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High Efficiency, Low Emissions And High Power: Iot Based Biomass Stove Fueled By Corn Cob And Coconut Shell For Sustainable Renewable Energy

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***Abstract**. The scarcity and high cost of LPG gas in rural areas, and the accumulation of rice husk waste that is not managed properly, the use of uncontrolled fossil energy has caused researchers to utilize agricultural waste to be processed into fuel integrated with the Internet of Thing (IoT). The research aims to test the efficiency and gasification of IoT-based biomass stoves with fuel variations in the form of rice husks, sawdust, corn cobs and coconut shells. The research was conducted at the Physics Laboratory of PGRI Silampari University from Jan to August 2025. The type of experimental quantitative research focused on gasification tests, thermal efficiency tests, stove power, emission tests and IoT connectivity. The experiment was carried out in three repetitions of boiling water to 100oC and analyzed descriptively quantitatively. The results showed that coconut shells provided very high power in a short time of 4 minutes and the lowest emissions related to CO and NO exhaust gases, although the energy conversion was relatively less efficient. In contrast, corn cobs showed a balanced combination of 8 minutes of combustion time producing the largest heat of 282,315 kJ. Corn cobs have very maximum energy efficiency and low emissions. The IoT system connectivity also performed well with 98.6% uptime, indicating the real-time monitoring system is reliable under various conditions. To expand the impact and sustainability of this innovation, an Arduino-integrated biomass stove was developed to monitor temperature and emission removal. This research provides a sustainable alternative solution that is environmentally friendly to overcome the scarcity of expensive LPG gas stoves and supports the Indonesian government's program of environmentally friendly renewable energy.*
***Keywords:** Biomass Stove, Internet of Thing (IoT), Low Emission, Renewable Energy*

1. INTRODUCTION

The world's energy problems today encompass two main issues: energy production that still largely produces greenhouse gas emissions and unequal energy access for hundreds of millions of people. The global energy crisis, characterized by an imbalance between energy supply and demand, is becoming increasingly apparent due to dependence on depleting fossil fuels and contributing to climate change. Energy production, mainly from fossil fuels (oil, coal and natural gas), is a major contributor to greenhouse gas emissions that cause climate change. Greenhouse gas emissions cause global warming, which results in extreme weather changes, rising sea levels and ecosystem damage.

The scarcity of LPG gas fuel in several villages in the Indonesian region has led to the high cost of LPG gas as the main source of community causes. There are still many people in rural Indonesia who do not have access to modern energy such as electric stoves, gas stoves for basic daily needs such as cooking, lighting and heating. Limited access to energy exacerbates socio economic disparities, hampering the development and welfare of rural communities. Therefore, the role of renewable energy such as biomass energy fueled by local resources, wind energy and water resources energy is increasingly important in overcoming energy and climate change problems(Ylipulli, Pouke, Ehrenberg, & Keinonen, 2023; Yustanti, Muharman, & Mursito, 2022).

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Technology development related to renewable energy is key to energy sustainability in the future. Building renewable energy infrastructure takes time and careful planning. There needs to be regulations that support the energy transition and encourage investment in the renewable energy sector(Surono, Subeni, Sanjaya, Pratama, & Alfarisaputra, 2023). The world's energy problems are complex problems that require solutions(Handayani, Overland, Suryadi, & Vakulchuk, 2023). Transitioning to sustainable energy, increasing energy efficiency, and more equitable energy access are important steps to address these challenges and ensure sustainable energy availability for future generations through the use of biomass energy(Igliński et al., 2024).

Biomass energy in Indonesia faces several challenges and problems. Despite being a renewable energy source, biomass utilization can have negative environmental impacts such as deforestation and greenhouse gas emissions, as well as economic issues related to investment and operational costs. Increased demand for biomass, especially for coal-fired power plants, can lead to new land clearing and conversion of forests to plantations to fuel energy, which can lead to deforestation and biodiversity loss(Hansen & Moe, 2022). Although considered cleaner than fossil energy, burning biomass also produces carbon dioxide and methane emissions, as well as air pollutants such as particulates and other harmful gases. Biomass has a lower energy density than fossil fuels, requiring more complex storage and distribution systems(Bamzadeh, Meyar-Naimi, & Moradi, 2021). Nonetheless, biomass energy still has great potential as a renewable energy source in Indonesia, especially to reduce dependence on fossil energy and increase the clean energy mix(Alkhalidi, Alqarra, Abdelkareem, & Olabi, 2022). It is important to address these challenges through technology development, appropriate policies and sustainable resource management(Sarkodie, Ofosu, & Ampimah, 2022).

The Internet of Things (IoT) plays an important role in the development and management of biomass energy(Singh, Yadav, Singh, & Moreira, 2025). This technology enables more efficient monitoring, control and automation in various aspects of biomass production and utilization as an energy source. Although research on biomass stoves has grown quite rapidly, most studies still focus on conventional aspects of thermal efficiency, fuel consumption, and emission reduction. Studies such as the one by (Khoa, Dai, Toan, & Tung, 2021) focus more on optimizing the stove design and the type of biomass fuel such as rice husk or sawdust without the integration of digital technology. Similarly, the study by (Gkoulis, 2025) is still limited to the effect of design variations on thermal efficiency, without an adaptive real-time monitoring system(T. S. Tran et al., 2023).

