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Development of Commercial Charcoal Kilns Using Thermal Control Techniques for High-Quality Charcoal Production

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ABSTRACT

Charcoal production at the community scale is frequently characterized by low thermal efficiency and heterogeneous product quality, primarily attributable to rudimentary kiln designs. This study evaluates the performance of a modified 200-liter charcoal kiln specifically engineered to mitigate these limitations by enhancing thermal regulation and insulation properties. A temperature control system incorporating an auxiliary regulation device was developed, and three distinct insulation materials—ceramic fiber, black rice husk, and sand—were comparatively assessed utilizing eucalyptus wood as the biomass feedstock. The conventional kiln exhibited a non-uniform temperature distribution, which led to incomplete pyrolysis and the production of charcoal with suboptimal physicochemical properties. In contrast, the modified kiln, particularly when insulated with black rice husk and integrated with the auxiliary temperature control device, demonstrated superior thermal uniformity. This configuration yielded charcoal with enhanced physicochemical properties, including a significant increase in yield (26.00 ± 0.50 %), a higher fixed carbon content (89.96%), and an improved calorific value (7,652.31 kcal/kg), alongside a substantial reduction in moisture, ash, and volatile matter content. The research transcended a mere assessment of isolated improvements, instead emphasizing the synergistic benefits derived from integrating a temperature control system with optimized insulation. The findings underscore the potential of this integrated approach within the scope of a 200-liter kiln using eucalyptus biomass to achieve efficient, high-quality, and environmentally sustainable charcoal production in rural contexts.

1. Introduction

The global energy sector has faced a persistent challenge over the past several decades: while socio-economic growth has been accompanied by technological advancement and industrial expansion, these benefits have coincided with severe environmental degradation. A critical contributor to this paradox is the continued reliance on traditional biomass utilization methods in rural and low-income regions, particularly for the production of cooking fuel. In Thailand, for instance, charcoal remains a primary household fuel for millions, especially in rural areas lacking affordable access to modern energy carriers such as liquefied petroleum gas (LPG) or electricity. However, the predominant production method—traditional earth kilns—is characterized by low thermal efficiency, high emissions of particulate matter and volatile organic compounds (VOCs), and inconsistent charcoal quality. These inefficiencies not only result in a waste of valuable biomass resources but also generate substantial local air pollution, contribute to greenhouse gas emissions, and pose direct health risks to both producers and nearby communities. Despite the existence of improved charcoal production technologies, their adoption remains limited in many communities due to several factors, including cost barriers, a lack of localized design adaptation, and insufficient technical knowledge regarding optimal kiln operation. This reflects a broader sustainability gap: abundant biomass resources are underutilized, while inefficient conversion technologies perpetuate environmental and health burdens. Addressing this gap requires targeted research that integrates engineering optimization, environmental performance assessment, and practical applicability at the community level. Biomass energy, recognized as a renewable and potentially carbon-neutral source, has gained policy-level attention worldwide for its dual ability to provide energy and manage waste streams [1].

Biomass encompasses a diverse range of organic materials derived from living or recently deceased organisms, including plant residues, animal waste, and municipal solid waste [2]. Specifically, biomass feedstocks include agricultural residues (e.g., rice husks, corn stover), forestry byproducts (e.g., sawdust, bark), energy crops (e.g., switchgrass, miscanthus), food industry byproducts, aquatic vegetation, and animal manure [3]. The diversity and widespread availability of biomass materials make them particularly attractive for localized energy production [4], especially in rural and off-grid regions. Energy conversion from biomass can be achieved through a range of technologies, broadly categorized into biological and thermochemical pathways. Among these, thermochemical methods are particularly noted for their rapid conversion rates and capacity to process high-moisture or lignocellulosic materials. Thermochemical conversion involves the application of high temperatures to induce chemical transformations in the biomass material, resulting in products such as syngas, bio-oil, and char [5]. The principal thermochemical processes include pyrolysis [6-7], gasification, combustion, steam reforming, carbonization, and hydrothermal carbonization. These processes differ in their operating conditions, such as temperature, pressure, and oxygen availability [8-9], and produce varying yields of solid, liquid, and gaseous products [10].

