



Comparison of combustion emissions between manual and machine set methods to reduce carbon monoxide (CO) in briquette manufacturing

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ABSTRACT

Background: Renewable energy from biomass is one solution to reduce dependence on fossil fuels and the impact of carbon emissions. One form of renewable energy from biomass is briquettes. This study aims to analyze the effectiveness of using modern technology in the form of a briquette production machine set consisting of a grinder, extruder, and burner integrated with a wet scrubber innovation to reduce carbon monoxide (CO) emissions from rice husk combustion in the burner machine compared to the manual method.

Methods: The research process was carried out through the stages of needs identification, CAD (Computer Aided Design)-based machine design, prototype production, and briquette performance testing using a Non-Dispersive Infrared (NDIR) analyzer. **Findings:** The test results showed that briquettes produced using the manual method had a higher density of 0.8 g/cm³ and produced an average CO emission of 220 ppm. These findings prove that mechanizing the process improves the physical quality of the briquettes while reducing CO emissions by around 39%. The integration of wet scrubber technology proved to be effective in absorbing additional exhaust gases and strengthening the environmentally friendly aspects of the combustion process.

Conclusion: The conclusion of this study confirms that the use of integrated machinery not only improves briquette quality and energy efficiency, but also makes a significant contribution to carbon emission control efforts at the local level. **Novelty/Originality of this Article:** The novelty of this study lies in its comprehensive analysis comparing manual and mechanized methods using burner machines with integrated wet scrubbers in the context of rice husk briquette production.

KEYWORDS: briket; rice husk; energy.

1. Introduction

The Paris Agreement, ratified on December 12, 2015, was a milestone in global climate policy. It established a comprehensive framework for addressing climate change for a low-carbon and sustainable future. The Paris Agreement stipulates that countries must improve and refine their nationally determined contributions (NDCs) every five years. It must also encourage a dynamic and progressive approach to climate action (Sihotang, 2025). On the other hand, global warming has become an international issue recently due to its significant effects on climate change. Biodiversity, human survival, and ecosystems are all threatened by global warming caused by daily human activities (Ariska et al., 2022). Countries with

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high populations and industrialization will have a high carbon footprint, which means they are responsible for most of the carbon emissions that cause global warming (Dian, 2024). Generating more than 704.4 million tons of carbon in 2023, Indonesia is the sixth largest carbon emitter in the Asia Pacific. In 2021, the Ministry of Environment and Forestry of the Republic of Indonesia (KLHK) reported that the energy sector contributed the most to carbon emissions, followed by industry and product use, forestry, agriculture, and waste, which were responsible for 60% of CO₂ emissions in the air, respectively (Sutanhaji et al., 2018).

Energy is one of the most important factors for human life around the world, and the availability of sufficient and sustainable energy determines the progress of a nation (Puspita, 2024). According to Sapthu (2023), countries with a stable energy supply generally have superior economic growth and their people enjoy a more prosperous quality of life. On the other hand, increasing energy demand also triggers new challenges, especially in dependence on fossil fuels, which cause environmental pollution and climate change (Tjiwidjaja & Salima, 2023). The burning of fossil fuels has become a major source of greenhouse gas emissions, one of which is carbon monoxide (CO) (Yoro & Daramola, 2020). This gas is trapped in the Earth's atmosphere and causes the greenhouse effect, which leads to global warming that triggers a negative domino effect, such as a gradual increase in the average temperature on Earth, extreme weather patterns, and disruption to ecosystems and biodiversity (Irma & Gusmira, 2024).

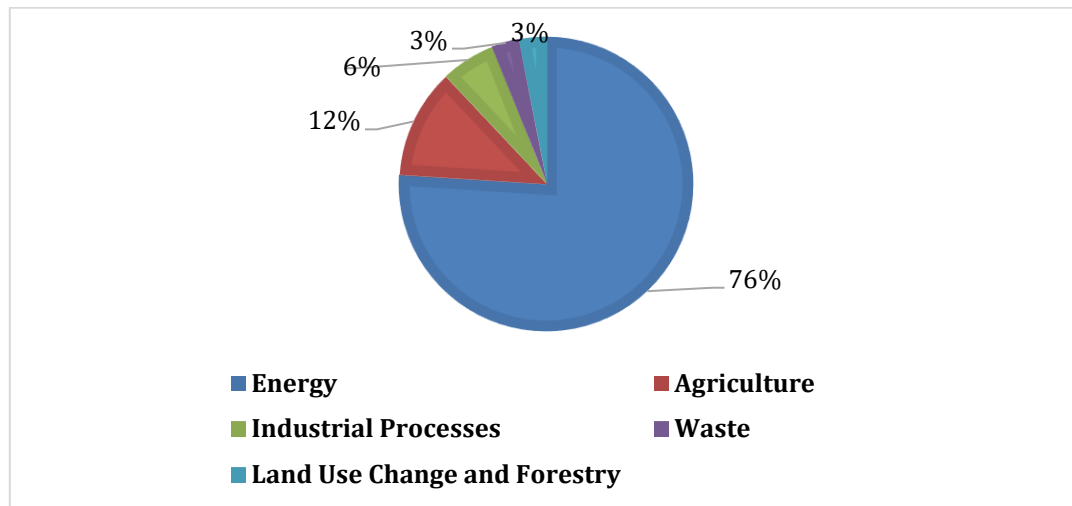


Fig. 1. Diagram of global greenhouse gas emissions by sector and end use (World Resources Institute, 2021)

Based on data from the World Research Institute in 2021, it is known that there are five main sectors that contribute the most to greenhouse gas emissions, with the energy sector being the largest contributor at 75.7% and the agriculture sector being the second largest contributor to greenhouse gas emissions. As much as 1.2% of rice cultivation contributes to greenhouse gas emissions from the agricultural sector. Rice cultivation by-products that are often neglected and simply burned, namely rice husks, are one of the reasons why rice cultivation is the second largest contributor to greenhouse gas emissions (Fathia et al., 2024). The continuous increase in rice production has led to an increase in the volume of rice waste in the form of husks (Purwadinata et al., 2023). Therefore, innovation is needed to optimize husk waste into products with economic value, one of which is by turning it into renewable energy products based on rice husk biomass (Fathonah et al., 2023). Referring to one of the objectives of the Indonesian State based on Law Number 18 of 2008 concerning sustainable waste or waste management, which is a form of responsibility for consumption and production that has been carried out, as well as SDG point 13 concerning climate action, which calls for immediate action to combat climate change and its impacts caused by increased greenhouse gas emissions and global warming.