Meanwhile, in the era of the Industrial Revolution 4.0, an Internet of Things (IoT) based approach has great potential to address the challenges of efficiency, safety, and sustainability in the use of alternative energy(Yalli, Hasan, Jung, & Al-Selwi, 2025). However, the integration of IoT in biomass stove systems is still very limited. Not many studies have specifically examined the performance effectiveness of IoT-based biomass stoves, both in terms of digitally monitored combustion efficiency(Cansee, Saenkham, Promtow, Hu, & Kanasri, 2025), real time temperature and emission data collection, and connection to household-scale energy information systems. Furthermore, most studies have not linked this innovation to the macro aspect, namely its contribution to national energy security(Zhang, 2025). The utilization of IoT-based biomass stoves in remote or 3T (frontier, outermost, under developed) areas has strategic potential in supporting the reduction of dependence on fossil energy, as well as encouraging local resource-based energy independence. Thus, there is a lack of empirical studies on the effectiveness of biomass stoves integrated with IoT technology and their relevance in supporting national energy security(Bamzadeh et al., 2021; Reddy & Kumar, 2021). This research is important and relevant to answer the need for renewable energy technologies that are adaptive, efficient, and can be widely utilized in the context of sustainable energy transformation in Indonesia.

Previous studies have examined the potential of biomass as a renewable energy source, both in terms of fuel thermal characteristics and energy conversion efficiency(Tulu, Atnaw, Bededa, Wakshume, & Ancha, 2022). Research emphasizes the importance of utilizing agricultural waste as an environmentally friendly biomass fuel in the context of a circular economy(Usón, Royo, & Canalís, 2023). However, the research has not integrated digital technologies such as the Internet of Things (IoT) in its energy conversion system, so the monitoring and control of the combustion process is still conventional and less responsive to real-time changes in environmental parameters. Meanwhile, a study by (Lasek, Matuszek, Hrycko, Głód, & Li, 2023) successfully evaluated the thermochemical efficiency of several types of biomass using a rigorous laboratory experimental approach. However, this study still focuses on the laboratory scale and has not yet led to the design of practical application systems in the form of ready-to-use biomass stoves equipped with monitoring and automation technology(Tibesso, Zeru, & Alemu, 2022).

Research by (Williams et al., 2023) explored gasification in a hybrid system for biomass energy efficiency improvement. While this approach shows promising results in terms of energy conversion, the study has not yet applied IoT technology approaches to support traceability, security, and operational efficiency in the context of household or local community use(Rey, Mujiyono, Nurhadiyanto, Perdana, & Rusly, 2025). Finally, research by (Surono et al., 2023) raises important issues regarding the social and environmental impacts of using traditional biomass stoves, and the need to transition to cleaner and more efficient solutions. However, this research has not offered concrete solutions based on digital technology that can optimize the combustion process, reduce harmful emissions, and provide sensor-based data for continuous evaluation of energy performance(Budhathoki, Choochuay, & Bhandary, 2024; Mambo, Basemera, Kitimbo, Nakiyini, & Kamugasha, 2024; Williams et al., 2023).

The utilization of biomass as an alternative energy source has become a global concern to realize a sustainable and environmentally friendly energy system. Several previous studies have focused on optimizing the biomass energy conversion process and its combustion efficiency. For example, a study by (Saputro et al., 2025; Watjanatepin et al., 2023) explored the integration of pyrolysis and gasification systems in a hybrid reactor to improve the energy efficiency of biomass(Sarkodie et al., 2022; Urhamdi, Bahri Widodo, & Cut, 2024). This study shows that conversion efficiency can be improved through reactor engineering and thermal control. However, there is no application of Internet of Things (IoT)-based systems to automate or monitor the combustion process in real-time, so the potential for adapting this technology for daily use remains unexplored(Li et al., 2024; Saputro et al., 2025).

Meanwhile, the research by (Raghutla & Kolati, 2023; Yustanti et al., 2022) focused on the design and optimization of biomass burners using experimental approaches and CFD (Computational Fluid Dynamics) simulations. The study successfully demonstrated that proper burner design can improve thermal efficiency and reduce pollution (H. Tran, Juno, & Arunachalam, 2023). However, the developed technology has not been accompanied by an IoT-based digital monitoring system, which allows users to access real-time stove performance information for the purpose of efficiency control, safety, and long-term emission reduction(Chaiyalap et al., 2023).

This research presents a novelty by utilizing IoT, the effectiveness of the stove is not only conventionally measured through thermal efficiency or fuel consumption tests, but also through a real-time monitoring system of combustion chamber temperature, gas emissions, and flame stability. This innovation enables accurate and continuous data collection, which can be used for the development of sensor-based automatic control systems. In addition, the novelty of this research lies in its approach that combines technical and macro-strategic aspects. Not only testing the technical performance of the stove, this research also links the implementation of IoT-based biomass stoves with the national energy security agenda, especially in the context of utilizing alternative energy based on local resources in 3T areas. This approach expands the scope of the benefits of biomass stoves, from just a household solution to part of a sustainable energy development strategy.

