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# The Design of an Efficient Charcoal Kiln Optimizing for Converting Areca Spathe Biomass into High-Yield Charcoal

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**ABSTRACT**

This study explores the use of Areca spathe biomass, a by-product from plate manufacturing, as a feedstock for charcoal production. A 50-liter custom-designed kiln was developed with an adjustable combustion chamber and variable air perforation sizes (1.59, 3.18, and 4.76 mm) to optimize the carbonization process. Temperature sensors were integrated to monitor thermal distribution, while computational simulations modeled airflow and heat dynamics to enhance efficiency. Experimental results showed that the highest charcoal yield, 41.53%, was achieved within one hour using 1.59 mm air perforations. Simulations closely aligned with empirical data, showing only ±0.65% deviation at 552.11°C. The findings revealed that shorter carbonization durations generally increased yield by reducing over-decomposition; however, the relationship was not entirely linear. Extremely short times led to incomplete carbonization, while longer durations reduced yield due to carbon burn-off and ash formation, particularly in trials like ASB9. An optimal carbonization window was identified, balancing heat exposure to maximize yield without degrading the product. The optimized kiln produced high-purity, porous charcoal with low volatile content. While promising, further research is needed to refine operational parameters for consistent quality. This study supports sustainable development by enhancing energy efficiency, lowering production costs, and enabling potential applications such as activated carbon production and soil amendment. Additionally, it offers a viable model for community-scale charcoal production, providing both environmental and economic benefits.

## 1. Introduction

Pyrolysis of biomass produces charcoal, used as fuel and soil amendment to enhance fertility, reduce carbon emissions, and mitigate climate change [1-2]. As the pyrolysis temperature increases, the water retention capacity of biochar improves, enhancing its adhesion, cohesion, and material porosity. The porous structure of biochar plays a critical role in retaining water, thereby improving nutrient exchange efficiency and enhancing the soil's chemical and physical properties. This improvement contributes to increased agricultural yields. The development of internal porous structures in biochar enhances soil structure, nutrient retention, and mineral content, creating optimal conditions for microbial growth and supporting the soil ecosystem [3]. Additionally, biochar's capacity to absorb organic and inorganic contaminants further improves soil health by reducing pollutant bioavailability. Traditional charcoal production emits toxic gases like methane and carbon monoxide, along with particulates, harming the environment and increasing greenhouse gases [4]. Retort kilns effectively reduce emissions by re-combusting pyrolysis gases; however, they remain economically and energetically demanding, particularly during the initial stages of operation [5]. Innovative technologies, such as Kon-Tiki flame curtain kilns, integrate traditional kiln simplicity with gas combustion in a flame curtain, reducing external fuel reliance and enhancing efficiency [4]. These kilns also demonstrate lower particulate emissions and quicker start-up times compared to conventional retort systems, making them more suitable for small-scale rural applications.

Charcoal production ranges from laboratories to industrial scales; however, in rural areas of developing countries, biomass is predominantly used for cooking without carbonization [6-7]. Developing household-scale charcoal kilns is essential for enabling fuel-efficient and low-emission charcoal production, thus providing both energy security and environmental benefits. Kiln types include closed kilns (Model I), externally circulating gas kilns (Model II), and internal circulating gas kilns (Model III). Closed kilns yield the highest-quality charcoal but require more fuel and time, whereas internally circulating gas kilns produce high-quality charcoal more efficiently [8]. New charcoal kilns employing pyrolysis gas circulation are increasingly popular for improving energy conversion efficiency and reducing emissions. These kilns produce high-carbon, porous charcoal suitable for use as absorbent material in wastewater treatment and soil remediation [9]. Further research is required to enhance kiln efficiency and minimize environmental impact, including the integration of real-time monitoring and control systems to optimize pyrolysis parameters [10]. Advancing charcoal production technology for households and rural communities can enhance soil quality, boost agricultural productivity, and reduce biomass combustion emissions. Developing efficient kilns tailored to rural needs is crucial for sustainable benefits [11]. The design and simulation of small biomass carbonization kilns aim to optimize charcoal production by analyzing air velocity, pressure, temperature, and flow rate using Finite Element Analysis (FEA) and the Finite Volume Method (FVM). Simulations showed kiln temperatures of 400-900°C, improving heat distribution, charcoal quality, and volatile reduction. The design minimizes pore-clogging and production costs, offering guidelines for scaling to industrial level [12]. A computational simulation was developed to design and analyze a charcoal kiln with dimensions of 500 mm in height and 380 mm in diameter. The kiln features a central combustion core with a diameter of 115 mm and is equipped with air vents, each measuring 6.35 mm in diameter. The simulation results were validated through comparison with experimental data. The temperature distribution within the kiln indicated that the maximum temperature was located at the core and gradually decreased radially toward the kiln wall. The average temperatures measured along the radial and axial directions were 293.3 ± 176.7°C, 363.4 ± 270.9°C, and 369.6 ± 277.1°C, respectively. In terms of biochar production, the yields obtained from different biomass feedstocks were as follows: 15.7% for corncobs, 24.3% for rice husks, and 11.4% for dried longan leaves [13]. Charcoal production faces challenges, including quality inconsistencies arising from the use of diverse biomass types [14]. Variations in density, pH, and toxic substances affect charcoal's effectiveness in soil improvement and carbon sequestration. High production costs, driven by advanced carbonization technologies, hinder accessibility, particularly for small-scale producers. Although modern pyrolysis systems, such as gas recirculation, reduce emissions, greenhouse gases like $CO_2$ and toxic gases remain a concern [15-16]. Moreover, the management of by-products such as wastewater and solid residues from charcoal production requires effective strategies to mitigate environmental impacts and enable resource recovery [17]. Emerging circular economy approaches propose valorizing these residues for secondary uses such as bioenergy or soil conditioners, thereby enhancing sustainability. Collaborative efforts involving researchers, policymakers, and local communities are necessary to develop affordable, efficient, and environmentally friendly charcoal production technologies that address socio-economic constraints and environmental goals.

The Home Hug Community Project in Tak Province, Thailand focuses on adding value to Areca spathe by producing eco-friendly products like natural plates and containers. The project also utilizes 60–270 kg/month of Areca spathe waste to produce charcoal, addressing challenges in quality control. To enhance production, the project seeks technology for producing high-quality activated charcoal meeting international standards, expanding its potential in global markets. Additionally, product diversification, such as soap production, aims to meet broader consumer needs see Fig. 1. The quality improvement of raw charcoal is a critical prerequisite before activation. Ensuring consistent and high-quality charcoal allows for effective conversion into activated carbon with desirable properties. This step supports the community’s goal of producing standardized, value-added products suitable for broader commercial markets.