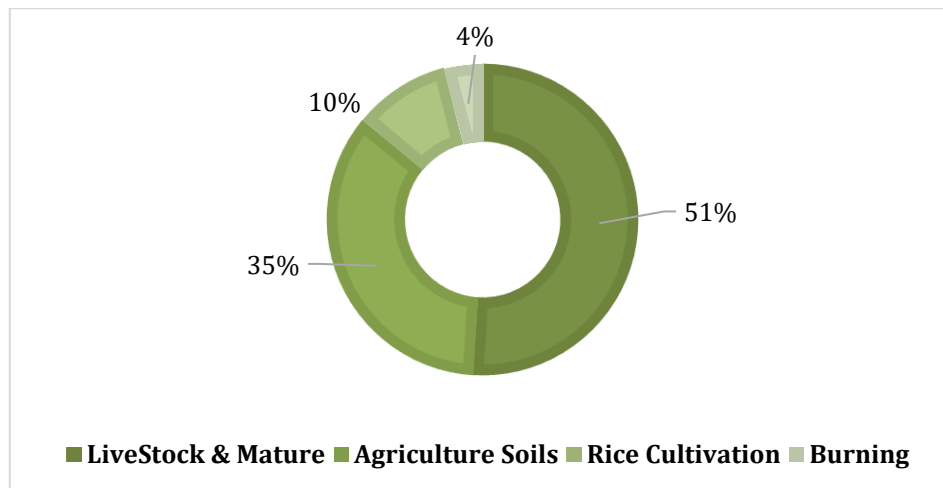


Fig. 2. Diagram of agriculture gas emissions
(World Resources Institute, 2021)

Biomass is organic material derived from plants and microorganisms (Kulikova et al., 2022). Renewable energy from biomass has been widely recognized as one of the most important energy alternatives by the United Nations (UN) and the US Energy Information Administration (EIA) due to its environmental friendliness and abundant availability. In Indonesia, a significant amount of biomass waste potential is found in rice husks (Sugiharto, 2021). This can be seen based on the results of rice production in Indonesia, which reached around 52.66 million tons of milled dry grain in the 2010-2020 period and continues to increase in the following years. This production fluctuates from year to year due to several factors such as land area and productivity, with the main target being to maintain national food security (Gomiero, 2016).

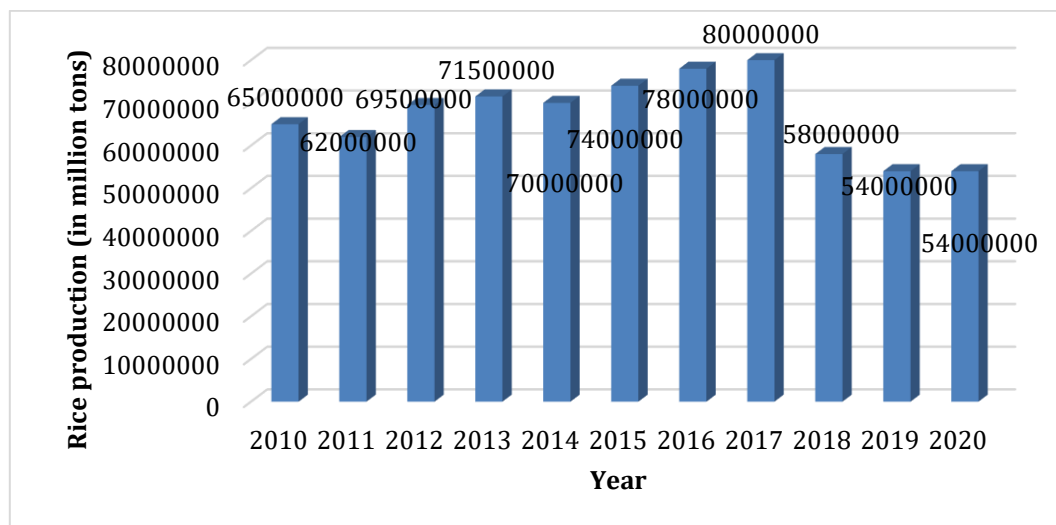


Fig. 3. Indonesian rice production chart
(Statistics Indonesia, n.d.)

Unfortunately, rice husk waste has not been utilized optimally. Rice husks are often burned directly, and the smoke from this (Quispe et al., 2017). However, wet scrubbers are ineffective in reducing carbon monoxide (CO) emissions because CO has very limited solubility in aqueous media and is chemically inert under normal operating conditions. To improve their performance, the scrubbing solution is usually modified by adding oxidizing agents or catalytic materials, which enable the partial conversion of CO to CO₂ (Rey et al., 2024). burning becomes a source of harmful gas emissions, including carbon monoxide (CO). Research shows that CO produced from open burning of rice husks can reach up to 128.9% of the baseline due to incomplete combustion, which releases large amounts of

carbon pollutants. Therefore, there is an urgent need to develop renewable energy, one of which is through the utilization of biomass waste. One of the efforts made by researchers to overcome this problem is to create alternative fuel in the form of briquettes made from rice husk waste.



Fig. 4. Rice husks into briquettes

In the process of making rice husk briquettes, there are two methods that have been used, namely the traditional method and the use of a briquette-making machine set. The traditional method of burning rice husks manually and openly often lacks adequate emission control, resulting in increased CO concentrations in the open air. Several modern alternatives have been researched and discovered, one of which is the use of a grinder, extruder, and burner system. These three machines have been proven capable of processing and optimizing rice husk waste into briquette products. One of the machines developed by researchers is a burner with a wet scrubber, which has been proven capable of implementing a pollution control system to reduce CO emissions.

Table 1. Comparison the effectiveness of absorbent use in wet scrubbers

Time	Absorbent type	Concentration (N)	Media height (cm)	Inlet CO ₂ (ppm)	Outlet CO ₂ (ppm)	Quality standard (ppm)	% Removal
09.00-10.00	KOH	2	20	22100	3700	1000	77.4
09.00-10.00	KOH	2	40	22100	3400	1000	81.9
09.00-10.00	KOH	4	20	22200	1200	1000	86.0
10.00-11.00	KOH	4	40	22280	1000	1000	86.5
10.00-11.00	KOH	6	20	22450	500	1000	95.5
10.00-11.00	KOH	6	40	22253	400	1000	96.0
11.00-12.00	NaOH	2	20	22700	4200	1000	60.4
11.00-12.00	NaOH	2	40	22780	4100	1000	62.7
12.00-13.00	NaOH	4	20	22880	2300	1000	73.8
12.00-13.00	NaOH	4	40	23100	2000	1000	78.4
12.00-13.00	NaOH	6	20	23130	1000	1000	91.4
12.00-13.00	NaOH	6	40	23140	900	1000	91.8
13.00-14.00	H ₂ O	-	20	23170	12000	1000	48.2
13.00-14.00	H ₂ O	-	40	23200	10000	1000	56.9

