RST RECENT SCIENCE AND TECHNOLOGY

Recent Science and Technology

Journal homepage: https:// www.tci-thaijo.org/index.php/rmutsvrj/index

ISSN: 3057-0786 (Online)

Research Article

Simulation of Temperature Distribution and Biochar Properties in a 50-Liter Kiln Using Corncob Feedstock

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Article history:

Received: 2024-07-17

Revised: 2025-01-24

Accepted: 2025-02-17

Keywords:

biochar;

slow pyrolysis;

simulation;

thermal characteristics

A B S T R A C T

Biochar has been widely recognized as a beneficial soil amendment, enhancing soil physical and chemical properties. The yield of biochar production, however, is influenced by various processes and kiln parameters. Thus, the objectives of this study are to investigate the thermal characteristics inside a 50-liter biochar kiln and the effect of core puncture row numbers on temperature distribution and biochar yield. In this study, a 50-liter biochar kiln with dimensions of 500 mm × 380 mm (height × diameter) was developed for the study. The kiln design included a central core with a diameter of 115 mm and puncture holes of 6.35 mm in diameter. Experiments were conducted using cores with three different puncture row configurations: 3, 4, and 5 rows. Corncobs served as the raw material, while briquettes derived from agricultural waste were used as fuel. The temperature distribution for each configuration was analyzed through both experimental and numerical methods. Simulation results were validated against experimental data. The simulation results illustrated that the highest temperature was found at the core and decreased transversely in radial direction toward the kiln wall. The average temperature over the radial and longitudinal positions inside the kiln with 3, 4, and 5-row configurations was found to be equal to 392.4 ± 174.2 °C, 357.4 ± 210.4 °C, and 358.6 ± 221.7 °C, respectively. The experiment revealed that the biochar yield was found to be equal to 12.9 wt.%, 11.4 wt.%, and 15.7 wt.% for the 3, 4, and 5-row configurations, respectively. The average pH and electrical conductivity (EC) of the biochar were 8.7 ± 0.3 and 0.6 ± 0.1 dS m^{-1}, respectively. This study provides a detailed understanding of the thermal characteristics within a biochar kiln and their effects on biochar yield. The graphical temperature distribution results offer valuable insights for optimizing kiln design and improving biochar production efficiency.

1. Introduction

Biochar is a material composed of carbon produced from biomass through the heating separation process without oxygen or with minimal oxygen (Pyrolysis) (Suksawang, 2009). Biochar can be utilized for keeping carbon in the soil in order to improve the soil physical properties due to its natural pores that help

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Cite this article as:

Panyoyai, N., Wongsiriamnuay, T., Intagun, W., Klinbun, J. and Khamdaeng, T. 2025. Simulation of Temperature Distribution and Biochar Properties in a 50-Liter Kiln Using Corncob Feedstock. **Recent Science and Technology** 17(2): 264055.

improve the air circulation, water percolation, water absorption, plant nutrient accumulation and microorganism activities. Biochar can absorb heavy metals in the soil (Rinkam *et al.*, 2022) and the alkalinity of biochar is beneficial for acidic sandy soil, helping to neutralize the soil acidity, increase the soil pH and improve the nitrification (Shaaban *et al.*, 2013). As a result, biochar reduces fertilizer use and increases yield production, providing higher income for farmers (Chen *et al.*, 2022). In addition, biochar has properties that make it suitable for use as an energy source since it produces more heat than general wood charcoal and can be produced using simple technology with low energy input. Moreover, the production of biochar can be applied at both the family and community levels (Kaewluan *et al.*, 2021). Several studies have investigated biochar production, and production conditions, such as pyrolysis temperature, can affect not only the yield of biochar but also inside the quality (Petchaihan *et al.*, 2019; Somparn *et al.*, 2019).

At present, numerical methods play a significant role in engineering design, as they can be used to design and predict results without trial and error. This leads to reductions in both capital and time, making it easier to produce suitable workpieces for engineering and economics. The forecasting of heat distribution on the heat circulating fin attached to the heat electrical appliance was studied and the results help designers efficiently evaluate and appreciate the shape and number of fins to be used (Techaumpai *et al.*, 2009). The heat distribution in a small water heater was simulated in order to help design an appropriate heating system based on low energy consumption (Missaoui *et al.*, 2021). The temperature changes within a 200-liter vertical charcoal kiln using the gasification technique with wood as the raw material were studied and the results showed that this system could reduce the production period and increase heat energy, resulting in higher quality charcoal compared to normal burning (Maneechote and Seni, 2015). The simulation of heat transfer and distribution in the pyrolysis furnace under various conditions has been investigated to enhance product yields and quality (Intagun *et al.*, 2018; Panyoyai *et al.*, 2019; Srisophon *et al.*, 2019).

