combustion process, temperature inside the burner chamber is continuously monitored using a K-type thermocouple coupled with a MAX6675 thermocouple amplifier module. The MAX6675 converts low-level thermoelectric signals into digital temperature data, allowing precise and reliable temperature measurement under high-temperature operating conditions. This temperature data serves as a critical parameter to ensure that the oxidation process of agricultural waste remains stable, efficient, and within predefined safety thresholds, thereby preventing incomplete combustion or excessive thermal stress on system components.

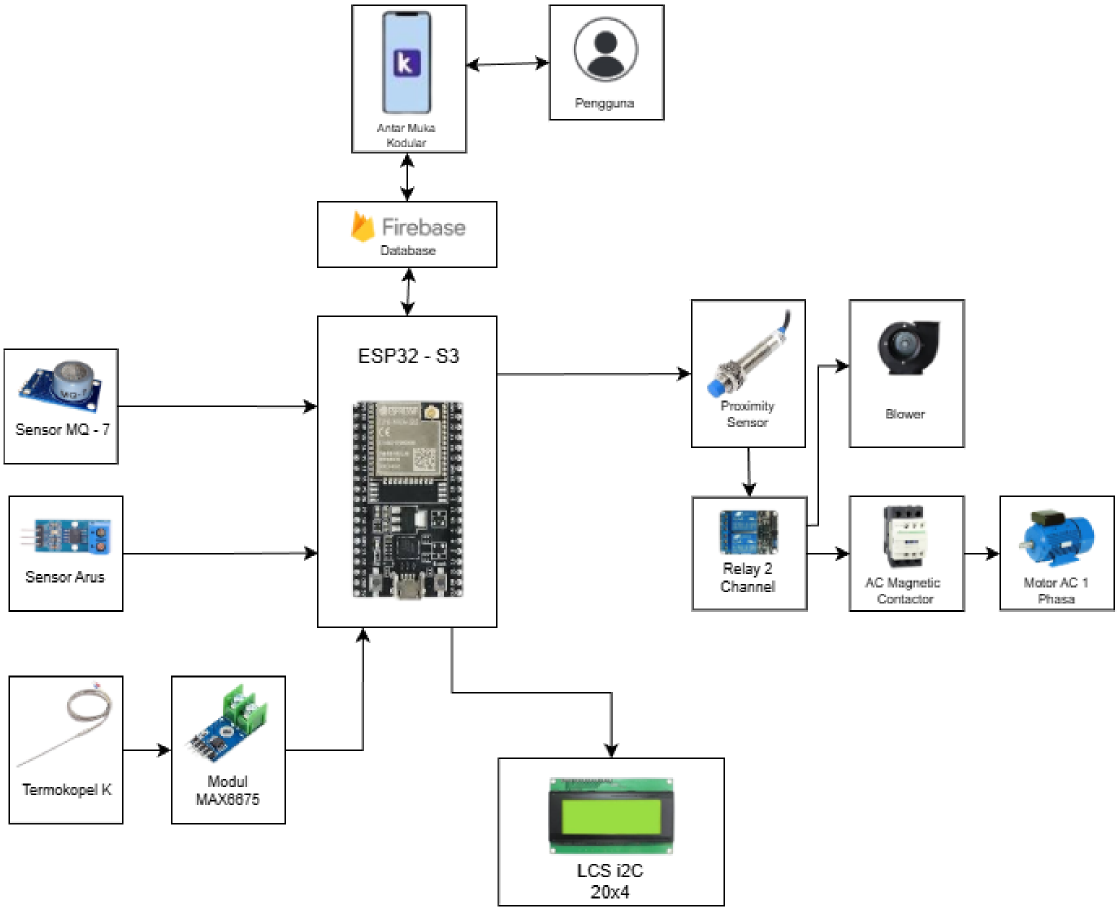

Fig. 9. System architecture diagram

In addition to temperature monitoring, exhaust gas conditions are observed using an MQ-7 gas sensor, which is utilized to detect carbon monoxide (CO) concentration as an indicator of combustion quality. Elevated CO levels may signify incomplete combustion, prompting corrective actions within the control system. Furthermore, an electrical current sensor is employed to monitor the power consumption of major electrical loads, enabling indirect assessment of actuator performance and operational efficiency. These sensor inputs collectively provide a comprehensive representation of the combustion and emission control conditions. The actuation subsystem is designed to regulate airflow and mechanical operations within the system. A proximity sensor is implemented as a safety and automation mechanism to detect the presence or position of mechanical components before enabling actuator activation. Based on sensor inputs and predefined control logic, the ESP32-S3 triggers a dual-channel relay module that interfaces with higher-power devices.