(Damayanti & Hendrasarie, 2025)

Research on the effectiveness of wet scrubbers in reducing carbon monoxide (CO) emissions has been conducted extensively. Based on research conducted by Damayanti & Hendrasarie (2025), wet scrubbers have been proven to be very effective in reducing carbon monoxide (CO) emissions produced from the combustion process in the brick manufacturing industry. This process works through an absorption mechanism, namely direct contact between exhaust gases and a basic chemical solution, so that pollutant gases can be captured and neutralized. Test results show that the use of a 6N KOH solution and a 40 cm pall ring media height can reduce CO levels by up to 97.9%, with the final level meeting the emission quality standards according to PP No. 22 of 2021, which is 400 ppm. This figure not only proves that wet scrubbers are capable of working optimally, but also shows that this technology can be relied upon as an air pollution control solution that is applicable and results-oriented. In addition to using KOH absorbent, other absorbents such as NaOH can reduce carbon monoxide (CO) emissions from combustion by up to 91.8%, and H₂O absorbent can reduce emissions by up to 56.9%.

Therefore, chemical liquids such as NaOH, KOH, and H₂O will be used as the main absorbents in the wet scrubber, which will be combined with a burner machine designed by the researchers. Previous studies have shown that these three types of liquids work in different ways to reduce carbon monoxide (CO). KOH was chosen because it has been proven to have the highest level of effectiveness with a 97.9% reduction in CO at a concentration of 6N and a pall ring media height of 40 cm. NaOH, although slightly lower, still showed a significant reduction in CO of 91.8%, while H₂O was used as a comparison and also to assess how effective non-chemical liquids are in absorbing pollutant gases. Although non-chemical liquids can only reduce CO by around 56.9%, it is still relevant to know the minimum performance limits of the system. By testing these three absorbents in a series of burner-wet scrubber systems, the researchers hope to obtain a comprehensive picture of the performance of the resulting technology. They also want to provide the best recommendations for the application of this technology on an industrial scale as well as on a small scale that requires effective and practical emission control solutions.

Several studies explain that the use of wet scrubbers can reduce fine particle emissions, but they provide minimal details on their effects on gases such as CO (Ramaswamy et al., 2022). In addition, research developed by Bianchini et al. (2018), found a combustion system with pollution control in a burner machine, but the burner machine design was not specifically integrated with a wet scrubber. Thus, there is a significant research gap, namely a comprehensive analysis of CO emissions from the combustion of rice husk waste using manual methods compared to mechanized systems using machines as CO emission control technology directly during the briquette manufacturing process. Based on the above description, this study was conducted to measure the effectiveness of wet scrubber technology in the context of briquette manufacturing from rice husk waste.

2. Methods

2.1 Overview

This study was conducted in Lamajang Village, Pangalengan Subdistrict, Bandung Regency, over a period of three and a half months. Lamajang Village, located in Pangalengan Subdistrict, Bandung Regency, has an area of 4,016.09 hectares with an average altitude of 983.89 meters above sea level and is located approximately 32 km from the center of Bandung City. With a hilly topography at an elevation of 900–1,200 meters above sea level, a wet climate with 1,700 mm/year of rainfall, and a majority of the population dependent on the agricultural sector (rice, vegetables, and plantations), land use is an important aspect in supporting economic activity. Of the total area, land use for agriculture includes 786.93 hectares of technical irrigation rice fields, 388.36 hectares of semi-technical irrigation rice fields, and 272.64 hectares of rainfed rice fields. Based on interviews with the Head of Lamajang Village, this village has the largest agricultural land in Pangalengan District. This condition also causes an abundance of rice husk waste every harvest season, but until now,

most of it is still utilized inappropriately, namely by burning it openly, which causes greenhouse gas emissions, especially carbon monoxide (CO). To clarify the research location, a satellite image map of Lamajang Village sourced from Google Earth (Figure 5) is presented, showing residential areas, rice fields, and the trial locations used in this study.



Fig. 5. Satellite image of Lamajang Village showing topography

This research involved a team of students working with the village community with the main objective of optimizing the use of rice husk waste into briquettes, as well as reducing carbon monoxide (CO) emissions generated from the open burning of rice husks. Using the reverse engineering method, the stages of the activity began with identifying system requirements and analyzing field conditions, followed by the design and prototype development process, then performance testing through briquette combustion, and finally an evaluation of the emission test results. This research compares two briquette production methods, namely the manual method and the machine-based method, with the aim of seeing how far mechanization can reduce CO emissions and improve briquette quality.

2.2 Reverse engineering

Reverse engineering in manufacturing is a method of reconstructing or recreating existing component models, sub-assemblies, or products without relying on original design documents or working drawings.

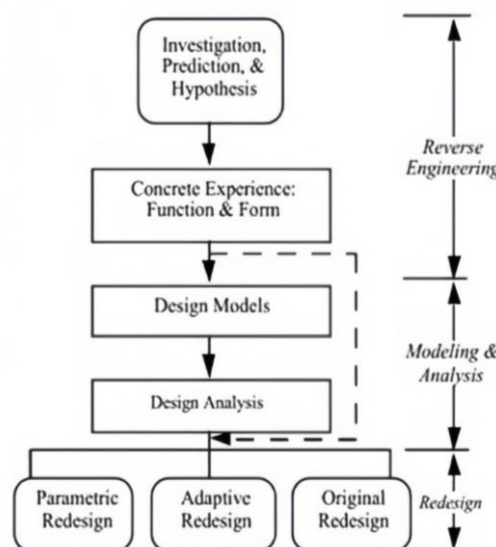


Fig. 6. Reverse engineering processes

Reverse engineering is useful for analyzing a system and retrieving its underlying design or blueprint. In briquette machine manufacturing research, reverse engineering is used to study existing machines so that they can be reconstructed, modified, and developed into new designs. This approach is relevant in briquette machine manufacturing research because the process allows for the design and development of machines by studying and adapting existing machine models, thereby producing new designs that are more suitable for the utilization of rice husk waste in Lamajang Village.