Furthermore, this research aims to test the efficiency and gasification of IoT-based biomass stoves with fuel variations in the form of rice husks, sawdust, corn cobs and coconut shells. The design of this biomass stove aims to determine fuel consumption (g), CO emissions (ppm), NO emissions (ppm), flame stability, temperature sensor response (seconds), IoT temperature data accuracy (% deviation) and IoT connectivity reliability (% uptime). So that by conducting effectiveness tests by comparing the use of four types of fuel, it is expected to produce an efficient biomass stove.

This research was conducted in the electronics laboratory of PGRI Silampari University, Indonesia from May to August 2025. This research uses an experimental quantitative approach. The research stages adapt and develop engineering technology that includes. Furthermore, in the Design stage, namely designing tools, making effectiveness test worksheets, the biomass stove is designed using a TLUD type gasification system (Top Lit Up Draft) is a process of converting solid fuel into combustible gas by burning fuel from above (top-lit) and directing air flow upwards (up-draft) through a pile of fuel. The gas produced can then be used as an energy source, for example for cooking or generating electricity. This IoT-based biomass stove has dimensions of 60 cm x 40 cm, made of cement with a combustion chamber capacity of 2 liters. Next is the Develop stage: Expert validation, laboratory testing, and field trials The initial design of the stove and IoT system was validated by experts (energy, digital technology, and energy security experts) using feasibility and content validity assessment instruments. The assessment was conducted quantitatively and qualitatively. The effectiveness test was conducted through laboratory experiments and field tests to measure the thermal efficiency (using the Water Boiling Test method) of boiling five liters of water for three repetitions, namely fuel consumption (g/liter of water), CO and NO emissions, flame stability and sensor response and accuracy of the IoT system. Each indicator was compared between the conventional biomass stove and the IoT based stove.

2. METHOD EXPERIMENT

The research was conducted at the Physics Laboratory of PGRI Silampari University from Jan to August 2025. The type of experimental quantitative research focused on gasification tests, thermal efficiency tests, stove power, emission tests and IoT connectivity. The experiment was carried out in three repetitions of boiling water to 100oC and analyzed descriptively quantitatively.

The effectiveness test of biomass stoves includes several important aspects such as effective flame duration, thermal efficiency, and fuel consumption, which are often measured using the Water Boiling Test (WBT) method with the Indonesian National Standard (SNI) 7926:2023 for Biomass Stove Performance. Water Boiling Test (WBT) plays an important role in ensuring the quality and safety of biomass stoves on the market by heating water to a boil(Maxwell, Gudka, Jones, & Williams, 2025; Otieno, Home, Raude, Murunga, & Gachanja, 2022). This test aims to ensure that the biomass stove works properly, efficiently and safely. Among the tests are;

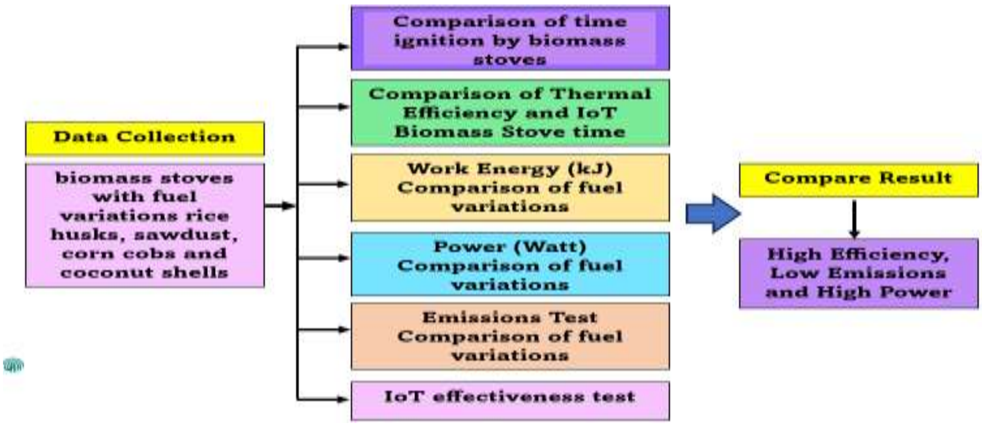

Fig.1 Research flow chart

2.1 Gasification Test

Gasification tests are a series of tests conducted to evaluate the performance of the gasification process, a thermal technology that converts solid feedstock into combustible gas with a limited supply of oxygen. These tests aim to understand the process characteristics, conversion efficiency, and quality of the gas produced. In this study, gasification tests were used to detect differences in the final temperature produced, the final mass (Volume) of water and the time required for each fuel in the gasification process(Flori, Frigo, Barontini, Gabbrielli, & Sica, 2024). The fuel uses rice husks, sawdust, corn cobs and coconut shells. This study was conducted three times to get the average value produced by each biomass stove with different fuel variations(Tulu et al., 2022). To measure the length of time required for the biomass stove to produce an effective flame length, which serves to measure the time required for the stove to boil a total of 5 liters of water. This is in line with previous research that uses water around 4-5 liters.