This research examines factors influencing charcoal quality, particularly air hole design in kilns, which optimizes airflow and combustion. Computer simulations of airflow and temperature distribution guide the design of efficient kilns. Areca spathe biomass,

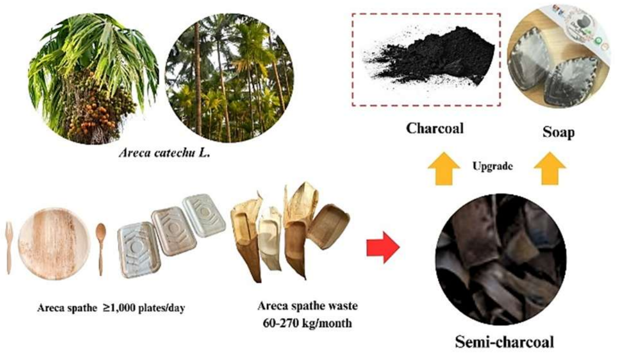


Fig. 1 Areca Spathe Waste to Charcoal and Eco-Friendly Products.

a by-product of plate production, has favorable physical properties, such as porosity and strength, enhancing airflow and heat distribution in kilns. The resulting charcoal demonstrates properties suitable for absorbent materials. Testing confirms its potential as a raw material for charcoal production. The production process can achieve a high conversion of biomass to carbon, reaching temperatures exceeding 350°C. The study aims to develop sustainable, high-charcoal yield products for applications in community businesses and biomass energy production, maximizing economic benefits for local communities.

## 2. Methodology

### *2.1 Biomass preparation and charcoal production process*

The charcoal production process begins with the preparation and weighing of biomass derived from Areca spathe (*Areca catechu* L.), which is dried to reduce the moisture content to below 10%. The mass of the biomass used depends on the density and size of the raw material, typically ranging from 10 to 20 cm in length. The biomass is densely packed into the biomass chamber of the kiln until it is filled. The kiln is then sealed with a lid and securely locked. Subsequently, it is placed on a pre-prepared base, and fuel sourced from *Acacia* wood also with a moisture content below 10% is added. The amount of fuel, ranging from 1.5 to 3.5 kg, is carefully weighed depending on the intended combustion duration, which is set between 1 and 3 hours. During combustion, the flame temperature within the combustion chamber is maintained at no less than 300°C [3].

Prior to entering the pyrolysis or carbonization stage, the biomass, prepared from Areca spathe waste remaining from the production of Areca-based plates, is loaded into the kiln in amounts up to 1.0 kg. The quantity of fuel used varies with the combustion duration: 1.5 kg for a 1-hour process, 2.5 kg for 2 hours, and 3.5 kg for 3 hours. The fuel has an approximate calorific value of 5,142 kcal/kg [23]. The kiln is insulated with ceramic fiber and equipped with K-type thermocouples connected to a WISCO real-time temperature data logger compliant with RS232 communication standards.

Operation begins with ignition of the fuel from the top of the combustion chamber. Heat is applied from the top to initiate combustion, and timing begins from the moment of ignition until the pre-determined test duration is completed. Following combustion, the kiln is allowed to cool either naturally or through active cooling, depending on experimental requirements [19]. The emission from the developed combustion kiln is measured at the flue gas stack using a TESTO 350 process gas analyzer [3].

After cooling, the charcoal identified by its blackened appearance is collected, weighed, and stored in sealed zip-lock bags. Solid by-products such as ash are also collected and weighed.

The entire experimental procedure is repeated three times to evaluate the consistency and efficiency of the charcoal production process. The yield of charcoal is calculated based on the mass balance, as defined in Equation (1). The ash content is determined using Equation (2), while the energy content of the syngas produced during pyrolysis is calculated using Equation (3). The overall energy efficiency of the process is assessed using Equation (4) [24–25].

$$Y_{BC} = \frac{w_f}{w_o} \times 100 \tag{1}$$

Where $Y_{BC}$ is Charcoal yield (%) $w_f$ is Weight of the charcoal produced (g), and $w_o$ is Initial weight of the biomass (g)

$$Y_{BC} = \frac{w_f}{w_o} \times 100 \tag{2}$$

Where $Y_A$ is Ash of process (%), $w_f$ is Weight of the ash produced (g), and $w_o$ is Initial weight of the biomass (g)

$$Y_G = \frac{w_o - w_f}{w_o} \times 100 \tag{3}$$

Where $Y_G$ is Produced gas (%), $w_f$ is Weight of total solid yields (g), and $w_o$ is Initial weight of the biomass (g)

$$EE = \frac{E_{out}}{E_{in}} \times 100 \tag{4}$$

Where EE is Energy Efficiency (%), $E_{out}$ is Output Energy (%), and $E_{in}$ is Input Energy (%)

*2.2 Design and computer simulation of the charcoal kiln*

The developed kiln consists of two main chambers: the Combustion Chamber, which is a closed-end steel pipe with drilled perforations ranging from 1.59 – 4.76 mm to facilitate controlled combustion and secondary air intake, and the Carbonization Chamber or Biomass chamber, a donut-shaped carbon steel tank surrounding the central combustion chamber designed to hold up to 50 liters of biomass for carbonization. The central combustion chamber (core) comprises 12 outer steel pipes, each with a diameter of 2.54 cm and a length not exceeding 10 cm, arranged in a circular pattern. Perforations for heat dissipation and gas outlet, with diameters of 1.59 mm, 3.18 mm, and 4.76 mm, are uniformly distributed around each pipe to ensure efficient heat transfer and gas flow. These perforation sizes were selected because they are representative of those commonly encountered in general engineering and industrial applications [18–19], and they cover a range that may significantly influence the mechanical behavior of the materials used in the Anila stove, making them suitable for comparative analysis on the performance of charcoal kilns [18–19]. The specific locations where perforation sizes have been modified include the walls of the combustion chamber pipes, where the drilled perforations regulate air inflow and gas outflow to optimize combustion efficiency, and the surrounding areas of the carbonization chamber, which benefit from the radial distribution of heat and gases to promote uniform temperature and minimize hot or cold spots. This design facilitates a radial flow of pyrolysis gases that are recirculated and combusted within the kiln, reducing the need for external fuel and enhancing energy efficiency. The overall design and analysis focus on the strategic distribution of these perforations to improve thermal dynamics and material performance. To further evaluate airflow and temperature distribution within the kiln, computational simulations were conducted using SOLIDWORKS software, providing insights into the thermal behavior and aiding in the optimization of the kiln's performance [20-21].

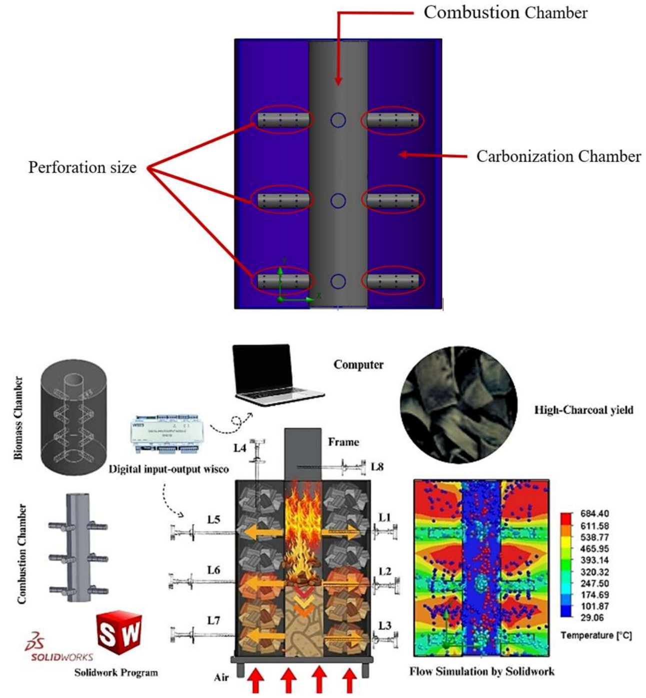


Fig. 2 The experimental process includes design, computer-based simulation, and result comparison testing.