One relay channel controls a blower unit responsible for regulating airflow into the combustion chamber, while the other channel actuates an AC magnetic contactor connected to a single-phase AC motor. This configuration allows safe isolation between low-voltage control circuits and high-voltage power systems, enhancing operational safety and system reliability. For local monitoring and user feedback, the system is equipped with a 20×4 I2C-based LCD module. This display presents real-time information such as combustion temperature, gas concentration status, and system operating modes, enabling operators to observe system conditions directly at the device level without relying solely on remote interfaces. At the application layer, a modular mobile interface enables bidirectional interaction between users and the system. Sensor data transmitted from the ESP32-S3 is uploaded to a Firebase-based cloud database, where it is stored and synchronized in real time. Users can access this data through the mobile application to monitor system performance, review operational status, and issue control commands when necessary. The integration of Firebase ensures scalable data handling and supports remote supervision without requiring complex server-side infrastructure.

3.3 3D model of the burner–wet scrubber machine

The exhaust gas generated during the combustion process is subsequently directed to the wet scrubber unit, as illustrated in Figure 10, which shows the physical integration between the burner chamber and the wet scrubber through a dedicated gas channel. This configuration ensures that combustion by-products are not released directly into the atmosphere, but instead undergo a controlled emission treatment process before discharge. Along the exhaust gas pathway, an MQ-7 sensor is installed to detect carbon monoxide (CO) concentration, while an opacity sensor is employed to measure the turbidity of the exhaust gas caused by fine particulate matter. These sensors operate simultaneously to provide a comprehensive representation of emission quality during the combustion process, serving as key indicators for environmental impact monitoring. All sensor data are transmitted to the ESP32-S3 microcontroller for processing and subsequently synchronized with a Firebase cloud database. The stored data are then visualized through a Kodular-based monitoring application, allowing users to monitor system conditions such as combustion temperature, CO concentration, and emission levels in real time. Through this mechanism, the agricultural waste processing system transitions from a previously passive operation to a transparent, data-driven system, in which critical combustion and emission control parameters can be continuously observed through an IoT-based monitoring framewor.

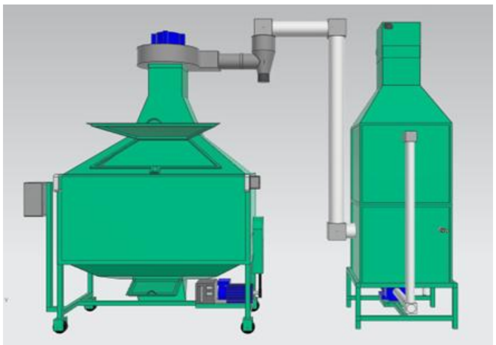

Fig 10. 3D model of the burner–wet scrubber machine

In addition to digital monitoring, the burner–wet scrubber system is designed with operational simplicity and user ergonomics in mind. The ash discharge mechanism is based on a simple karakuri principle, whereby combustion residues are released downward using gravitational force through an opening mechanism located at the bottom of the burner chamber, as shown in Figure 11. This design reduces the need for manual lifting and minimizes operator workload during cleaning and maintenance processes.

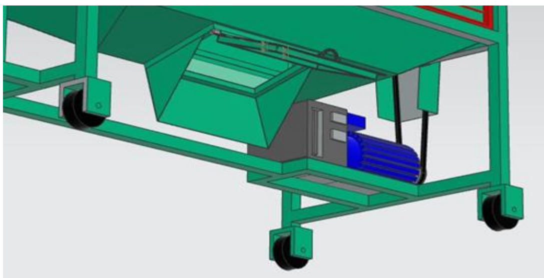

Fig. 11. Gravity-based ash discharge mechanism (karakuri system) at the bottom of the burner chamber

To support mobility and operational flexibility in field applications, the machine is equipped with rolling wheels integrated into the lower frame structure. This feature allows the system to be easily moved or repositioned according to site-specific requirements. The overall top view and structural layout of the machine, including the arrangement of major components, are presented in Figure 12, which illustrates the compact and mobile design of the burner–wet scrubber system.