An understanding of the temperature distribution within a biochar kiln is important for optimizing the biochar process and production, which is influenced by core puncture row numbers. The core puncture row number is essential for enhancing heat distribution and gas management, as it enable uniform heating and efficient ventilation, leading to improved operational efficiency and consistent product quality. Validating the numerical simulation results with experimental data will increase the reliability of predictive models, allowing for better control over the production process. Additionally, exploring the relationship between temperature distribution and biochar yield and properties (such as pH and electrical conductivity) can provide valuable insights into producing high-quality biochar with desirable chemical and physical characteristics.

Therefore, the main objective of this study was to investigate the temperature distribution inside the biochar kiln under different core puncture row numbers. The experimental results were compared with the numerical simulation results to validate the model. The temperature distribution then was evaluated in this study. The biochar yields and properties were also investigated.

2. Materials and Methods

2.1 Biochar Kiln Design

Figure 1 illustrates the 50-liter biochar kiln used in the experiment with a 380 mm diameter and a 500 mm height. The kiln is made of steel and has a closing lid with a 115 mm central hole.

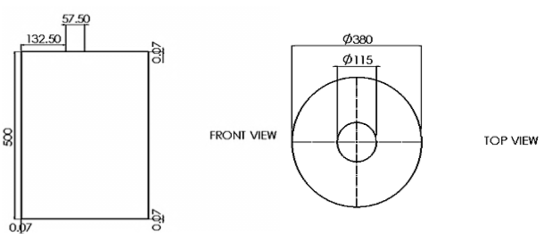
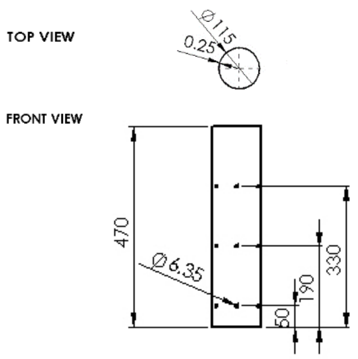


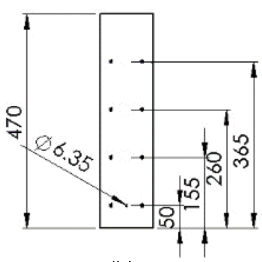
Figure 1 Biochar kiln (dimensions displayed in millimeters)

2.2 Core Configuration of Biochar Kiln

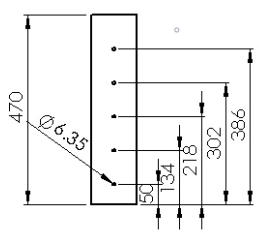
Figure 2 illustrates the core of cylindrical biochar kiln, which has a 115 mm diameter and 6.35 mm core hole diameter. The core was designed with 3, 4 and 5 rows of 6.35 mm holes. For the core with 3 rows, there were 6 holes per row, with the first, second and third rows positioned 50, 190 and 330 mm, respectively, above the floor as shown in Figure 2(a). For the core with 4 rows, there were 5 holes per row, with the first, second, third and fourth rows positioned 50, 155, 260 and 365 mm, respectively, above the floor as shown in Figure 2(b). For the core with 5 rows, there were 4 holes per row which the first, second, third, fourth and fifth rows were 50, 134, 218, 302 and 386 mm, respectively, above the floor as shown in Figure 2(c).



(a)



(b)



(c)

Figure 2 Core of cylindrical biochar kiln with (a) 3 (b) 4 and (c) 5 rows of 6.35 mm holes (dimensions displayed in millimeters)

2.3 Biochar Production Process

Seven kilograms of raw material, corncob with a length of 10-20 mm, were thermo-chemically decomposed in the biochar kiln after being dried to minimize humidity. Three kilograms of heat fuel briquette were placed into the upper core for 0-15 minutes and the biochar pyrolysis process was conducted for 3 hours. The outputs of the process, including completed biochar, non-completed biochar and ash, were weighed using a digital scale with an accuracy of ±0.1 g.