*2.3 Computational simulation using SOLIDWORKS*

The methodology involves analyzing the structural strength of the model and simulating airflow through the 3D model using the finite volume method for closed-system flow under atmospheric pressure in Chiang Mai Province, Thailand. Chiang Mai's climate is warm and tropical, with an annual average temperature of 25.1°C. At sea level, atmospheric pressure is approximately 100,325 Pa, decreasing with altitude. At an elevation of 310 m above sea level, Chiang Mai's atmospheric pressure ranges between 100,300 and 100,500 Pa. Although the wind speed was not directly controlled, the combustion chamber temperature was actively regulated throughout the experiment. Real-time temperature monitoring equipment was utilized to continuously track and verify environmental conditions, ensuring that the temperature remained within a range consistent with the average conditions in Chiang Mai during April 2024, as reported by the Thai Meteorological Department (2024). The observed values during the experiment were in alignment with the reported averages, confirming the appropriateness of the environmental conditions for the study. In April 2024, the average weather conditions in Chiang Mai were as follows: average temperature of 29.1°C, average maximum temperature of 35°C, and average minimum temperature of 23.7°C. The average wind speed was 9.3 km/h or approximately 2.59 m/s [22]. The actual combustion chamber temperature obtained from experimental tests in Chiang Mai was used as an input parameter for simulating airflow and temperature distribution within the charcoal kiln using SOLIDWORKS software. The objective of the simulation was to verify whether the predicted temperature distribution closely matched the experimental results under controlled conditions, including atmospheric pressure, wind speed, ambient temperature, and combustion characteristics. Regarding porous material parameters inside the kiln, the porosity of areca spathe was set between 0.65 to 0.72, based on measured bulk density, true density and calculated using a standard porosity formula, to accurately represent its permeability. The thickness of the porous layer was defined in the range of 0.1 to 0.2 m to reflect the actual material packing during operation.

Additionally, the effective cross-sectional area for biomass loading was calculated to be approximately 0.81 m². These parameters collectively ensured that the simulation could effectively model the gas flow and heat transfer phenomena within the charcoal kiln under real operating conditions. The combustion chamber temperature used as input for the simulation was obtained from experimental measurements conducted in triplicate. This repeated testing ensured consistency of the input values, thereby increasing the reliability of the simulation results and reducing the standard deviation of the predicted temperature distribution. And the combustion chamber temperature was measured accordingly. The entire process, as shown in Fig. 2, involves the design of a charcoal kiln comprising a combustion chamber and a biomass chamber. The kiln is equipped with thermocouple sensors and operated through a computer-controlled system. Additionally, airflow and temperature simulations are integrated to optimize the efficiency of charcoal production.

**3. Results and Discussion**

*3.1 Results of Computer Simulation of Airflow Conditions*

The computer simulation was conducted under average atmospheric conditions in Chiang Mai Province, with an air temperature of 29.1°C, pressure of 100,325 Pa, and wind speed of 2.59 m/s [22]. Combustion chamber temperatures were set at 594.60°C, 585.30°C, and 684.40°C. The simulation results for the 50-liter charcoal kiln indicated that the maximum combustion chamber temperatures closely matched the set values, with kiln wall temperatures reaching 468.91°C, 461.70°C, and 538.77°C, respectively. Fluid density ranged from 0.48 to 1.15 kg/m³ at a 3.18 mm perforation sizes, with lower temperatures corresponding to higher air density. Air velocity peaked at 36.54 m/s at a 1.59 mm perforation size. The maximum air pressure ranged from 100,145.79 to 120,073.48 Pa. at a 1.59 mm perforation size.

Temperature distribution within the air and kiln ranged from 29.00°C to 684.40°C, as shown in Fig. 3, summarized in Table 1. The simulation results demonstrate that airflow and temperature distribution in the combustion chamber directly affect heat exchange and charcoal production efficiency. The designed perforation sizes of 1.59 mm, 3.18 mm, and 4.76 mm improved airflow and heat distribution [18], leading to higher-quality charcoal by reducing ash content and increasing the yield of fully carbonized material [8]. However, uneven heat distribution in certain areas was identified as a limit, potentially affecting product consistency. Computational Fluid Dynamics (CFD) simulations proved effective for analyzing fluid flow and temperature distribution, identifying key areas of conduction, convection, and radiation [26].

Improvements to the model are needed to enhance efficiency, including incorporating biomass properties such as density, thermal conductivity, and combustion rates to better reflect real conditions [1-2]. Regular comparisons with experimental data are essential to improve the model's reliability [20]. Additionally, the simulation should include heat transfer analysis at the structural level of the kiln, including walls and perforations. Although the activation process was not performed in this study, the resulting charcoal shows physical characteristics favorable for further development as activated carbon. The measured BET surface area (1.71–108.61 m$^2$/g) and visible pore structures indicate its potential for chemical or physical activation. These findings support the use of Areca spathe-derived charcoal as a promising precursor material in future studies targeting water filtration, air purification, or energy storage applications [27]. Designing a kiln that accurately controls airflow, and temperature can improve charcoal quality for this purpose and reduce environmental impacts, such as enhancing energy efficiency, lowering greenhouse gas emissions, and optimizing agricultural waste biomass use [15-16].

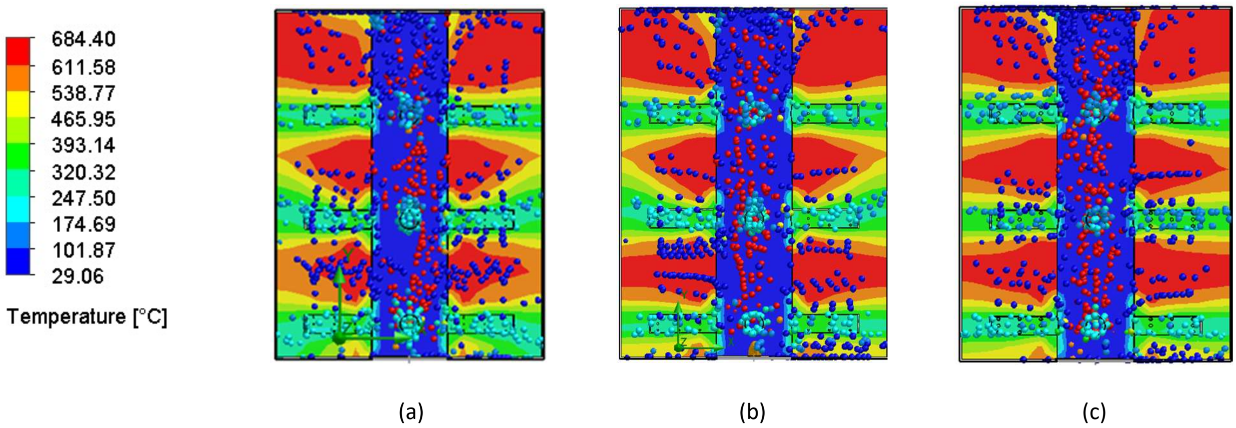


Fig. 3 Simulation of temperature distribution in a charcoal kiln for converting areca spathe biomass into charcoal, focusing on central perforation sizes of 1.59 mm (a), 3.18 mm (b), and 4.76 mm (c).