2.3 Identification of needs and field observations

This preliminary study involved identifying needs and conducting field observations necessary to ensure that the technology developed was appropriate for the community. The process of identifying needs can help researchers and communities to select training needs or performance deficiencies (Darmawan et al., 2021). At this stage, technical system requirements were identified through literature studies, field observations, and discussions with local farmer groups. The identified needs included the availability of raw materials, machine designs that were suitable for the village's production capacity, and emission test specifications. The raw materials used in this study were rice husks, starch adhesive, and water with a composition of 80% husks and 20% adhesive. The ratio of starch to water was set at 1:5 in accordance with the briquette manufacturing process design. Rice husks were chosen as the raw material due to their abundant availability in Lamajang Village, while starch adhesive was chosen because it is easily obtainable, environmentally friendly, and capable of increasing the mechanical strength of the briquettes. Water is used as a mixing medium to optimize the homogenization process. In addition, sustainability is also considered, as this briquette technology is expected to not only reduce the practice of open burning of rice husks, but also provide economic added value to the community through the utilization of agricultural waste as an alternative energy source.

2.4 Design

Design is a field of study closely related to the process of designing or planning something, which is generally expressed in the form of two-dimensional drawings, which can then be realized into a three-dimensional form (Suryatini et al., 2021). By understanding the basic concepts of design, a designer can clearly formulate the message to be conveyed through their work and create innovative designs that accurately convey that message (Irvanto et al., 2020). This stage is carried out by assembling the tool architecture, which includes the frame, combustion chamber, and emission flow. The design is carried out using CAD (Computer Aided Design) software to produce an exploded view model (Fig. 7). This design considers mechanical aspects, air flow, and emission.

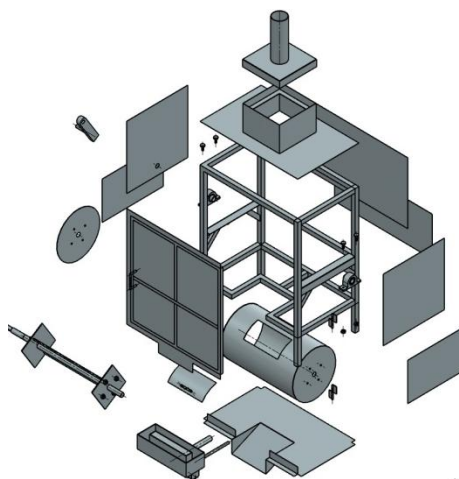


Fig. 7. Exploded view model

The design will be followed by a simple flow and heat distribution simulation. In addition, at this stage, the emission measurement mechanism will also be determined, namely by using a Non-Dispersive Infrared (NDIR) analyzer that works based on the principle of infrared absorption by CO molecules (Sun et al., 2025).

2.5 Prototype and briquette production

The next step was to build a prototype based on the design. This involved welding a steel frame, installing a drum as the combustion chamber, and adding a chimney and blower for air supply. The assembly process resulted in a briquette combustion test engine (Fig. 8).



Fig. 8. Briquette combustion testing machine

In addition to designing and manufacturing the machine, this research also included testing the production of briquettes using two different methods. The first method was carried out manually, which involved mixing rice husks, starch adhesive, and water according to a predetermined composition, then shaping the mixture using a simple mold and drying it naturally. The second method was carried out using a set of machines consisting of a grinder to crush the raw materials, an extruder to mold the dough into briquettes, and a burner as a tool to test the combustion performance.

2.6 Emissions testing and system manufacturing

Emissions testing is carried out by burning briquettes in a combustion furnace placed under a measured flow hood. The combustion gases are channeled through a pipe equipped with a sampling probe, and the CO concentration is continuously monitored using a Non-Dispersive Infrared (NDIR) analyzer. Another line is fed into a wet scrubber containing a lime water solution to capture dissolved gases. A wet scrubber is an air pollution control device that removes solid particles and acidic gases from exhaust gas streams from stationary sources (Environmental Protection Agency, 2025). The use of a wet scrubber is intended to evaluate the effectiveness of exhaust gas emission reduction before it is released into the air, as well as to ensure that the concentration entering the test chamber is not excessive. According to Sun et al. (2025), CO measurements are performed using the principle of infrared radiation absorption by CO molecules. The NDIR analyzer is calibrated using standard gas before use, with zero calibration (zero gas) and span calibration (CO gas with a known concentration). The CO concentration obtained from the analyzer is then recorded in ppm units continuously every 1-10 seconds. After that, the ppm data is converted into mass concentration (mg/m^3) by calculating the temperature and pressure of the gas, then combined with the volumetric flow rate of the exhaust air to calculate the total mass of CO (g).

In addition, part of the gas flow is also directed into a simple wet scrubber system to evaluate the effectiveness of reducing exhaust emissions. This wet scrubber technology has been proven effective in reducing tar and some emissions from biomass combustion (Lanjekar & Panwar, 2025). If the initial results show flow variations of more than 10% or instrument drift, repairs will be carried out in the form of recalibrating the analyzer, repairing the hood seal, and adjusting the standard briquette size.

3. Results and Discussion

3.1 Research approach

In this study, the briquette production process was carried out using two different approaches. The comparison of these two methods aimed to determine the extent to which the differences in the processes affected the quality of the briquettes, particularly in terms of combustion results, shape consistency, and production time efficiency. The first approach was the manual method, which is the process of making briquettes without using machines. The stages include mixing rice husks, starch adhesive, and water according to the specified composition, then the mixture is put into a simple mold and pressed manually into briquettes. After that, the briquettes are dried naturally using sunlight. The second approach is the use of a briquette production machine set, which consists of a grinder unit to reduce the size of the raw materials, an extruder unit to shape the briquettes to the desired size, and a wet scrubber to reduce dust and particle emissions during the process. The briquettes produced by this machine are then dried using the same method, so that the results can be measured more accurately.

3.1.1 Manual method

In the manual method, the briquette production process begins with the collection of rice husks as the main raw material. Rice husks are chosen because they are widely available as agricultural waste, although their use as an alternative energy source is still limited.



Fig. 9. Open burning of rice husks

The next stage is the charring of rice husks through open burning, producing charcoal that is ready for further processing. This process is relatively simple, but it produces large amounts of exhaust emissions, such as carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), and dust particles, which have the potential to pollute the air and reduce the sustainability of biomass energy (Junpen et al., 2018). After being turned into charcoal, the husks are then crushed or sieved to obtain a more uniform particle size. These fine particles are mixed with natural adhesives, such as tapioca flour solution, which serve to increase the compactness and mechanical strength of the briquettes. The mixture is then placed in a manual mold to be shaped to the desired size. Because it relies solely on manual pressure, the density of the briquettes tends to be lower than that of briquettes produced using a mechanical process. Next, the formed briquettes undergo natural drying in the sun

until their moisture content is significantly reduced. The end result is ready-to-use rice husk charcoal briquettes, which can be used as an alternative solid fuel, although the quality still depends on the homogeneity of the materials, the amount of adhesive, and the effectiveness of the drying process.