2.4 Temperature Measurement

The temperature was measured at seven different points by use of the thermocouple as shown in Figure 3. The thermocouple probes with temperature range of 0 to 1,000°C were placed inside the kiln at radial positions 49 mm, 129 mm, and 187 mm from the kiln center and at longitudinal directions 108 mm, 244 mm, and 366 mm from the bottom of the kiln. Real-time temperatures were acquired and stored using a data logger (Wisco Online Datalogger OD04). The temperature was continuously recorded within 3 hours during the pyrolysis process and the temperature that reached steady state was selected for comparison with the simulated temperature.

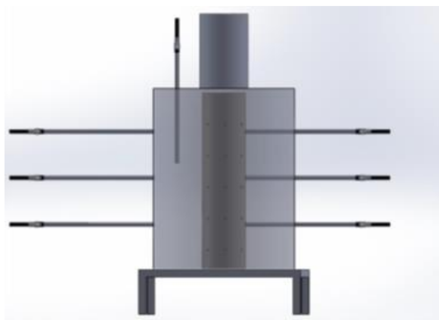


Figure 3 Thermocouple position

2.5 Simulation Methodology

The biochar kiln model has three main domains: the kiln wall, the core wall, and the pyrolysis gas fluid within the kiln. The kiln's core is used for fuel loading, with heat from combustion transferring radially outward to the kiln wall. To simplify the model, the following assumptions were made:

1. Heat transfer was considered under steady-state conditions.
2. Heat transfer from the inner core surface to the outer core surface occurred through conduction.
3. Heat transfer from the outer core surface to the pyrolysis chamber occurred through conduction and convection.
4. Heat transfer from the outer kiln wall to the surroundings occurred via natural convection.

The temperature results obtained from the biochar kiln simulation, based on the numerical scheme illustrated in Figure 4, were compared with experimental results from the pyrolysis process. The test conditions focused on varying the numbers of rows of holes on the core, which significantly influenced biochar productivity. The simulation was conducted using a model developed in Abaqus, which set the pyrolysis temperature at the kiln rim to analyze air circulation and temperature distribution under stable heat conditions. The governing equations for the simulations included the Navier-Stokes equations for fluid dynamics and the energy equation for temperature distribution. These equations were solved using the finite element method to simulate heat transfer and airflow within the kiln. The simulated temperatures were then compared with those recorded experimentally during the pyrolysis process in the biochar kiln. To ensure the accuracy and reliability of the simulation results, the experimental temperature data were compared with the simulated temperature profiles for each core configuration. The temperature measurements were taken at multiple radial and longitudinal positions within the kiln and averaged for comparison. Error percentages were calculated to quantify the deviation between experimental and simulated values.

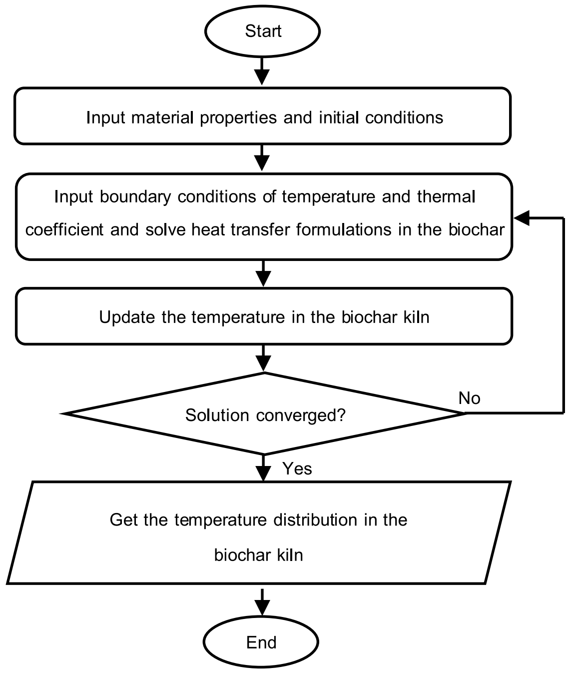


Figure 4 The diagram of numerical scheme

2.6 Yields and Properties Determination

The percentage of the biochar yield was calculated as follow:

$$\%Biochar\ Yield = \frac{W_{biochar}}{W_{biomass}} \times 100 \tag{1}$$

where $W_{biochar}$ is the weight of completed biochar after the pyrolysis and $W_{biomass}$ is the weight of raw material before the pyrolysis.