Table 1 Computer Simulation of Airflow in the Charcoal Kiln Using Areca spathe.

| Simulation Parameters<br>Central perforation sizes | Density (kg/m³) | Pressure (Pa) | Velocity (m/s) | Temperature (°C) |
|---|---|---|---|---|
| 1.59 mm | 0.47–1.15 | 100,145.79–120,073.48 | 0–36.54 | 29.00–594.60 |
| 3.18 mm | 0.48–1.15 | 100,161.11–119,866.77 | 0–33.27 | 29.08–585.30 |
| 4.76 mm | 0.43–1.15 | 100,148.15–119,821.59 | 0–35.12 | 29.06–684.40 |

This approach improves traditional charcoal production methods, addressing challenges like long production times, uneven temperature distribution, high ash content, and incomplete carbonization, all influenced by biomass properties, production duration [24-25], and the kiln's heat input rate [19]. These factors are interconnected and crucial for developing efficient charcoal kilns.

Computational studies have shown that parameters such as wind speed, airflow, and temperature significantly affect combustion efficiency [4]. Among these, the size and placement of air perforations in the combustion chamber are especially critical, as they govern airflow, heat distribution, and combustion completeness. Well-designed perforations optimize oxygen supply, stabilize temperature, and improve charcoal quality and yield. Moreover, understanding the relationship between combustion time and charcoal yield is essential for process optimization [28]. Adjusting variables such as fuel input and carbonization duration can balance efficiency, product quality, and cost [29]. These insights underscore the importance of integrating design and operational strategies to enhance the performance and sustainability of charcoal production systems.

*3.2 Results of comparison of charcoal production in kilns using computer simulation*

The temperature simulation within the charcoal kiln covering the core, middle, walls, and flame revealed discrepancies between simulated and experimental results. These differences arise from model assumptions based on heat transfer theory, which states that temperature peaks at the heat source (core or combustion chamber) and decreases with distance [13]. This model is less complex than the phenomena observed in the tests involving areca spathe. Importantly, the development of the charcoal kiln contributes to energy savings [30], not only reducing production costs but also minimizing environmental impacts, such as air pollution, the release of dust from burning agricultural waste, and the reduction of harmful chemicals that could harm the environment [3],[19]. A comparative analysis between computer simulation and experimental results was conducted to evaluate the temperature distribution within a charcoal production kiln utilizing *Areca* spathe as fuel. The study investigated three different air perforation sizes in the combustion chamber: 1.59 mm, 3.18 mm, and 4.76 mm. For the 1.59 mm perforation, the experimental temperature ranged from 444.0°C to 574.3°C, while the simulated values ranged from 440.49°C to 552.11°C. In the case of the 3.18 mm perforation, the experimental range was 418.6°C to 578.9°C, and the simulation range was 455.29°C to 594.66°C. For the 4.76 mm perforation, experimental temperatures ranged from 379.3°C to 619.8°C, whereas simulation results ranged from 415.08°C to 653.11°C.

These findings indicate a strong correlation between simulated and experimental data across all perforation sizes. In all cases, the temperature distribution followed a consistent trend: the highest temperatures were recorded radially near the central axis of the combustion chamber, gradually decreasing toward the kiln's inner wall. This pattern reflects the combustion zone's proximity to the fuel loading area, where airflow is most effective, thereby generating greater thermal intensity. Conversely, the decline in temperature toward the kiln wall suggests heat loss through the structure, likely due to thermal dispersion and dissipation from the biomass, resulting in reduced combustion efficiency in peripheral zones. Overall, the close agreement between simulated and experimental results confirms the accuracy of the computational model in predicting temperature distribution under varying airflow conditions and perforation configurations. Fig. 4 presents a comparative analysis between simulated temperatures and airflow patterns and actual temperature measurements obtained during the charcoal production process from areca spathe, employing perforation sizes ranging from 1.59 to 4.76 mm. The abbreviation "AS" denotes the experimental data on temperature recorded during the charcoal production process from areca spathe, whereas "Sim" refers to the simulated airflow temperature results derived from computational modeling [12]. The observed temperature deviations for perforation sizes of 1.59 mm, 3.18 mm, and 4.76 mm ranged from -10.56% to 3.44%, -11.39% to 8.76%, and -0.56% to 25.28%, respectively. The corresponding standard deviations were recorded as 2.54–38.68°C, 1.56–46.63°C, and 1.83–92.79°C. These findings highlight the consistency and reliability of the simulated data when compared to empirical measurements during the charcoal production process. The carbonization or pyrolysis process in charcoal production operates on the principles of convection, conduction, and radiation, employing controlled-air or incomplete combustion to convert biomass into charcoal without complete oxidation to ash. The movement of hot air, which is critical to the efficiency of this process, is strongly influenced by the combustion chamber's design, specifically its vertical geometry and the configuration of air inlets. Factors such as the number, size, spacing, and orientation of air perforations or pipes, as well as their positioning, directly affect airflow patterns and heat transfer within the kiln. Natural convection plays a central role: heated air rises due to reduced density, drawing cooler air from below to establish a circulation loop. This convective flow promotes uniform temperature distribution, enabling consistent carbonization and resulting in charcoal with high fixed carbon content, low brittleness, and minimal ash. Inadequate or uneven airflow, by contrast, can cause partial carbonization or over burning, leading to suboptimal charcoal quality. Kilns with appropriately placed inlets (e.g., bottom air perforations) and outlets (e.g., top exhaust vents) enhance the chimney effect, facilitating efficient upward airflow and rapid heat transfer throughout the biomass.

However, excessively rapid heat flow can reduce charcoal quality, necessitating careful balance between airflow rate and production time to optimize cost and yield [33–34]. This study focuses on the design and CFD (Computational Fluid Dynamics) simulation of a charcoal kiln, particularly examining how the direction and size of air inlet perforations influence internal airflow and heat distribution. Simulations revealed that small perforations (1.59 mm) restrict air volume but increase velocity, whereas larger perforations (4.76 mm) allow greater air inflow at lower velocities, potentially leading to uneven heat distribution depending on kiln conditions. These findings, supported by temperature distribution data (Table 1), align with observed percentage error trends between experimental and simulated results. Accurate simulation requires careful definition of boundary conditions, including chamber temperature, ambient conditions, airflow velocity, pressure, turbulence, and biomass characteristics (porosity, particle size, loading volume, and heat exchange surface area).

Matching these parameters to specific biomass types ensures practical and precise modeling outcomes. The balance between air inlet size, biomass type, and kiln dimensions is therefore essential for maximizing carbonization efficiency. Results from this study are consistent with prior research. For example, in kilns using corn cobs, the minimum temperature error was 0.4 ± 0.1% at the base (80 mm height), with a maximum of 17.7 ± 25.2% at the middle (261 mm) [13]. For rice husks, errors ranged from 0.8% to 12.0%, and for dried longan leaves, from 1.2% to 22.4%, depending on kiln height. In another study [18], temperature errors across three radial positions and heating durations (3–9 hours) averaged 12.0–14.5%. Research using insulated Anila-type kilns of various sizes showed that a 200-liter kiln operating for 3 hours produced the most uniform temperature distribution, with simulation error as low as 0.7 ± 0.6% [19].