2.2 Emission test

The emission test is conducted to detect the level of pollutants produced by the biomass stove during the combustion process(Mainkaew, Kaewluan, Pattiya, & Jansri, 2023). The aim is to ensure that the biomass stove meets applicable emission standards and is safe to use. This test involves measuring the levels of exhaust gases such as carbon monoxide (CO), Nitrogen Monoxide (NO)(H. Tran et al., 2023). CO emissions are measured using a suitable CO measuring device. The general standard is that the CO emission limit should not exceed 67 grams per kg of fuel. NO emissions are measured using an NO meter, and are usually measured in ppm (parts per million). NO emissions from biomass pellets, for example, may vary depending on the type of biomass and combustion conditions(Otieno et al., 2022). By conducting an emission test, we can ensure that the biomass stove in use is safe, efficient and environmentally friendly, and contribute to reducing the negative health and environmental impacts of biomass burning.

2.3 Biomass stove thermal efficiency test

The thermal efficiency test in this study was calculated based on the amount of energy transferred to the water during boiling, compared to the energy released by fuel combustion. To measure the thermal efficiency of the biomass stove(Cansee et al., 2025). it is calculated using equation 1.

$$\Pi = \frac{ma.ca.\Delta T + mp.cp.\Delta T + mu.H}{mbb\ .E} \qquad (1)$$

ma = mass of water (kg), ca = specific heat of water (J/Kg0C), mp = mass of panic, Cp = specific heat of panic (J/Kg0C), mu = mass of water vapor, H = heat of water vapor, mbb = mass of fuel and E = calorific value of fuel (kJ/Kg).

2.4 Thermal power test

Output power testing refers to the amount of heat energy produced by the stove per unit time(Williams et al., 2023). Output power testing is usually done by measuring the time it takes to boil a certain volume of water, then calculating the power produced. The output power of a biomass stove can be affected by various factors, such as stove design, fuel type, and airflow speed. Biomass stove power is calculated using Equation 2. Where P is power (kW), E is total energy (kJ).

$$P = \frac{E}{t} \qquad (2)$$

2.5 IoT effectiveness test

Testing the effectiveness of IoT biomass stove is seen from several parameters, namely temperature sensor response, accuracy of IoT temperature data (% deviation), accuracy of IoT emission data (% deviation) and reliability of IoT connectivity (% uptime)(Zhang, 2025). Needs analysis conducted expert discussions related to the design of IoT-based biomass stove prototypes, preparing microcontroller tools and materials and their uses in biomass stoves listed in table 1.

Table 1. IoT sensors used

Componen	Usability
 temperature sensor DS18B20	The DS18B20 temperature sensor is a digital sensor that uses single-wire bus communication, has an operational temperature range of -55°C to +125°C, and an accuracy of up to ±0.5°C. Power Supply 3V to 5.5V. Current Consumption of 1 mA during active temperature

	conversion. Conversion time is less than 750ms.
 CO, NO gas sensor (MQ-7)	The MQ-7 sensor is a gas sensor designed to detect the presence of carbon monoxide (CO) gas in the air, and can also detect Nitrogen Monoxide (NO) gas. The advantages of this sensor lie in its high sensitivity, stability, and longevity.
 **DHT11 humidity sensor**	The DHT11 sensor is a popular type of sensor used to measure air temperature and humidity in digital format. Temperature measurement range: 0-50°C. Humidity measurement range is 20-90% RH. Accuracy: ±2°C for temperature and ±5% for humidity and the reading speed is about 1 second.
 **mikrokontroler ESP32**	The ESP32 microcontroller serves as the brain or controller equipped with Wi-Fi and Bluetooth modules that allow it to connect wirelessly. ESP32 has various peripherals such as Analog-to-Digital Converter, Digital-to-Analog Converter that interact with various sensors and devices.

3. RESULTS AND DISCUSSION

Based on the results of our experiments carried out for three repetitions by cooking water until it boils to a temperature of 100^{O}C to test the effectiveness of the IoT based biomass stove with four fuel variations, namely rice husks, sawdust, corn cobs and coconut shells, the data obtained are shown in Table 2.

Table 2. Average biomass stove testing results

No	Parameters for data are taken as an average of 3 repetitions.	Fuel			
		Rice husks	Corn cobs	Wood powder	Coconut shells
1	Mass of kerosene (g)	50	50	50	50
2	Initial temperature (°C)	32	32	32	32
3	Initial water mass (g)	5000	5000	5000	5000
4	Temperature around the stove (°C)	78	76,5	82,1	92,5
5	Initial fuel mass (g)	2000	2000	2000	2000
6	Ignition time (minutes)	5	8	9	4

7	Water boiling time (minutes)	29,93	32,24	34,60	25,20
8	Final water temperature (°C)	100	100	100	100
9	Final water mass (g)	4594	4963	4760	4810
10	Charcoal mass (g)	193,67	268,67	158,7	18,58