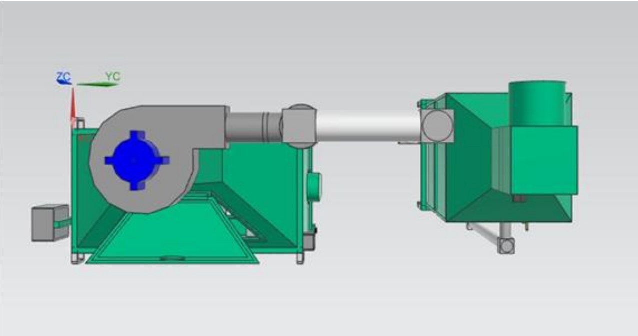

Fig. 12. Top view and 3D design of the burner–wet scrubber system showing blower and gas flow configuration

From the actuation perspective, the system incorporates a blower responsible for conveying exhaust gas from the burner chamber to the wet scrubber unit. The blower and combustion unit are driven by a single-phase AC motor, which is interfaced with the control system via a 5 V relay module and an AC magnetic contactor. To enhance operational safety, a proximity sensor is integrated into the control system, as illustrated in Figure 13**.** This sensor detects the presence of objects or human activity within hazardous areas surrounding the machine. When abnormal conditions are identified, the ESP32-S3 automatically interrupts system operation by deactivating the relay and magnetic contactor. This safety mechanism reflects the application of the Jidoka principle, in which the system is designed to autonomously halt operations when deviations occur, thereby reducing the risk of accidents and minimizing potential environmental and operational hazards.

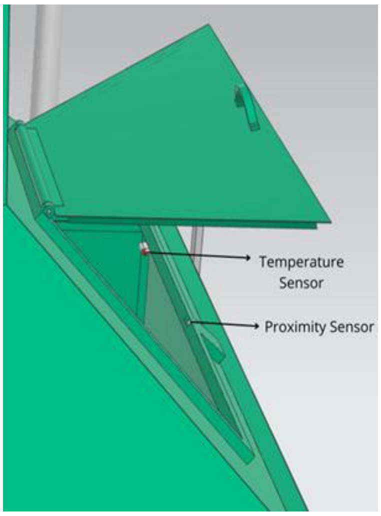

Fig. 13. Implementation of the Jidoka safety principle using a proximity sensor integrated with the control system

3.4 Machine capacity design and technical specifications

The design of the IoT-based burner–wet scrubber system is developed to accommodate the characteristics of agricultural waste at a village-scale combustion capacity. Physically, the machine has overall dimensions of 2100 × 1100 × 3200 mm, with a total processing chamber volume of 2500 liters (2.5 m^3). This capacity represents a practical compromise between the need to manage a significant amount of agricultural waste and the spatial and power limitations commonly encountered in field applications. With an electrical power consumption of approximately ±1200 W, the system remains suitable for operation in rural areas with extensive agricultural land and limited electrical infrastructure. The machine operates as a closed oven system employing controlled pyrolysis or regulated combustion, allowing agricultural waste to be processed under low-oxygen conditions while maintaining precise temperature control. To ensure effective heat circulation and gas flow during the carbonization process, the actual loading capacity is set at 95% of the total chamber volume, assuming dry biomass conditions. This design strategy optimizes space utilization without compromising thermal stability and process efficiency. The overall machine dimensions and general technical specifications are summarized in Table 1.

Table 1. General dimensions and specifications of the burner–wet scrubber system

Parameter	Specification
Overall dimensions (L × W × H)	2100 × 1100 × 3200 mm
Total processing volume	2500 L (2.5 m^3)
Effective loading capacity	95% of total volume
Electrical power consumption	±1200 W
Operating mode	Closed-system controlled pyrolysis
Target application scale	Village-level agricultural waste processing