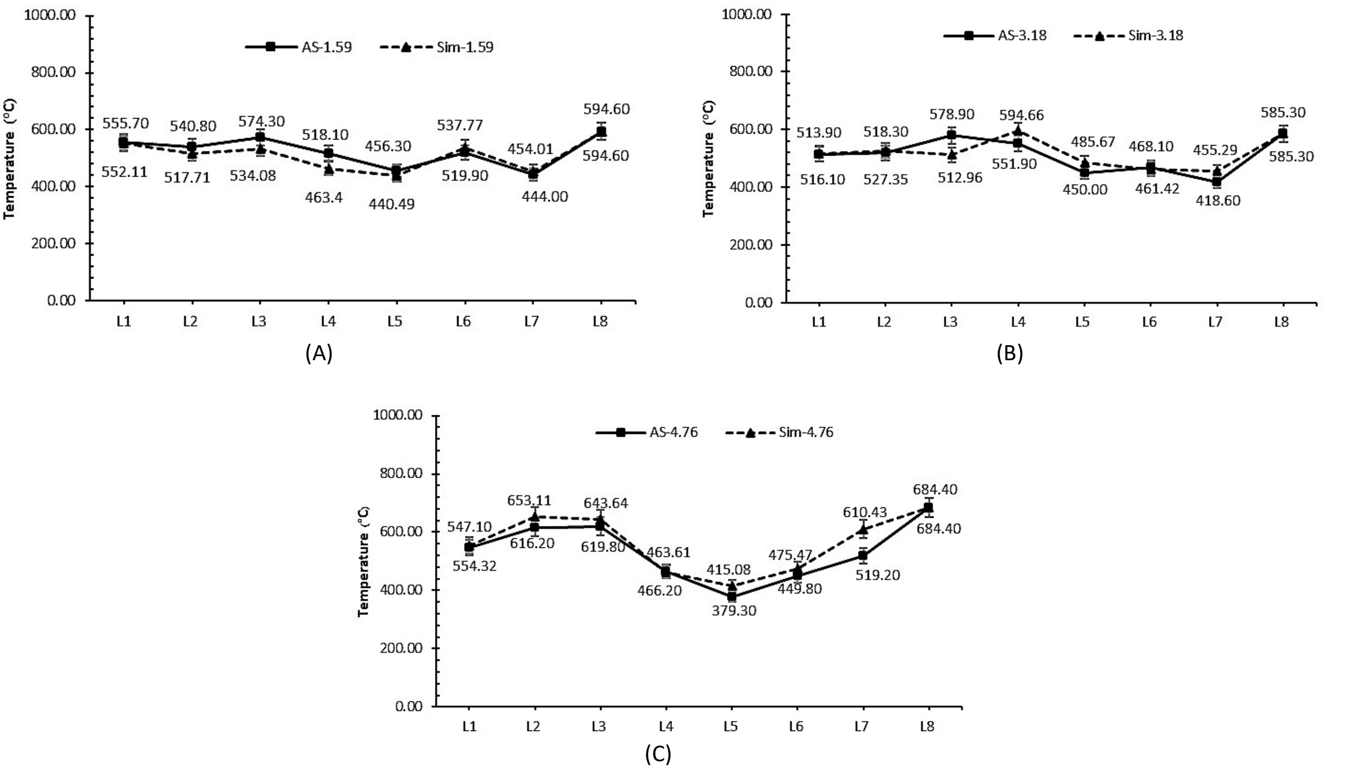


Fig. 4 Comparison of simulated temperature and airflow results for a charcoal kiln with different perforation sizes of 1.59 mm (A), 3.18 mm (B), and 4.76 mm (C).

This study provides a deeper understanding of how heat penetrates biomass and interacts with kiln walls, revealing that larger air inlet perforations may result in greater deviations between simulation and experiment. Unlike earlier work that focused primarily on temperature measurements, CFD simulations in this study offer insights into airflow dynamics and optimal perforation configurations. By integrating varying perforation sizes with validated airflow models, this research enhances understanding of how air distribution affects combustion uniformity, heat retention, and thermal exchange. The ability to simulate and confirm radial and vertical temperature gradients affirms the model's effectiveness in balancing gas flow and heat distribution—key factors for complete and efficient combustion [18–19]. Ultimately, the findings support the development of more efficient, sustainable, and cost-effective combustion chambers for real-world charcoal production applications [26].

*3.3 The products in charcoal production, cost, and environmental evaluation of the charcoal kiln*

The primary outputs of the biomass carbonization process using a charcoal production kiln are solid charcoal and syngas (pyrolysis gas), both of which are generated through the thermal decomposition of biomass under limited oxygen conditions. This process commonly referred to as pyrolysis or carbonization is governed by several critical factors, including temperature distribution, airflow rate, and the structural design of the kiln. In particular, the size and configuration of air perforations in the combustion chamber play a pivotal role in regulating airflow dynamics, which in turn influence heat transfer efficiency, combustion completeness, and overall carbonization performance. These design parameters directly affect the quality of the resulting charcoal, the yield of byproducts, and the energy efficiency of the system. To enhance understanding and inform the optimization of kiln operation, the following section presents a comparative analysis of charcoal yield obtained from experimental trials conducted with varying air perforation sizes. The highest charcoal yield of 41.53 wt.% was observed after 1 hour of pyrolysis using a 1.59 mm perforation size (ASB1), while yields decreased with longer durations, accompanied by increasing ash formation, as shown in Figure 5. After three hours of pyrolysis utilizing a perforation size of 1.59 mm, the ash content was measured at 2.23 wt.%, while the yields of pyrolysis gas ranged from 58.47 wt.%, 61.33 wt.%, to 66.97 wt.%. In the scenario employing a perforation size of 3.18 mm, the ash content observed during the 2 to 3 hours of pyrolysis varied from 1.37 wt.% to 2.77 wt.%, with the pyrolysis gas content reported at 62.60 wt.%, 62.70 wt.%, and 67.43 wt.%, respectively. For the perforation sizes of 4.76 mm, charcoal yields over the intervals of 1, 2, and 3 hours were noted at 32.90 wt.%, 29.60 wt.%, and 19.87 wt.%, respectively. The corresponding ash content for this perforation size ranged from 1.43 wt.% to 6.83 wt.%, while the pyrolysis gas yields increased over the same period, measuring 65.67 wt.%, 67.57 wt.%, and 73.30 wt.%, respectively, as shown in Fig. 5. These findings highlight the optimization of carbonization processes, addressing challenges related to incomplete carbonization, managing ash content, and enhancing production conditions. Such improvements not only ensure that the produced charcoal conforms to requisite quality standards but also minimize waste and bolster overall production efficiency (IBI Biochar Standards, 2024) [6]. The analysis of energy efficiency across different experimental conditions ASB1 to ASB3 (air perforation size 1.59 mm, processing durations of 1, 2, and 3 hours), ASB4 to ASB6 (3.18 mm), and ASB7 to ASB9 (4.76 mm) revealed notable variations in performance shown in Figure 6. The recorded energy efficiency ranged from 6.68% to 32.78%, indicating a wide spectrum of outcomes influenced by both perforation size and processing duration. ASB1 achieved the highest energy efficiency at 32.78%, while ASB9 recorded the lowest at 6.68%.