3.1.2 Briquette production machine set

In order to improve the efficiency and quality of the briquette production process while reducing the negative impact on the environment, a series of briquette production machines integrated with a wet scrubber-based emission control system are used. This system allows the combustion of raw materials, namely rice husks, to take place in a semi-enclosed manner so that the resulting exhaust gas emissions can be minimized

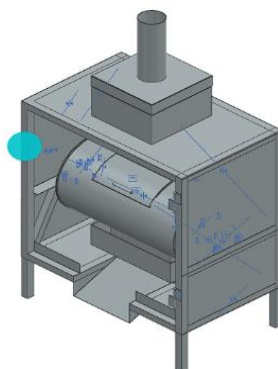


Fig. 10. Burner machine drafting

The application of wet scrubber technology at the combustion stage aims to reduce odors and lower the concentration of solid particles and hazardous gases such as carbon monoxide (CO), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) commonly found in biomass combustion gases (Supriyadi et al., 2021). The burner is a key component in the semi-closed rice husk carbonization process. This combustion system is equipped with a wet scrubber system to minimize the harmful gases produced by burning rice husks.

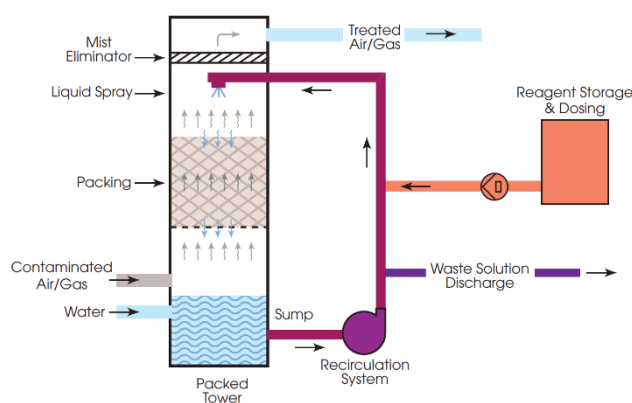


Fig. 11. Wet scrubber mechanism

A wet scrubber is an air pollution control system designed to clean exhaust gases of solid particles and gaseous pollutants using a scrubbing liquid. The mechanism begins when a contaminated gas stream (particulate-laden gas stream), such as from the briquette combustion process, enters a chamber. Simultaneously, the scrubbing liquid, which is generally water, is sprayed from nozzles at the top of the chamber, producing fine liquid droplets. The gas stream moves upward, in the opposite direction to the water droplets falling due to gravity. Intensive contact between the particles in the gas and the water droplets is at the heart of the cleaning process; the particles stick to the water droplets

through a process of impact and friction (scrubbing action). The mixture of water and collected particles, called slurry, flows to the bottom of the chamber and is collected in a sump. At the top of the chamber, a mist eliminator captures any water droplets that may be carried along, ensuring that only clean gas is released into the atmosphere Liu et al. (2019). The slurry collected at the bottom is then sent for further processing, and the treated water can be recirculated back into the system for reuse.



Fig. 12. Grinder machine

With this mechanism, the wet scrubber system plays an important role in reducing the levels of harmful particles and gases produced from the rice husk combustion process in briquette manufacturing. The gas produced from rice husk combustion is known to contain carbon monoxide (CO) and fine particulates that can potentially harm health and pollute the environment (Piyathissa et al., 2023). Through the contact process between the gas flow and the washing liquid, gas and particulate pollutants can be bound and dissolved in the liquid, thereby reducing the concentration of emissions released into the atmosphere. Thus, the application of a wet scrubber in a semi-closed combustion system can improve the air quality around the production area while supporting a more environmentally friendly briquette manufacturing process. After the rice husk carbonization process is complete, the rice husk charcoal enters the grinding stage. In this stage, the grinder functions to reduce the size of the burnt rice husk charcoal into fine grains of uniform size. This stage is crucial because smaller particle sizes significantly increase the surface area, which facilitates the mixing process with the adhesive and ultimately improves the quality of the resulting briquettes.



Fig. 13. Extruder machine

The grinding process is carried out mechanically with a motor-driven rotary blade system, producing rice husk charcoal powder that is ready to enter the adhesive mixing stage. The importance of particle size is supported by research findings. According to Pang et al. (2019), although the raw materials studied were different, their research results

generally showed that smaller particle size was positively correlated with increased density and mechanical strength in briquettes. This is in line with the principle that finer particles will fill empty spaces more efficiently, creating a tighter and more compact packing. Thus, the process of grinding rice husk charcoal into fine particles is a fundamental step in producing briquettes with superior physical quality and combustion characteristics.

The extruder serves to shape the mixture of fine rice husk charcoal and adhesive into briquettes with a shape that matches the mold. In this study, an extruder with a 3 cm x 3 cm briquette mold was used, which produced uniformly sized cube-shaped briquettes. The extruder works by pressing the mixture of charcoal and adhesive using a motor-driven screw system, then pushing or pressing it out through a box-shaped mold. This pressing process also increases the density of the briquettes, resulting in higher calorific value and longer burning time. This is supported by research by Bello & Onilude (2021), which found that an increase in compaction pressure during the extrusion process correlates directly with an increase in the density, strength, calorific value, and burning duration of the briquettes.

3.2 Overview of test materials

The experiment was conducted using 50 liters of rice husks with a bulk density of 0.09 kg/L, resulting in a total mass of approximately 4.5 kg. Based on literature data from Arranz et al. (2021), rice husks contain about 40.8% carbon, 5.9% hydrogen, 0.5% nitrogen, and 0.06% sulfur, indicating relatively low nitrogen and sulfur content which is beneficial in reducing the formation of NO_x and SO₂ emissions during combustion. From a proximate analysis perspective, rice husks have a volatile matter content of 80.6%, ash content of 9.7%, and a fixed carbon fraction of around 9.7%, which reflect a fuel with high reactivity but also with the drawback of elevated ash formation.