3.5 Thermal characteristics and operating temperature range

The thermal characteristics of each type of agricultural waste form the basis for determining the operational temperature range of the system. Rice husk begins to react at temperatures of 250–300 °C, with optimal char formation occurring at 350–450 °C, while the maximum safe temperature is limited to ≤500 °C to prevent excessive silica ash formation. Rice straw exhibits a slightly lower initial reaction temperature of 230–280 °C, with an optimal carbonization range of 300–400 °C and a maximum safe temperature of ≤450 °C, as straw tends to degrade rapidly at higher temperatures. Corn cobs require higher thermal input, with an initial reaction temperature of 280–320 °C, an optimal range of 400–500 °C, and a safe upper limit of ≤550 °C, making them suitable for producing hard char or briquette feedstock. Coffee husk displays intermediate thermal behavior, with optimal carbonization occurring at 350–450 °C and a maximum safe temperature of ≤500 °C, considering the tendency for increased ash content at excessive temperatures. The thermal operating ranges for different agricultural wastes are presented in Table 2.

Table 2. Thermal characteristics and safe operating temperature ranges of agricultural waste

Waste type	Initial reaction temperature (°C)	Optimal carbonization range (°C)	Maximum safe temperature (°C)
Rice husk	250–300	350–450	≤500
Rice straw	230–280	300–400	≤450
Corn cob	280–320	400–500	≤550
Coffee husk	260–300	350–450	≤500

3.6 Processing capacity, duration, and char yield

Based on a processing chamber volume of 2500 liters and the bulk density of each agricultural waste type, the system is capable of handling varying masses of dry biomass per operational cycle. Dry rice husk, characterized by a relatively low bulk density, can be processed at approximately 200–250 kg per cycle, with an estimated processing time of 10–18 hours. Dry rice straw can be processed at 100–175 kg per cycle with a processing duration of 8–14 hours. For higher-density biomass, such as dry corn cobs, the system can accommodate 500–875 kg per cycle, with processing times ranging from 14–24 hours. Dry coffee husk can be processed at 350–500 kg per cycle, with an estimated processing duration of 10–16 hours. These processing capacities and durations are summarized in Table 3.

Table 3. Processing capacity and estimated carbonization time per cycle

Waste type	Processing capacity (kg/cycle)	Estimated processing time (hours)
Rice husk	200–250	10–18
Rice straw	100–175	8–14
Corn cob	500–875	14–24
Coffee husk	350–500	10–16

3.7 Char yield estimation

The final char yield is strongly influenced by waste type and operating conditions. Overall, the char yield ranges from 25–35% of the initial dry biomass weight. Rice husk and coffee husk exhibit relatively higher yields of 30–35%, while rice straw produces 25–30%, and corn cob yields range from 28–33%. Considering the effective loading capacity of 95%, the system is capable of producing a substantial amount of char per cycle, as summarized in Table 4.

Table 4. Estimated char yield per processing cycle

Waste type	Char yield (%)	Estimated char output (kg/cycle)
Rice husk	30–35	57–67
Rice straw	25–30	30–36
Corn cob	28–33	167–196
Coffee husk	30–35	114–133

4. Conclusions

The findings of this study show that the IoT-based Burner-Wet Scrubber system functions effectively as a transitional and context-appropriate engineering solution for agricultural waste combustion, enabling more stable combustion conditions inside the burner chamber and reducing visible particulate dispersion when compared to open burning practices commonly found in rural farming areas. These results indicate that the system has the potential to support local-scale emission mitigation efforts in agricultural environments where access to advanced waste-processing technologies and environmental control infrastructure remains limited. Beyond its technical outcome, the study contributes to the broader discourse on sustainable environmental engineering by demonstrating how engineering design, environmental risk reduction, and technological adaptability can be integrated into a practical solution that responds to real-field operational constraints.

The contribution of this study is also aligned with the global sustainability agenda, particularly with Sustainable Development Goal 9 (Industry, Innovation and Infrastructure) and Sustainable Development Goal 13 (Climate Action). The system provides an example of appropriate-technology innovation that strengthens technological capacity at the community level while encouraging safer and more environmentally responsible agricultural practices. In accordance with the aim and scope of this journal, the study offers empirical evidence on how engineering-based interventions can generate both environmental and socio-technical benefits, while simultaneously supporting emission-reduction initiatives and the transition toward more sustainable agricultural waste-management systems.

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Author Contribution

The authors were solely responsible for all aspects of this study, including conceptualization, methodology, data analysis, and manuscript preparation.

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