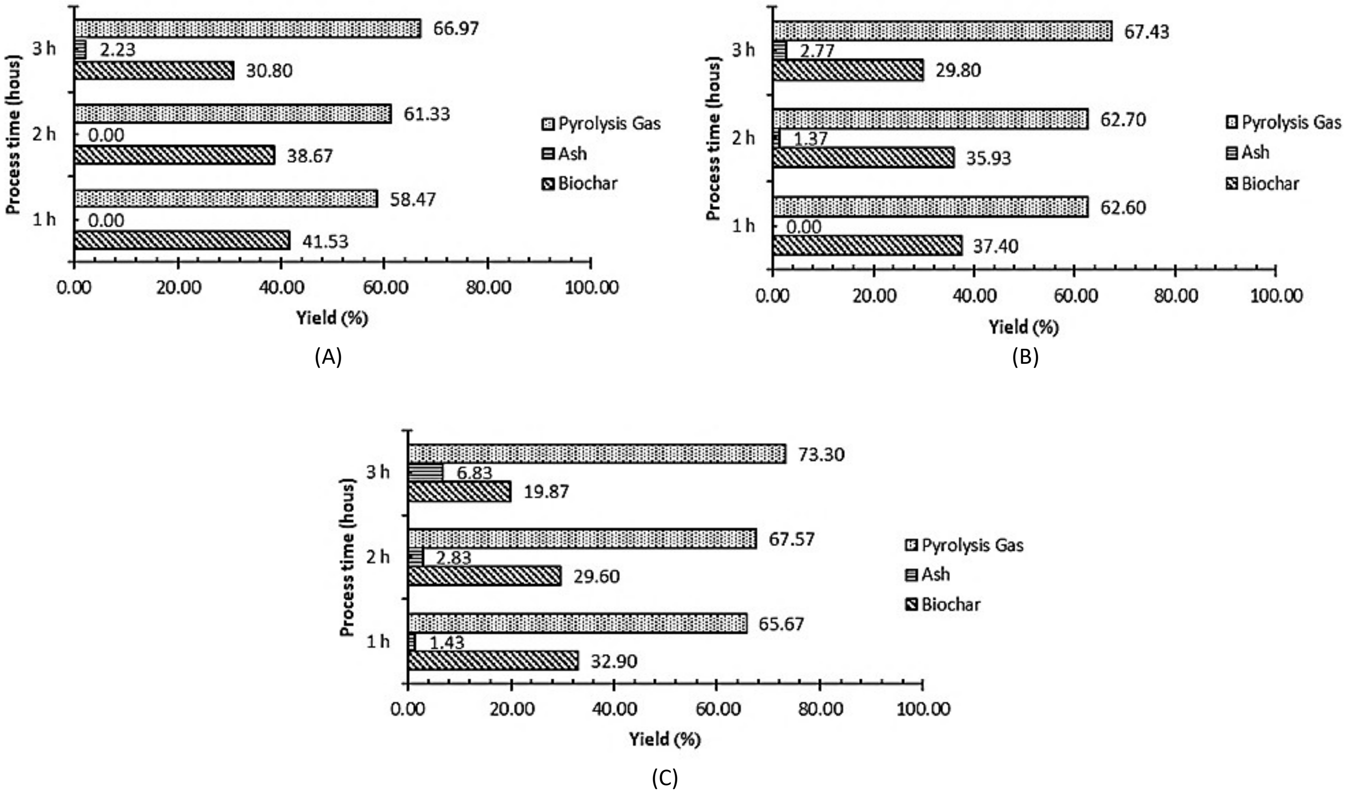


Fig. 5 The charcoal yield from charcoal kiln using areca spathe with different perforation sizes of 1.59 mm (A), 3.18 mm (B), and 4.76 mm (C).

The data demonstrate that energy efficiency generally decreased with increasing processing duration, likely due to cumulative heat losses over time. A comparative analysis of trials conducted with equal durations (1 hour) further underscores the influence of perforation size. ASB1 (1.59 mm) outperformed ASB4 (3.18 mm) and ASB7 (4.76 mm), with energy efficiencies of 32.78%, 28.88%, and 25.69%, respectively. These findings suggest that smaller air perforations, coupled with shorter carbonization durations, enhance energy retention and reduce thermal losses. This observation is consistent with diffusion rate control theory and principles of heat and mass transfer within pyrolysis systems [3],[29]. Nevertheless, while smaller perforation sizes appear advantageous in terms of energy efficiency, their impact on system ventilation warrants further investigation. Excessively small perforations may impede the release of vapor and pyrolytic gases, potentially leading to internal pressure buildup, delayed heat transfer, inefficient moisture removal, or inconsistent carbonization factors that can compromise product quality and operational safety. These concerns align with prior CFD simulation results. Consequently, the selection of air perforation size should be tailored to the specific biomass characteristics, and operational parameters should be optimized to ensure a balance between energy efficiency, gas release, and process safety.

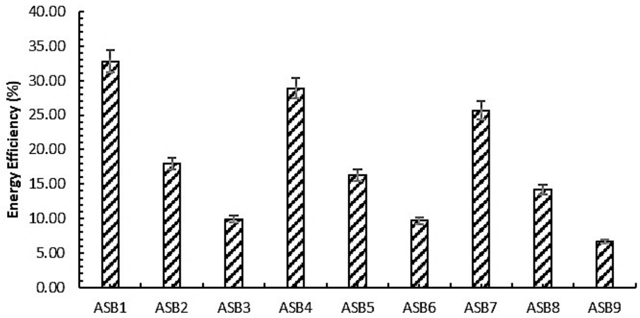


Fig. 6 The results of energy efficiency for each condition.

Table 2. The experimental evaluation of charcoal production from areca spathe (ASB) using three combustion chamber perforation sizes (1.59 mm, 3.18 mm, and 4.76 mm) across pyrolysis durations of 1 to 3 hours revealed distinct trends in yield and thermal degradation behavior. The highest charcoal yield was achieved with a 1.59 mm perforation at a 1-hour duration (ASB1), producing 41.53 wt.% charcoal and 58.47 wt.% pyrolysis gas. As pyrolysis duration increased, charcoal yield declined across all perforation sizes, while ash and gas production rose, reflecting the intensified decomposition of biomass. After 3 hours, the yields for ASB3 (1.59 mm), ASB6 (3.18 mm), and ASB9 (4.76 mm) were 30.80%, 29.80%, and 19.87%, respectively, with corresponding ash contents of 2.23%, 2.77%, and 6.83%. ASB9 also exhibited the highest gas yield at 73.30 wt.%, indicating more extensive thermal degradation and reduced solid residue. When compared with other biomass types, areca spathe demonstrated superior carbonization performance, particularly within shorter durations. For example, corncob subjected to a 3.18 mm perforation yielded only 3.03 wt.% charcoal at 1 hour, increasing to 34.50 wt.% at 3 hours [3], still lower than the yield from areca spathe under similar or shorter conditions. Rice husks showed an increasing trend, yielding 11.50% at 1 hour and 45.60% at 3 hours, although pyrolysis gas content remained high at 45.80%. Similarly, longan peel produced 10.60% charcoal at 1 hour and 31.50% at 3 hours, with gas yields peaking at 68.50%. Coffee peel and longan branch yielded 1.60% and 5.40% charcoal at 1 hour, increasing to 30.60% and 27.60% at 3 hours, respectively, but both showed substantial non-charcoal residue early in the process, indicating slower carbonization kinetics. Additional studies [13], [18] reported that rice husk and corncob carbonized with 6.35 mm perforations yielded 24.30% and approximately 17.10% charcoal, respectively, after 3 hours. Even with extended durations of 5–9 hours, corncob yields only reached approximately 24.3% at 7 hours. These findings emphasize the efficiency of areca spathe in shorter pyrolysis times. As shown in Table 2, the modified kiln, incorporating perforations of 1.59 mm, 3.18 mm, and 4.76 mm, significantly improved charcoal yield from areca spathe, particularly within the initial 1–2 hours of pyrolysis.