The test results of the IoT-based gasification stove prototype showed significant variations in thermal performance and combustion efficiency based on the type of biomass fuel used. The four types of local fuels tested, namely rice husks, corn cobs, sawdust, and coconut shells, have different combustion characteristics as shown in Table 3. From the experimental results, coconut shells produced the highest flame temperature of 925°C, with the fastest ignition time (4 minutes) and the shortest water boiling time (25.20 minutes). This indicates high thermal efficiency compared to the other fuels. In contrast, sawdust had a lower flame temperature (821°C) and longer boiling time (34.60 minutes), and produced more charcoal residue (158.7 grams) than coconut shells (18.58 grams). This shows that although sawdust is quite stable, it is still less efficient than coconut shells.
These results are in line with findings showing (Budhathoki et al., 2024; Flori et al., 2024) that coconut shells have higher lignin and caloric content, providing better combustion efficiency and less char residue than other biomass. In addition, it was also noted that gasification-based stoves using coconut shells as fuel were able to reduce energy consumption by up to 20% compared to rice husks, as well as significantly speed up boiling time. The integration of Internet of Things (IoT) technology in this stove also plays a role in monitoring the flame temperature, boiling time, and fuel consumption in real-time. The utilization of IoT-based sensors provides accurate information on combustion efficiency and flame stability, allowing users to exercise more precise control over stove performance. This supports the findings of(Lasek et al., 2023), which showed that the application of IoT sensors in biomass-based cooking devices can improve fuel use efficiency by up to 15% and significantly reduce CO emissions(Mainkaew et al., 2023).

Table 3. Average efficiency of biomass stoves

fuel	Working Energy (kJ)				Absorbed heat energy (kJ)		Efficiency
	Fuel	Kerosene	Charcoal Remaining	Total	Latent heat	Sensible heat	
Rice husks	153.712	6834	14.885	175.431	4.579	353.077	14.885
Corn cobs	242.857	6834	32.624	282.315	4.947	602.650	32.624
Wood powder	183.390	6834	14.552	487.091	4.744	436.467	14.552
Coconut shells	229.905	6834	2.136	443.651	4.794	552.921	2.136

The thermal efficiency test results of the IoT-based biomass stove developed in this study show variations in energy performance based on the type of local biomass fuel used. Table 3 presents data on the working energy, absorbed heat energy (latent and sensible heat), and overall thermal efficiency of the four fuel types: rice husk, corn cob, sawdust, and coconut shell. From the data obtained, corn cob showed the highest energy efficiency, with a total work energy of 282,315 kJ and absorbed calorific energy (latent and sensible heat) of 602,650 kJ. This high efficiency is supported by the optimal cellulose and lignin content in corn cob, as well as the residual charcoal residue (32,624 kJ) which indicates that the combustion is not fully complete but is still within the efficient threshold. In contrast, sawdust showed the largest total work energy (487,091 kJ), but had a lower thermal efficiency, as most of the energy was lost in the form of unabsorbed heat and considerable residual combustion. Coconut shells, despite having high combustion power as shown in Table 4 earlier, have relatively low efficiency in terms of low energy from charcoal residue (2,136 kJ) and total energy absorbed, indicating more explosive combustion but not optimal thermal energy absorption.

These results are in line with (Cansee et al., 2025; Tulu et al., 2022) those stating that the thermal efficiency of gasification stoves is strongly influenced by the type of fuel and initial moisture content. In his research, corn cobs and rice husks are materials that produce more stable efficiency than coconut shells, because they have a more controlled combustion rate. Meanwhile, it noted that high work energy is not always synonymous with efficiency, especially if most of the heat is not directly utilized. The researcher suggests the need for real-time temperature monitoring and control systems, such as those that have been applied to the IoT-based stoves in this study, to improve energy conversion and system efficiency(Flori et al., 2024). The advantage of this prototype lies in its ability to monitor thermal energy distribution through IoT sensors, which provide accurate data on temperature, fuel consumption, and residual combustion heat. The integration of these technologies enables fuel optimization based on its specific characteristics and supports the use of clean energy from local sources. With the highest efficiency achieved with the use of corn cobs, this prototype shows great potential to support the diversification of biomass-based national energy sources and the utilization of agricultural waste.

Table 4. Average thermal efficiency and power generated

Fuel type	Thermal efficiency (%)	Time (minutes)	Work energy (kJ)	Power (kW)
Rice husks	8,48	5	175.431	584,77
Corn cobs	11,6	8	282.315	588,16
Wood powder	2,99	9	487.091	902
Coconut shells	0,48	4	443.651	1848,55

Based on Table 4, the experimental results related to the thermal efficiency and power of the IoT-based biomass stove show that the type of fuel plays a significant role in the performance of the energy produced. Table 5 shows that corn cob has the highest thermal efficiency of 11.6%, followed by rice husk (8.48%), sawdust (2.99%), and coconut shell (0.48%). However, when viewed in terms of power generated, coconut shells actually produce the highest power of 1848.55 kW, far exceeding the other fuel types. This indicates a trade-off between thermal efficiency and output power, where coconut shells provide a very high energy impulse in a short period of time (4 minutes), although the energy conversion is relatively less efficient. In contrast, maize cobs showed a balanced combination of burning time (8 minutes), work energy (282,315 kJ), and thermal efficiency, making them a potential fuel for sustainable household applications.