The gas produced by pyrolysis was inferred from the loss of total weight after the process, i.e.

$$\%Gas = \frac{W_{biomass} - W_{solid\,yields}}{W_{biomass}} \times 100 \tag{2}$$

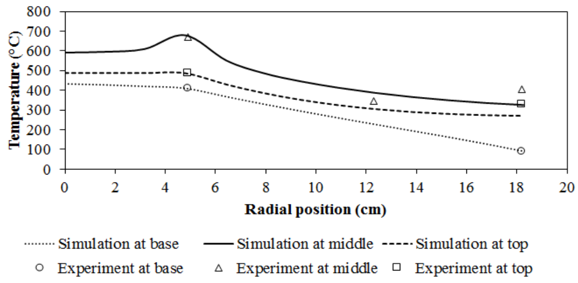
where $W_{solid\ yields}$ is the weight of total solid yields obtained after the pyrolysis, i.e., completed biochar, non-completed biochar and ash.

The pH of the biochar was measured according to the DIN ISO 10390 standard using a 1:5 (W:V) ratio of biochar to 0.01 M $CaCl_2$-solution, with 60 minutes of shaking, and the measurement was taken directly in the suspension. The EC was measured according to the DIN ISO 11265, by adding a 1:10 (W:V) ratio of H_2O to the sample, shaking for 60 min, followed by filtration of the solution.

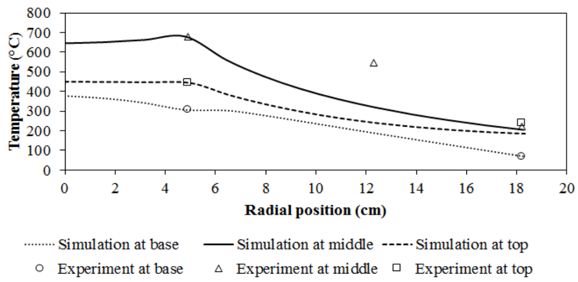
3. Results and Discussion

3.1 The experimental results compared with the simulating by the computer program

The temperatures obtained from the pyrolysis in the biochar kiln and from the computer program simulation based on 3, 4 and 5 rows of 6.35 mm holes were compared (Figure 5). The results from the condition simulation provided some values that could not be measured in the experiment, as they were based on certain assumptions, such as radiation value, heat convection etc. These unmeasured values contributed to errors between the temperature results from the experiment and simulation. The error percentages found for the core with 3, 4 and 5 rows of 6.35 mm holes were 8.2 ± 10.8, 10.8 ± 15.2 and 10.8 ± 16.8, respectively.



(a)



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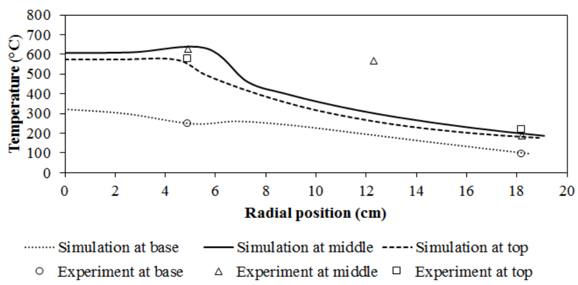


(c)

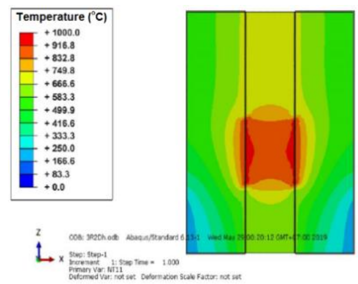
Figure 5 Comparison of temperatures from experiment and computer program simulation of (a) 3 (b) 4 and (c) 5 rows with 6.35 mm holes

For future work, the study should focus on investigating the temperature distribution affected by the placement of drilled holes and refining simulation models to enhance the validation of experimental and simulation results.

3.2 Vertical temperature distribution in the biochar kiln

The temperatures in the biochar kiln were distributed from the air holes at its core. The highest temperature was found at the core. The biomass around the core could therefore heat up quickly throughout the biochar kiln. The vertical temperature distributions in the biochar kiln with 3, 4 and 5 rows of 6.35 mm holes at the core are shown in Figure 6(a)-(c), respectively. The average temperatures over the radial and longitudinal positions in the biochar kiln with 3, 4 and 5 rows of 6.35 mm holes at the core were found to be equal to 392.4 ± 174.2 °C, 357.4 ± 210.4 °C, and 358.6 ± 221.7 °C, respectively.