Table 2 The total solid yields and produced gas for each biomass type.

| Sample | Durations (hour) | Charcoal (wt.%) | Ash (wt.%) | Non-charcoal (wt.%) | Pyrolysis Gas (wt.%) | Reference |
|---|---|---|---|---|---|---|
| ASB1 (1.59 mm) | 1 | 41.53 | - | - | 58.47 | This study |
| ASB2 (1.59 mm) | 2 | 38.67 | - | - | 61.33 | |
| ASB3 (1.59 mm) | 3 | 30.80 | 2.23 | - | 66.97 | |
| ASB4 (3.18 mm) | 1 | 37.40 | - | - | 62.60 | |
| ASB5 (3.18 mm) | 2 | 35.93 | 1.37 | - | 62.70 | |
| ASB6 (3.18 mm) | 3 | 29.80 | 2.77 | - | 67.43 | |
| ASB7 (4.76 mm) | 1 | 32.90 | 1.43 | - | 65.67 | |
| ASB8 (4.76 mm) | 2 | 29.60 | 2.83 | - | 67.57 | |
| ASB9 (4.76 mm) | 3 | 19.87 | 6.83 | - | 73.30 | |
| Corncob (3.18 mm) | 1 | 3.03 | - | 93.27 | 3.70 | |
| | 2 | 17.80 | - | 64.30 | 17.90 | |
| | 3 | 34.50 | - | 8.40 | 57.10 | |
| Rice husk (3.18 mm) | 1 | 11.50 | - | 77.00 | 11.50 | |
| | 2 | 16.37 | - | 68.60 | 15.03 | |
| | 3 | 45.60 | - | 8.60 | 45.80 | |
| Longan peel (3.18 mm) | 1 | 10.60 | - | 51.50 | 37.90 | |
| | 2 | 16.40 | - | 45.80 | 37.80 | |
| | 3 | 31.50 | - | - | 68.50 | |
| Coffee peel (3.18 mm) | 1 | 1.60 | - | 79.80 | 18.60 | [3] |
| | 2 | 4.60 | - | 67.60 | 27.80 | |
| | 3 | 30.60 | - | 19.40 | 50.00 | |
| Longan branch (3.18 mm) | 1 | 5.40 | - | 91.10 | 3.50 | |
| | 2 | 8.60 | - | 62.80 | 28.60 | |
| | 3 | 27.60 | - | 33.80 | 38.60 | |
| Rice husk (6.35 mm) | 3 | 24.30 | - | 32.84 | 42.86 | [13] |
| Corncob (6.35 mm) | 3 | ≈ 17.10 | n.d. | n.d. | n.d. | |
| | 5 | ≈ 20.0 | n.d. | n.d. | n.d. | |
| | 7 | ≈ 24.3 | n.d. | n.d. | n.d. | [18] |
| | 9 | ≈ 16.0 | n.d. | n.d. | n.d. | |

*Sample ASB is Charcoal from areca spathe and n.d. = not determined

The highest yields were consistently obtained using the smallest perforation size (1.59 mm), while larger perforations and prolonged pyrolysis resulted in decreased charcoal output and increased ash formation, indicating over-carbonization. Compared to conventional biomasses, which typically require longer durations to achieve acceptable yields, the modified kiln achieved superior performance in less time. This improvement can be attributed to enhanced heat distribution and more controlled thermal degradation, underscoring the critical role of combustion chamber design and perforation optimization. The modified kiln improved charcoal productivity by up to 10–15 times during the first hour of operation. Smaller perforation diameters enabled more stable carbonization conditions and uniform heat transfer. Conversely, larger perforations and extended heating such as in ASB9 led to increased ash formation and reduced charcoal yield, reflecting excessive carbon loss. Pyrolysis gas output also rose with larger perforations and longer durations, signifying energy loss as volatile gases. Although certain biomasses like rice husk and longan peel achieved moderate yields after 3 hours, the modified kiln demonstrated equivalent or superior results from areca spathe within just 1–2 hours. These findings highlight the advantages of integrating a perforated combustion chamber, particularly when tailored to specific biomass characteristics. The combustion system, composed of twelve closed-end steel pipes (2.54 cm diameter, 10 cm length) featuring three perforation sizes, facilitated efficient heat circulation and maintained operational temperatures between 379.30°C and 619.80°C. This optimized design contributed to improved charcoal yields and enhanced syngas production, ultimately increasing the overall efficiency and scalability of the charcoal production process [31].

According to pyrolysis theory, the optimal temperature range for biochar production lies between 350–600 °C. In slow pyrolysis, both the rate of temperature increase, and the peak temperature significantly influence the physical and chemical characteristics of the resulting biochar such as porosity, fixed carbon content, and gas yield. Additionally, the residence time, or the duration biomass is maintained at a given temperature, plays a pivotal role in determining biochar yield and its quality under varying operational conditions [6]. Structural configuration of the pyrolysis system also contributes to the versatility and functional quality of the charcoal produced. As demonstrated in previous studies [13], such configurations can enhance the effectiveness of charcoal in agricultural applications, particularly in improving soil fertility by increasing moisture retention and nutrient availability. The highly porous nature of biochar further enables its application in environmental remediation, where it serves as an effective medium for adsorbing toxins and odors [9]. Efficient heat distribution within the kiln is essential for improving the yield and consistency of charcoal production. This aligns with findings in [28], which emphasize structural optimization and simulation-based design of combustion chambers to achieve optimal thermal profiles.

Gas emissions from the developed kiln were measured at the exhaust stack using a TESTO 350 gas analyzer. The observed concentrations were as follows: carbon monoxide (CO) up to 3377 ppm, nitrogen oxides (NOx) up to 76.8 ppm (including NO and $NO_2$), sulfur dioxide ($SO_2$) up to 147 ppm, and carbon dioxide ($CO_2$) up to 20.07%. These values varied depending on combustion stages and airflow conditions controlled by the perforation size and duration. The measurements were conducted continuously for up to 3 hours, which was the maximum testing duration in this study, representing the most extended and complete combustion cycle. The results indicate active combustion and gas generation processes typical of small-scale biomass pyrolysis systems. The emission levels recorded during the kiln's operation fall within the typical range for biomass combustion stack emissions and are consistent with values previously reported for small-scale kilns lacking in gas treatment systems [3]. Although the measured emissions exceed ambient air quality standards such as those issued by the World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA) [35-36] they remain within expected limits for stack emissions and do not surpass general emission thresholds for this type of technology as outlined in EPA stack emission guidelines. The kiln's design, which includes adjustable air perforation sizes, contributes to improved combustion completeness.