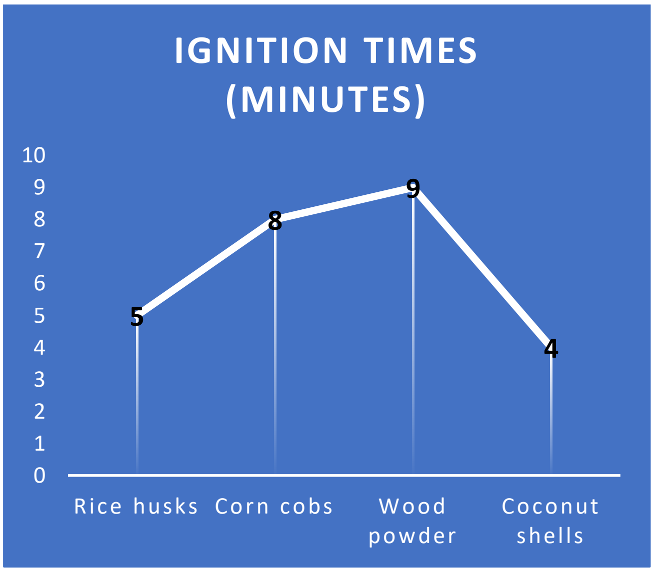

Fig.2. Comparison of time ignition by biomass stoves

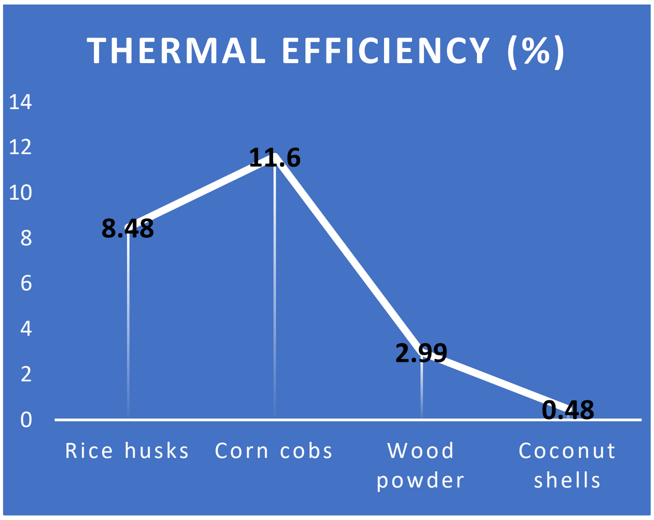

Fig.3. Comparison of Thermal Efficiency and IoT Biomass Stove time

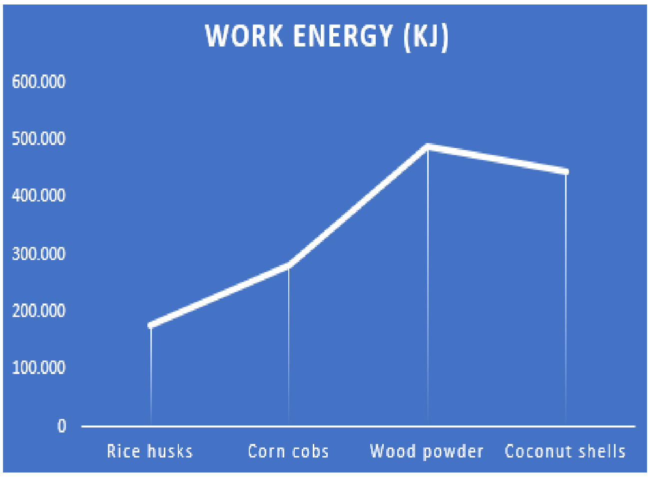

Fig.4. Work Energy (kJ) Comparison of fuel variations

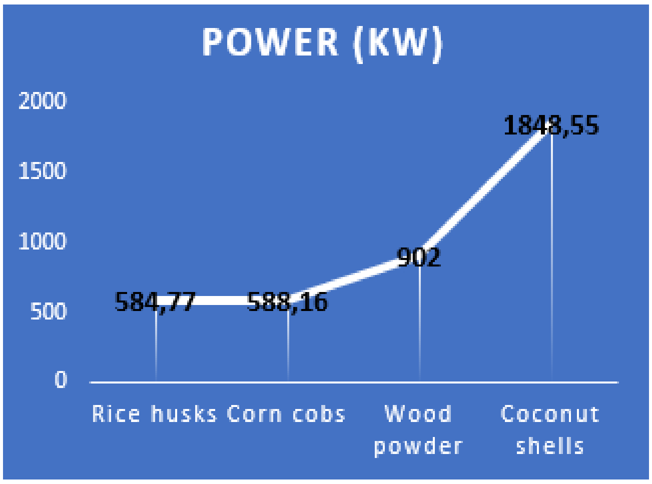

Fig.5. Power (Watt) Comparison of fuel variations

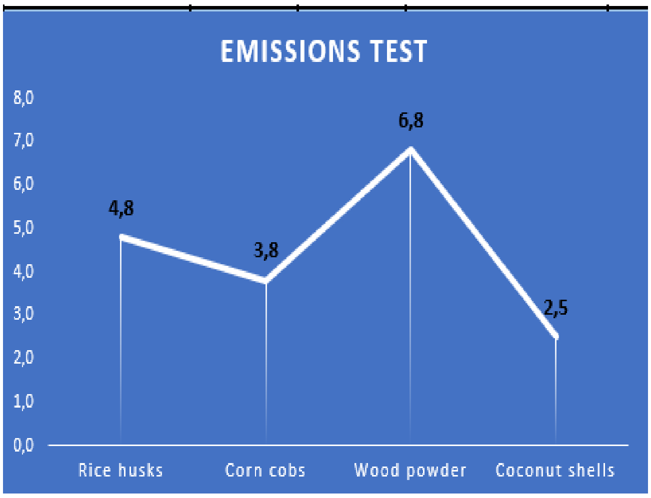

Fig.6. Emissions Test Comparison of fuel variations

This finding is in line with research by (Atmoko, Riyadi, Utomo, Jamaldi, & Nugroho, 2023), which revealed that biomass from agricultural waste such as corncobs has better thermal stability and higher efficiency performance than husks and sawdust, due to its denser and more stable cellulose structure when converted through gasification(Flori et al., 2024). Meanwhile, coconut shells have a high calorific value that can produce large power in a short time, but also require more precise emission and temperature control technology to increase efficiency(Surono et al., 2023). The advantages of this stove prototype are strengthened by the integration of IoT technology, which is able to monitor combustion time, flame temperature, and output power in real-time through temperature and heat load sensors. This technology allows users to optimize the use of local fuel according to its characteristics and minimize energy waste and carbon emissions. The data results are in line with research conducted by (Cansee et al., 2025; Hailu, 2022) showing that the use of IoT in combustion systems can improve efficiency control by up to 20% and accelerate the adaptation of renewable energy in rural communities. Thus, the development of IoT-based biomass stoves not only provides technical solutions in the utilization of alternative energy from agricultural waste, but is also strategic in supporting national energy security based on local and sustainable resources(Walmsley et al., 2023).

Table 5. Test Results of IoT-Based Biomass Stove

Parameter	Average Test Results	Reference Standard	Description
Fuel consumption (g)	185	< 200 (efficient)	Efficient, fuel efficient
CO emissions (ppm)	350	< 400 (SNI 7927:2013)	Within safe limits
NO emissions (%)	6,2	5–10% (complete combustion)	Relatively complete combustion
Flame stability	4,5	≥ 4 (stable)	Stable flame during testing
Temperature sensor response (seconds)	1,5	< 2 seconds (fast)	Sensors responsive to changes
IoT temperature data accuracy (% deviation)	±2%	< ±5% (accurate)	Sensors more accurate than thermometers
IoT emissions data accuracy (% deviation)	±3,2%	< ±5% (accurate)	Compliant with reference instruments

IoT connectivity reliability (% uptime)	98,6%	≥ 95%	Stable and accessible