(a)



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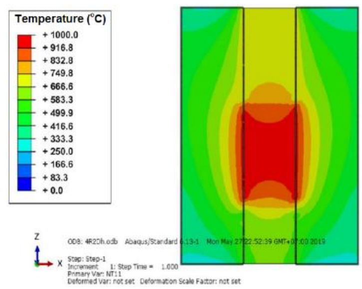

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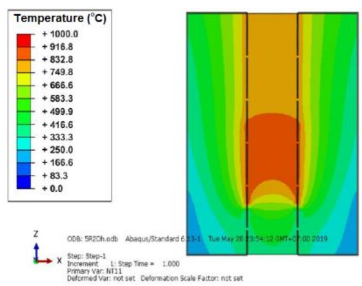

Figure 6 Vertical temperature distribution in the biochar kiln with (a) 3 (b) 4 and (c) 5 rows of 6.35 mm holes at the core

Table 1 Products and properties (pH and EC) obtained from each experiment

Number of rows	3	4	5
Non-Biochar (kg.)	3.6	3.47	3.3
Biochar (kg.)	0.9	0.8	1.1
Ashes (kg.)	0.09	0.07	0.14
Gas (wt.%)	34.4	38.0	35.1
Biochar (wt.%)	12.9	11.4	15.7
pH	8.45	8.98	8.67
EC (dS m^{-1})	0.57	0.50	0.74

As the number of rows of holes increases (from 3 to 4 or 5 rows), the gas flow in the kiln also increases. This enhances the distribution of heat across the kiln, which can reduce the temperature difference within the kiln. For example, with 4 and 5 rows of holes, the average temperature (357.4°C and 358.6°C, respectively) is lower than with 3 rows (392.4°C), as the increased gas flow helps distribute heat more efficiently. However, the overall temperature at the core remains the highest and decreases radially toward the kiln wall.

3.3 Yields and properties obtained from the experiment of biochar kiln

Table 1 summarizes the yields obtained from the experiment of biochar kiln with 3, 4, and 5 rows of 6.35 mm holes at the core. It was found that the biochar kiln with 5 rows of 6.35 mm holes at the core showed the highest yield of biochar equal to 15.7 wt.% while the core with 3 rows of 6.35 mm holes showed the highest yield of non-biochar around 51.4 wt.%. In addition, the biochar kiln with 4 rows of 6.35 mm holes at the core showed the highest yield of gas around 38.0 wt.%. The yield of gas was found to vary inversely with the yield of biochar which was in agreement with the findings of earlier studies (Sun *et al.*, 2014).

From pyrolysis temperature in this study, it was found that the biochar was alkaline, with a pH range of 8.45 to 8.98, which can adversely affect microorganisms in the soil. The pH of biochar derived from corncob was approximately 8-10 which was suitable for medium to strong acid soils (Somparn *et al.*, 2019). The electrical conductivity (EC) of biochar ranged from 0.50 to 0.74 which was suitable for improving soil with strong alkalinity (Enders *et al.*, 2012).

4. Conclusion

The study evaluated the performance of a biochar kiln with cores having 3, 4, and 5 rows of 6.35 mm holes, utilizing corncob biomass as feedstock. The results demonstrated that the kiln configuration with 5 rows of 6.35 mm holes achieved the highest biochar yield, producing 15.7 wt.% of biochar. Conversely, the 3-row configuration yielded 12.9 wt.% of biochar. This shows that the core with 5 rows of 6.35 mm holes gives the highest yield of biochar and can be attributed to the increased gas flow and more efficient heat distribution inside the kiln. The average temperature in the biochar kiln with 5 rows of 6.35 mm holes at the core was found to be 358.6 ± 221.7 °C. As the number of rows of holes increased (from 3 to 4 or 5), the average temperature decreased, indicating that the increased gas flow helped distribute heat more uniformly throughout the kiln, resulting in a slightly lower average temperature. The temperature measurements and simulations revealed that the core with 3 rows of 6.35 mm holes provided the closest agreement between experimental and simulated temperatures, with the lowest error percentage of 8.2%. The core configurations with 4 and 5 rows had higher error percentages, both at 10.8%. These findings highlight that while the 5-row configuration maximizes biochar yield, the 3-row configuration offers the best alignment with simulated temperature data, suggesting a trade-off between yield and temperature accuracy.

5. Acknowledgments

This study was supported by the Thailand Research Fund (Contract no. RDG6250016) and the Faculty of Engineering and Agro-Industry, Maejo University, Chiang Mai, Thailand.

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