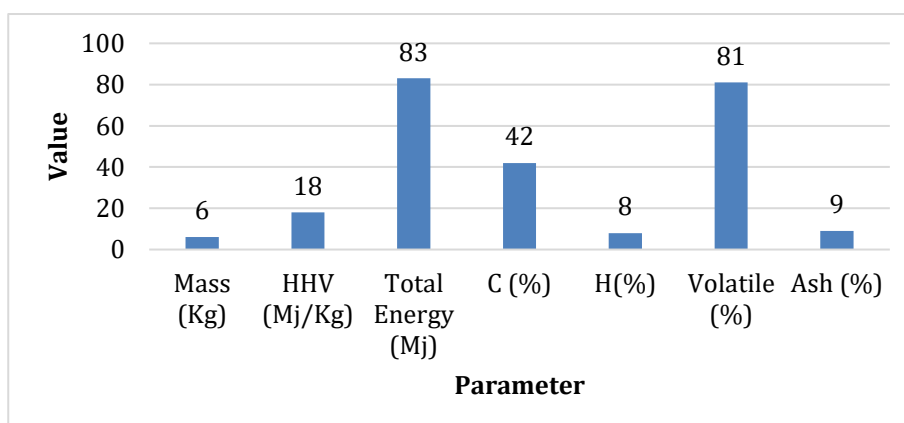


Fig. 14. Graphic overview materials

The higher heating value (HHV) of rice husks is reported to be 18.14 MJ/kg, so that the total energy potential of the 4.5 kg husks used in this study reaches approximately 81.6 MJ. This value places rice husks in a comparable category with other agricultural residues such as corn cobs (16–18 MJ/kg) and sugarcane bagasse (17–19 MJ/kg), but still lower than commercial coals (25–30 MJ/kg). The relatively high HHV confirms that rice husks can serve as an effective alternative biomass fuel for small-scale energy production. However, the high ash content ($\approx 9.7\%$) and low bulk density ($\approx 90 \text{ kg/m}^3$) remain significant challenges. High ash leads to frequent fouling and slagging problems in combustion chambers, while low density reduces the overall energy per unit volume, limiting efficiency in transport and storage. These disadvantages can be addressed through densification into briquettes or pellets, which increase bulk density from $\sim 90 \text{ kg/m}^3$ to $600\text{--}1200 \text{ kg/m}^3$ and improve combustion stability. In summary, the physico-chemical properties of rice husks demonstrate a material with promising energy potential, relatively low pollutant precursors

(N and S), but requiring technological interventions such as densification and emission control systems to enhance its performance as a sustainable biofuel.

3.3 Briquette test results

The rice husk briquette production process in this study was carried out using a series of equipment consisting of a grinder to reduce the particle size of the husks, an extruder to shape the briquettes, and a burner as the combustion testing device. For comparison purposes, briquettes were also produced manually using simple molds. The test results revealed a significant difference between the two methods. Manual briquettes had an average density of 0.55 g/cm³, while machine-made briquettes reached 0.80 g/cm³. This increase in density was directly related to combustion performance, where denser briquettes tended to burn more evenly and stably. In terms of emissions, combustion of manual briquettes produced an average carbon monoxide (CO) concentration of 360 ppm, with a peak of 520 ppm. In contrast, briquettes produced using the machine showed an average emission of only 220 ppm, with a peak of 320 ppm. Thus, there was a reduction of approximately 39% in CO emissions when briquettes were produced using the machine method. These findings indicate that the densification process not only improves the physical properties of briquettes but also significantly reduces exhaust gas emissions.

Technically, this difference can be explained by three main factors: Briquette density, where machine-made briquettes are denser, allowing better oxygen diffusion and enhancing the oxidation of CO into CO₂, porosity distribution, where manual briquettes contain larger and irregular pores, which tend to cause incomplete combustion; and moisture content, where manual briquettes are more difficult to control in terms of water content, resulting in higher emissions. When compared with previous studies, these results are consistent with the findings of Dhiman & Khamba (2024), who reported that manually produced briquettes tend to generate higher CO emissions (233–333 ppm) compared to densified products. Meanwhile, modern combustion systems such as pellet stoves can further reduce CO emissions to the range of 5–62 mg/Nm³ (≈4–54 ppm). Therefore, although the CO emission level of machine-made briquettes in this study (220 ppm) has not yet reached the efficiency of modern pellet systems, it is already far better than that of traditional manual methods.

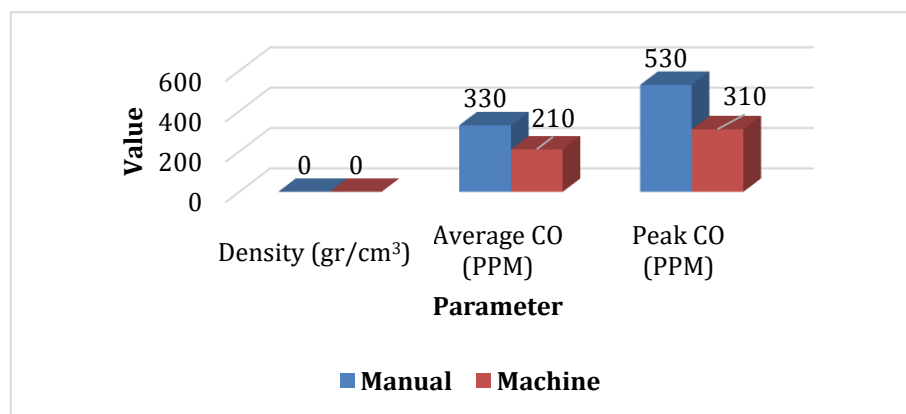


Fig. 15. Graphic PPM

3.4 Factor

The differences in combustion performance between manually produced briquettes and machine-produced briquettes are influenced by several factors. First, briquette density plays a crucial role; machine-made briquettes exhibit higher and more uniform compaction, allowing for a more consistent combustion process at relatively stable temperatures. Second, the internal structure and the distribution of air and moisture also contribute significantly. Mechanical molding produces a homogeneous structure with smaller cavities

and more controlled moisture content, thereby supporting optimal oxygen diffusion and a more complete oxidation reaction. In contrast, manually produced briquettes tend to have larger cavities and higher moisture content, which hinder airflow and result in uneven combustion. Third, the efficiency of the carbon oxidation process is enhanced in machine-made briquettes due to their homogeneity, which facilitates the effective conversion of carbon monoxide (CO) into carbon dioxide (CO₂).

In manual briquettes, however, this process is less effective, leading to higher CO emissions. In addition, cost, scalability, and operational challenges must also be critically analyzed to ensure practical relevance. Machine-based production requires a higher initial investment for equipment, energy, and maintenance; however, the resulting briquettes generally have greater density and calorific value, making them more efficient in terms of transportation and combustion performance (Dragusanu et al., 2023). Furthermore, the use of biomass briquettes in industrial boilers has been reported to reduce fuel costs by as much as 30–40% compared to coal (Pradhan et al., 2019). From a scalability perspective, manual production is limited in volume, whereas mechanized production enables large-scale manufacturing with consistent quality, thereby supporting implementation in both rural and industrial contexts. Nevertheless, several operational challenges remain, including the sustainable availability of biomass feedstock, the technical demands of machine maintenance, and the level of acceptance by communities and industries toward adopting this technology.