The technical performance test results of the IoT-based biomass stove prototype in Table 5 show performance that meets efficiency and safety standards, both in terms of combustion and digital aspects of system monitoring. Based on Table 5, the average fuel consumption is 185 grams, which is below the efficiency threshold of <200 grams, indicating that this prototype is fuel efficient. In terms of emissions, the stove produces carbon monoxide (CO) emissions of 350 ppm, which is still within safe limits according to SNI 7927:2013 (<400 ppm). NO emissions were recorded at 6.2%, within the ideal range for complete combustion (5-10%), indicating relatively high combustion efficiency. In the aspect of flame stability, the stove recorded a score of 4.5 out of a scale of 5, fulfilling the "stable" category, which is important for constant heating over a long period. Meanwhile, the advantages of this prototype are further highlighted by the IoT sensor system, which shows a very fast temperature sensor response (1.5 seconds) and the accuracy of temperature and emission data is ±2% and ±3.2% respectively, well below the maximum deviation threshold of ±5%, indicating high accuracy in the monitoring system. The IoT system connectivity also performed well with an uptime of 98.6%, indicating that the real time monitoring system is reliable under various conditions.

These results are in line with a study (Senyapar, 2023; Surono et al., 2023) that emphasized the importance of fuel efficiency and emissions stability in the development of biomass stoves for households. The study also noted that the ideal fuel consumption ranges below 200 grams per cooking cycle to be feasible in rural communities. Meanwhile, previous research conducted by (Ross, Day, Ivanova, McLeod, & Lockshin, 2022) reported that the integration of IoT systems in thermal devices such as biomass stoves allows users to monitor and control temperature and emissions precisely, thus accelerating user adaptation to new technologies. Furthermore, research conducted by (Qin, Liu, & Grosvenor, 2017; Wang, Li, & Guo, 2022) states that IoT sensor measurement error tolerance below ±5% is considered highly accurate for household and small industrial applications, and >95% connectivity is considered an indicator of a stable system ready for scalability. With results that demonstrate fuel efficiency, emission safety, and IoT system accuracy and reliability, this stove prototype is not only superior in technical aspects but also relevant as a solution to support national energy security. The utilization of local biomass waste as fuel, plus a smart control system, makes this stove a form of sustainable innovation that is in line with the direction of Indonesia's clean energy transition(Ross et al., 2022; Usón et al., 2023).