Charcoal, the solid product obtained predominantly through carbonization and pyrolysis, holds historical significance as one of the earliest forms of fuel utilized by human civilizations. Its extensive use spans metallurgy, cooking, and heating. In modern contexts, charcoal retains considerable relevance in domestic energy applications, especially in developing countries where access to modern energy carriers like liquefied petroleum gas (LPG) or electricity is limited or prohibitively expensive. In Thailand, for instance, charcoal continues to be widely used by rural populations for cooking purposes [11]. Despite government initiatives to promote cleaner fuels, many rural households favor charcoal due to its availability, affordability, and ease of storage. Traditionally, charcoal in rural Thailand is produced using the earth kiln method, which involves the slow carbonization of wood under a controlled, oxygen-limited environment within a pit or mound. Although this method is simple and cost-effective, it suffers from significant drawbacks, including low thermal efficiency, high emissions of smoke and volatile organic compounds (VOCs), and inconsistent product quality. The resulting charcoal often exhibits a high tar content, elevated levels of volatiles, and poor energy density, thereby limiting its utility and environmental acceptability [11].

In response to these limitations, various researchers and development agencies have sought to design and implement improved charcoal production technologies suitable for decentralized, community-level deployment. A notable innovation is the use of 200-liter oil drum kilns, which offer a more structured and efficient alternative to traditional earth kilns. These kilns are low-cost, relatively easy to construct, and adaptable for household-scale applications, typically configured in either vertical or horizontal orientations [12]. The basic design of a single-drum kiln, as illustrated in Kirk R. Smith’s study [13], involves a standard 200-liter oil drum with four air inlet apertures (each 2.5 cm in diameter) at the base and additional air intake holes of identical diameter on the side. A single chimney is positioned on the drum's lid. In this direct draft carbonization process, the fire is ignited at the base of the kiln, and the charcoal yield typically ranges from 0.25 to 0.32 [12]. Subsequent research has endeavored to enhance the performance of drum kilns through structural modifications and process innovations. Timothy et al. [14] noted that comparing available kiln designs is challenging due to the unavailability of certain data or its derivation from trials using a singular feedstock. Their qualitative schematic analysis revealed that drum retort kilns are most appropriate for many applications in low-income environments. In Thailand, Sataklang et al. [15] modified a prototype smokeless charcoal kiln constructed from a 200-liter steel drum to enhance its thermal efficiency. The design was divided into three sections: a fuel chamber, a carbonization chamber, and a gas duct. This duct was designed to direct the gas generated during carbonization into the fuel chamber to serve as an auxiliary fuel, thereby eliminating toxic gas components through combustion. To address the issue of flame propagation from the sides of the kiln, the research team proposed installing an outer wall and heat transfer fins to control the flames and elevate the internal temperature. The results indicated that this novel kiln design conserved energy and increased the temperature within the carbonization chamber. Other notable efforts include a study by Panyoyai et al. [16], who designed a biochar kiln with varying central core configurations to maximize biochar yield. They used computer software to simulate temperature distribution and validated the simulation results with experimental data. The simulation outcomes revealed specific characteristics of temperature distribution that influenced biochar production and quality. Similarly, Ketsripongsa et al. [17] developed a high-efficiency charcoal kiln design for communities in Buriram province, Thailand, utilizing a vertically oriented, perforated, and transportable steel drum. Experimental results indicated a reduction in smoke emissions due to more complete combustion, with the heating process taking 120 minutes. This enabled three charcoal production cycles per day. Beyond Thailand, Kanouo et al. [18] investigated a pilot-scale retort kiln using two types of biomass: corn cobs and eucalyptus bark. The production efficiency of the kiln varied between 33 and 68 percent, which was notably higher than the 10-20 percent achieved with traditional kilns. Furthermore, the resulting biochar met the criteria of the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI).