3.5 Comparison with other studies

The results obtained in this study are generally consistent with several previous research findings that have investigated carbon monoxide (CO) emissions from different types of biomass briquettes and combustion systems. Carbon monoxide is one of the most important pollutants produced during the combustion of solid fuels, as it is a toxic gas that indicates incomplete combustion. Therefore, evaluating CO emissions is a key parameter in assessing the environmental performance and efficiency of briquettes as alternative energy sources. Pilusa et al. (2013) reported that manually produced biomass briquettes, when tested with traditional ceramic stoves, generated CO emissions of around 74 ppm. Although this value is considered relatively low compared to some other biomass-based fuels, it is still significantly higher than what is typically expected from modern combustion appliances. Another investigation on acacia charcoal briquettes prepared manually revealed that average CO emissions ranged from 233 to 333 ppm, with peak concentrations reaching as high as 422 ppm. This indicates that differences in raw material, production method, and combustion device strongly influence the final emission outcomes.

Further studies have shown that briquette formulation also plays an important role. For example, rice husk briquettes that incorporated molasses and glycerin as binding agents were found to produce much higher CO emissions, varying between 465 and 1128 ppm. The emission levels in this case were strongly dependent on the excess air ratio applied during combustion. Such findings highlight that the use of additives in briquette production does not always lead to better performance; in fact, under certain conditions, it can worsen combustion efficiency and increase pollutant output. In contrast to these relatively high-emission cases, advanced combustion technologies such as pellet stoves have been shown to achieve significantly better results. Research conducted in Polonini et al. (2019) on modern pellet stoves demonstrated remarkably low CO emissions, reported in the range of 5–62 mg/Nm³, which corresponds to approximately 4–54 ppm. These values are substantially below those observed in most traditional or manually produced briquette systems, reflecting the benefits of improved combustion chamber design, optimized air supply, and standardized pellet quality.

When the present study is compared to the findings above, the results show that machine-made briquettes produced an average CO emission of about 220 ppm. This outcome indicates a meaningful improvement relative to several types of manually made briquettes, especially those that reached average values above 300 ppm or peaks over 400

ppm. It suggests that the mechanical briquette production process contributes to more uniform density, better compaction, and more consistent burning characteristics, all of which can lower CO emissions. However, the emission level of 220 ppm is still considerably higher than what is achieved by modern pellet stoves, underscoring the gap that remains between semi-traditional briquetting methods and highly optimized combustion technologies.

Table 2. Comparison of CO emissions (PPM) across various methods

Briquette type/technology	CO emissions (PPM)
Manual – Ceramic stove	74
Manual – Acacia charcoal	422
Manual – Rice husk + molasses	465 – 1128
Modern pellet stove	54
Mesin – Rice husk	220

Overall, the findings of this study contribute to the growing body of knowledge on biomass utilization and support the view that machine-made briquettes represent a promising alternative to manual production methods. Nonetheless, they also highlight the need for further research and development. Future studies should focus on optimizing briquette composition, binder selection, and stove design to reduce pollutant emissions even further. By narrowing the performance gap with modern pellet systems, biomass briquettes could become a more sustainable, affordable, and environmentally friendly energy solution for households and small industries in developing regions.

3.6 Research implications

This research has several important implications. From an energy perspective, machine-produced briquettes demonstrate higher efficiency because combustion is more stable, heat distribution is more consistent, and the flame can be maintained for a longer duration, which improves the usability of briquettes for continuous cooking or heating processes. From an environmental perspective, the reduction in CO emissions by nearly 40% indicates a safer and cleaner combustion process, reducing potential health risks from indoor air pollution and lowering the contribution to greenhouse gas accumulation. From a technological perspective, the use of an integrated machine set consisting of a grinder, extruder, and burner enables a standardized production process, ensuring more uniform size, density, and moisture content of the briquettes; this uniformity makes the briquettes easier to handle, store, and transport while maintaining consistent combustion performance.

3.7 Calculation methodology

Before calculating emission of Carbon Monoxide (CO), input data obtained from measurements and technical assumptions must first be determined. This data is used as the basis for converting pollutant concentrations (ppm) to mg/Nm^3 (dry, O_2 corrected), as well as for calculating emission rates and emission factors (g/kg of fuel). The following input data is used in the calculation.

Table 3. Input data for emission calculations

Method	CO (ppm)	T (°C)	P (atm)	RH (%)	O_2 (%)	Velocity (m/s)	Area (m^2)	Time (minute)
Manual (Open burning)	360	150	~1	12	16	0.3	7.85×10^{-3}	60
Burner + wet scrubber	220	450	~1	12	10	1	7.85×10^{-3}	30

In the calculation of flue gas emissions, the first step is to perform an oxygen correction. This step is essential because the measured concentration of a gas (such as CO) is strongly influenced by the oxygen content in the exhaust gas. By applying Equation (1), the measured concentration C_{meas} can be corrected to a reference concentration C_{Corr} by taking into account both the reference oxygen level and the actual measured oxygen level. This correction ensures that data from different operating conditions remain comparable, even when the oxygen content varies. The input data is then used for calculations using standard formulas, namely.

$$C_{\text{Corr}} = C_{\text{meas}} \times \frac{21 - O_{2,\text{ref}}}{21 - O_{2,\text{meas}}} \quad (\text{Eq.1})$$

The corrected concentration of the gas (C_{Corr}) represents the measured concentration of the gas (C_{meas}) adjusted to the reference oxygen concentration ($O_{2,\text{ref}}$) of 12%. The measured oxygen concentration ($O_{2,\text{meas}}$) is used to calculate the correction, ensuring that the gas concentration reflects the standard condition at the specified oxygen level.

Once the corrected concentration has been obtained, the next step is to convert the gas concentration from ppm to mg/Nm^3 . This conversion is necessary to express the results in terms of mass per standard cubic meter, a unit commonly used in air quality analysis and emission regulations. By applying Equation (2), the concentration in ppm C_{ppm} is multiplied by the molecular weight of the gas and a conversion factor, then divided by the molar volume of the gas under standard conditions. The result is the gas concentration in mg/Nm^3 , which provides a more representative basis for evaluation and comparison.

$$C_{\text{mg}/\text{Nm}^3} = \frac{C_{\text{ppm}} \times MW \times 1000}{22.414} \quad (\text{Eq.2})$$

The parameter ($C_{\text{mg}/\text{Nm}^3}$) represents the gas concentration expressed in milligrams per normal cubic meter, while (C_{ppm}) indicates the gas concentration in parts per million. The molecular weight (MW) of the gas, such as carbon monoxide with $MW_{\text{CO}} = 28.01 \text{ g/mol}$, is used in the conversion between these two units. The constant value 22.414 refers to the molar volume of an ideal gas at standard temperature and pressure (STP), measured in liters per mole.