This research makes an important contribution to the development of biomass-based renewable energy technology by integrating the Internet of Things (IoT) as a smart monitoring and control system(Bamzadeh et al., 2021; Li et al., 2024). This research addresses the gap through the development of an IoT-based biomass stove prototype that is able to monitor fuel consumption, combustion chamber temperature, and CO and NO emissions directly(Feng & Zheng, 2022; Rey et al., 2025; Walmsley et al., 2023). Improving combustion efficiency through sensor integration. Furthermore, it supports the national energy security program by providing technological solutions that are based on local resources but digitally oriented. In addition, this development also contributes to the reduction of carbon emissions and the utilization of biomass waste such as rice husks and sawdust that have not been optimally utilized. This is in line with the policy direction of the SDGs, especially Clean Energy and Climate Change Management(Rao, Sahoo, & Yanine, 2025; Wei, Yin-Cheung Wong, & Yong, 2024).

Thus, this research is not only applicable, but also strategic in encouraging appropriate technology innovations based on digital intelligence that are relevant to the Indonesian social and environmental context. This research has produced an IoT-based biomass stove prototype that shows significant potential in improving energy efficiency, minimizing carbon emissions, and supporting national energy security efforts. However, to expand the impact and sustainability of this innovation, further research is needed. Future development directions include the integration of artificial intelligence (AI) systems to enable automatic control based on historical usage and combustion data. The development of mobile applications and monitoring dashboards is also recommended to support user engagement in monitoring energy consumption and emissions in real time.

The limitations of this research lie in (1). Testing of the IoT-based biomass stove prototype in this study was carried out on a laboratory scale, so it has not been fully tested in the community such as at home. (2). The IoT system is simple and not yet connected to the cloud, that is, even though it has adopted IoT technology, the system used is still local and not yet connected to a cloud platform for long-term data management or multi-device integration. Thus, historical data is not well stored for long-term trend analysis of efficiency or emissions. (3). The study only measured carbon monoxide (CO) and nitrogen monoxide (NO) emissions, while other parameters such as toxic compounds have not been analyzed. This limits a comprehensive assessment of the environmental and health impacts of biomass combustion processes. (4). The stove prototypes developed are still simple, and have not been tested for long-term durability, corrosion, or thermal damage from intensive use. This may affect the reliability and longevity of the appliance in daily practice. (5). The research has not touched on perception, ease of maintenance, or long-term economic impact.

6. CONCLUSION

This research integrates the Internet of things (IoT) on biomass stoves fueled by rice husk waste, sawdust, corncobs and coconut shells for renewable energy. Based on the results by heating 5 liters of water to a boiling point of 100^0C shows (a). The efficiency test of the corn cob stove has the highest thermal efficiency of 11.6%, followed by rice husk 8.48%, sawdust 2.99%, and coconut shell 0.48%. (b). The Power Test produced by coconut shells actually produces the highest power of 1848.55 kW, far exceeding other types of fuel. (c). The highest gasification test of corn cobs showed that the total work energy reached 282,315 kJ and the absorbed heat energy latent heat of 602,650 kJ so that it was categorized as the highest energy efficiency. (d). The stove emission test resulted in carbon monoxide (CO) emissions of 350 ppm, which is still within safe limits according to SNI 7927:2013 < 400 ppm, while NO emissions were recorded at 6.2%, within the ideal range for complete combustion (5-10%), which indicates relatively high combustion efficiency. (e). The fastest time coconut shell-fueled biomass stove provides very high energy impulses in a short time (4 min), although the energy conversion is relatively less efficient. In contrast, corncobs showed a balanced combination of burning time (8 min), work energy (282,315 kJ), and thermal efficiency, making it a potential fuel for sustainable household applications(Selçuk, Kurt Konca, & Kaya, 2025). The IoT reliability test shows that the temperature sensor response is very fast (1.5 seconds) and the accuracy of temperature and emission data is ±2% and ±3.2% respectively, well below the maximum deviation threshold of ±5%, indicating high accuracy in the monitoring system. The IoT system connectivity also performed well with an uptime of 98.6%, indicating that the real-time monitoring system is reliable in various conditions so that the IoT integration shows better stove performance in detecting emissions, and controlling combustion temperature.
Further studies also need to focus on evaluating the socio-economic impact, including the extent to which this technology can be implemented by micro-enterprises by improving user welfare and reducing dependence on fossil fuels. In addition, aspects of technical standardization and product certification are important steps towards commercialization and mass production. In addition, the incorporation of other renewable energy sources, such as solar panels, can create environmentally friendly energy, especially for remote areas. Finally, this research opens up opportunities for the establishment of social business models and cross-sector collaborations that support the dissemination of innovations to the community at large. Thus, the sustainability of this research does not only focus on technical aspects, but also encourages the formation of an inclusive and sustainable energy innovation ecosystem, in line with the national development agenda and global SDGs goals.

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