This is reflected in the moderate peak levels of carbon dioxide ($CO_2$) and nitrogen oxides ($NO_x$) observed during continuous monitoring. These gases are naturally present in the combustion of wood or biomass-based fuels due to their inherent composition. Moreover, the biochar produced shows promising potential for carbon sequestration, which could partially offset greenhouse gas emissions when applied to soil. It is recommended that further improvements be made to the kiln's insulation and combustion control, along with the incorporation of cost-effective emission mitigation strategies, such as afterburners or filtration systems, to reduce greenhouse gas outputs. Future research will include continuous monitoring to evaluate real-time emission behaviors.

The environmentally friendly design of the kiln, combined with its ability to utilize agricultural waste materials, not only aligns with global sustainability goals but also presents noteworthy commercial potential. The system's low operating cost results in a charcoal production cost ranging from approximately 5.0 to 9.0 THB/kg, while the high-quality charcoal produced can be sold at prices of around 30 to 50 THB/kg. Its reliance on locally sourced materials further enhances its feasibility for use in rural areas. When compared to traditional charcoal production methods, such as open-pit or earth mound kilns which generally exhibit lower efficiency and higher emissions, the developed kilns demonstrate improved combustion control, higher charcoal yield, and reduced environmental impact. Furthermore, its modular and portable design supports decentralized applications, enabling local entrepreneurs to engage in biomass-to-energy ventures. These features collectively suggest that the system can serve as an effective tool for rural economic development while promoting cleaner production practices

Similarly, the application of computational fluid dynamics (CFD) in stove development has demonstrated improvements in combustion efficiency and reductions in smoke emissions [30]. Such design enhancements share a unified objective of optimizing system performance while minimizing environmental impact. Moreover, biochar serves as a precursor for producing activated carbon, thereby expanding its utility across agricultural and environmental domains. As indicated in [31], biochar can be refined into activated carbon composites [32], which exhibit enhanced purity and functionality. The combustion chamber system employed in this study, constructed from closed-end steel pipes connected to a central axis, offers several operational advantages. The robust, heat-resistant design not only supports system durability but also allows for easy disassembly and maintenance. This facilitates regular inspection and removal of soot or tar residues, a critical feature when processing biomass feedstocks with high oil or resin content, which may otherwise lead to perforation clogging and system inefficiencies.

Importantly, the system's airtight configuration ensures effective control of the anaerobic pyrolysis environment, thereby influencing the consistency and quality of the final product—particularly when targeting high-grade charcoal or activated carbon with elevated fixed carbon levels. The kiln's modular and flexible design also enables parameter manipulation for research purposes, including variation in biomass types, airflow control, and integration with supplementary systems. Such versatility supports not only experimental investigations but also the system's scalability, making it suitable for deployment in community settings [11], small-scale industries, or larger industrial applications [10], [17]. Although the developed charcoal kiln has demonstrated satisfactory performance on the laboratory scale, several challenges remain to be addressed to achieve successful scale-up for community or industrial applications. One major challenge is ensuring a consistent and sufficient supply of suitable biomass feedstock, which may vary seasonally or regionally. Operational consistency also requires effective control of combustion parameters, such as airflow and temperature, to maintain product quality and minimize emissions. Maintenance is particularly critical when processing biomass with high resin or oil content, which can lead to tar accumulation and clogging of perforations, as well as oxidation-induced rusting. Therefore, regular cleaning and inspection protocols must be established to ensure long-term operational efficiency and prevent system degradation. In terms of economic impact, this kiln holds significant potential to enhance local livelihoods by converting agricultural residues, often regarded as waste, into high-value charcoal products. This can provide additional income streams for smallholder farmers and rural communities, reduce reliance on fossil fuels, and promote sustainable resource utilization. Moreover, the use of locally available, low-cost materials for kiln construction supports affordability and accessibility, especially in remote or resource-limited areas. These socioeconomic benefits align with broader goals of rural development and circular bioeconomy initiatives. Future research should focus on pilot-scale implementation to evaluate practical challenges of scaling up, including logistics, user training, and emission control strategies, alongside continuous monitoring of environmental impacts. The use of locally available, low-cost materials enhances the economic feasibility of the system, particularly in rural or remote areas where smallholder farmers can benefit from converting agricultural waste into value-added products. This development pathway is consistent with the evolution of low-emission biochar systems such as the Kon-Tiki stove [4], which features low greenhouse gas emissions [16] and cost-effective construction and operation [7], [14]. In addition to producing high-quality charcoal, the kiln described here demonstrates reduced fuel consumption, akin to the Model III stove [8].

Overall, this research supports the development of a circular bioeconomy, aligning with sustainability goals such as energy self-reliance [1] and long-term environmental stability [2]. The system's portability and adaptability render it well-suited for use in diverse settings including forests, rural communities, households, and agricultural fields. Its functionality parallels that of the flame cap kiln [14], offering a robust and field-deployable solution for decentralized biochar production. As such, this work underscores both the environmental benefits and the practical potential of portable pyrolysis systems, particularly for efficient biomass utilization in off-grid and resource-constrained environments [15].

## 4. Conclusion

This study investigates the design and operational performance of charcoal kilns operating within a temperature range of 370–620°C for durations between 1 and 3 hours, with a focus on optimizing air perforation sizes. The objective of this optimization is to improve thermal efficiency, enhance charcoal quality, reduce production time, minimize fuel consumption, and decrease energy wastage. The findings indicate that a 50-liter kiln, when used to produce charcoal from Areca spathe, based on the yield and energy efficiency, air perforation 1.59 mm, 1 hour was identified as the optimal condition for charcoal production. However, quality analysis of the products is required for a comprehensive evaluation.

This study provides initial findings toward producing high-purity charcoal with desirable properties such as elevated porosity and minimal volatile matter; nevertheless, further research is required to establish optimal operating parameters for commercial-scale production. Temperature and airflow simulations conducted during the study exhibited low deviations and high accuracy, with recorded temperatures of 552.11°C, 516.10°C, and 463.61°C, accompanied by error margins of ±0.65%, ±0.43%, and ±0.56%, respectively. Standard deviations for these temperatures were found to be 2.54°C, 1.56°C, and 1.83°C across the three tested air perforation sizes.

The results underscore the significant influence of production time on charcoal yield, presenting opportunities for further optimization that could be applicable across various biomass types. This study contributes to the advancement of sustainable charcoal production practices, with potential benefits for local enterprises, job creation, cost reduction, and energy efficiency. Additionally, it lays the groundwork for future commercial development in the charcoal industry. The results indicate promising performance of the kiln; however, continuous refinement and validation under varied conditions are necessary to ensure consistent production of high-quality charcoal.

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