After determining the corrected concentration of the gas, it is also necessary to calculate the flow and quantity of the exhaust gas in order to estimate the total emissions released. The first step is to determine the gas flow rate, which is obtained using Equation (3). The volumetric flow rate Q is calculated as the product of the gas velocity v and the cross-sectional area of the duct or pipe A . This provides the rate at which the gas passes through the system per unit of time.

$$Q = v \times A \quad (\text{Eq.3})$$

The volumetric flow rate (Q) is the product of the gas or fluid velocity (v) and the cross-sectional area of the duct or pipe (A). The gas or fluid velocity (v) is measured in meters per second (m/s), and the cross-sectional area (A) is measured in square meters (m^2). Therefore, the volumetric flow rate (Q) is expressed in cubic meters per second (m^3/s).

The volumetric flow rate (Q) represents the volume of gas or fluid flowing through a duct or pipe per unit of time. It is determined by multiplying the gas or fluid velocity (v) by the cross-sectional area (A) of the duct or pipe. This relationship provides a fundamental basis for calculating the total flow of gases or fluids in various engineering and environmental applications.

Once the flow rate is known, the total gas volume can be calculated using Equation (4). The total volume V is derived from the product of the flow rate Q and the duration of the

flow t . This step is important because it accounts for the accumulation of gas over the operating period.

$$V = Q \times t \quad (\text{Eq.4})$$

The total volume of gas or fluid (V) is obtained by multiplying the volumetric flow rate (Q) in cubic meters per second (m^3/s) by the time duration of flow (t) in seconds (s), resulting in a total volume expressed in cubic meters (m^3).

Finally, with both the corrected concentration and the total volume available, the mass of carbon monoxide released can be determined using Equation (5). In this equation, the mass of CO m_{CO} is obtained by multiplying the corrected concentration of CO C_{corr} by the total gas volume V . This provides a direct measure of the total pollutant emitted, which is essential for evaluating the environmental impact of the combustion process.

$$m_{\text{CO}} = C_{\text{corr}} \times V \quad (\text{Eq.5})$$

The mass of carbon monoxide (m_{CO}) is obtained by multiplying the corrected concentration of CO at the reference oxygen level (C_{corr}) in milligrams per cubic meter (mg/m^3) by the total gas volume (V) in cubic meters (m^3), resulting in the mass of CO expressed in milligrams (mg) or grams (g).

After calculating the total mass of carbon monoxide released, it is important to normalize this value with respect to the amount of fuel consumed. This normalization is expressed through the emission factor (EF), as shown in Equation (6).

$$EF = \frac{m_{\text{CO}}}{m_{\text{fuel}}} \quad (\text{Eq.6})$$

The emission factor (EF) represents the mass of carbon monoxide emitted per unit of fuel burned, expressed in mg/g or g/kg . The mass of carbon monoxide emitted (m_{CO}) is measured in milligrams (mg) or grams (g), while the mass of fuel consumed (m_{fuel}) is measured in grams (g) or kilograms (kg).

The emission factor is defined as the ratio between the mass of CO emitted m_{CO} and the mass of fuel consumed m_{fuel} . By using this approach, the emission level is no longer dependent only on the volume of exhaust gas, but instead provides a standardized indicator of emissions relative to fuel usage. This makes it possible to compare the environmental performance of different combustion methods or systems under varying operational conditions.

Table 4. Comparison of CO emission calculations between manual method and the burner and wet scrubber method

Method	CO (mg/Nm^3 , O_2 -corr)	Emisi (g/min)	Total (g/batch)	EF (g/kg)
Manual (Open burning)	527.47	0.04812	2.888	0.642
Burner + wet scrubber	84.79	0.01507	0.453	0.101

From these formulas, the summary of calculations is presented in the Table 4. Based on Table 4 it can be seen that the burner and wet scrubber system produces much lower CO emissions compared to the manual combustion method. Total CO emission in the burner and wet scrubber system were recorded at $0.453 \text{ g}/\text{batch}$ with an emission factor of $0.101 \text{ g}/\text{kg}$ husk, while manual combustion produced $2.888 \text{ g}/\text{batch}$ or $0.642 \text{ g}/\text{kg}$ husk. Thus, there was a reduction in CO emissions of $\pm 84.3\%$ when combustion was carried out using the burner and wet scrubber system. This reduction can be attributed to a more controlled combustion process through the use of burners and exhaust fans, as well as cooling and exhaust gas filtration stages through wet scrubbers, which serve to reduce pollutant

content. Technically, these results show that briquette production machine technology, namely burners equipped with the wet scrubber features, is more effective in reducing CO emission than traditional open burning methods, and has the potential to become a more environmentally friendly alternative for processing rice husk waste.

4. Conclusions

This study confirms that rice husks have considerable energy potential, with a calorific value of 18.14 MJ/kg, equivalent to 81.6 MJ from the 4.5 kg sample tested. The densification process through a series of grinder, extruder, and burner machines successfully produced briquettes with higher density (0.80 g/cm^3) compared to manually produced briquettes (0.55 g/cm^3). This difference in density directly influenced combustion performance, as reflected in the reduction of CO emissions by about 39% (220 ppm versus 360 ppm). More importantly, the integration of a burner system equipped with a wet scrubber provided a significant breakthrough in emission control. Under this system, total CO emissions decreased drastically from 2.888 g/batch (0.642 g/kg husk) in manual combustion to only 0.453 g/batch (0.101 g/kg husk), representing a reduction of approximately 84.3%. This substantial improvement can be attributed to the more controlled combustion enabled by the burner and the cooling-filtration mechanism of the wet scrubber, which effectively reduces both gaseous pollutants and fine particulates.

These findings highlight that combining briquette densification with wet scrubber technology not only improves fuel quality and combustion efficiency but also delivers substantial environmental benefits. Therefore, the transition from manual to machine-based briquette production, complemented by wet scrubber emission control, offers a viable and more sustainable solution for utilizing rice husk waste as an alternative energy source at household and small industrial scales, while contributing to broader efforts in reducing air pollution and promoting cleaner biomass energy utilization. To maximize its impact, policymakers are encouraged to introduce incentives or subsidies for small-scale industries adopting briquette densification and emission control technologies, while manufacturers should prioritize affordable, easy-to-maintain equipment designs to accelerate widespread adoption in rural and peri-urban communities.

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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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Conflicts of Interest

The authors declare no conflict of interest.

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