Collectively, the existing body of research suggests that although charcoal production technologies have advanced, significant challenges persist in balancing efficiency, cost, and environmental impact, particularly for community-scale applications. The literature review highlights a critical research gap concerning the systematic optimization of key operational parameters—such as internal temperature profiles and insulation strategies—in simple, low-cost kiln designs. A comprehensive investigation is therefore required to understand how these parameters interact to influence charcoal yield, product quality, and overall energy efficiency. While previous studies have explored aspects of kiln optimization, the novelty of this work lies in its integrated approach to addressing the identified gap. Specifically, this research introduces the development of a cost-effective auxiliary temperature control device and presents a systematic comparative analysis of various insulation materials. This research aims to enhance kiln performance under community-level conditions, with a particular focus on:

(1) The deployment of temperature regulation mechanisms to increase the efficiency of charcoal production.

(2) The influence of insulation materials on internal temperature profiles and heat retention.

(3) The relationship between thermal performance and charcoal yield and quality.

By elucidating the underlying thermodynamic and material science principles governing charcoal production, this study seeks to optimize kiln performance, enhance product quality, and contribute to the broader goals of sustainable energy development in rural contexts. Furthermore, the research is aligned with national and international sustainability goals, including the promotion of clean energy technologies, the reduction of carbon emissions, and the valorization of agricultural and forestry residues through environmentally responsible energy production systems.

2. Experiment

2.1 Description of charcoal kiln

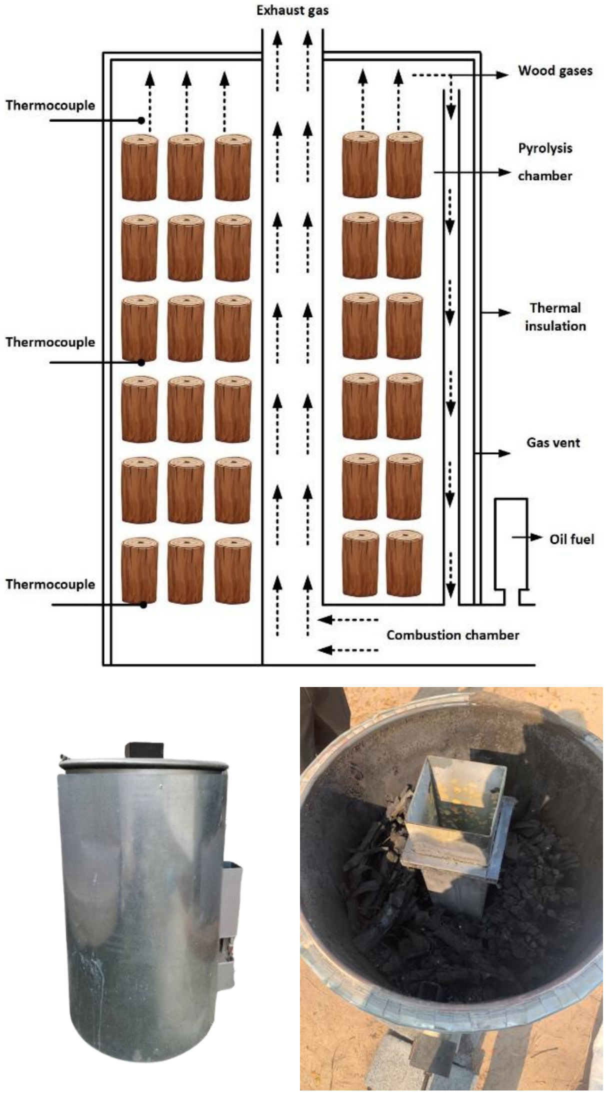

Fig. 1 The primary components of a charcoal retort kiln.

The charcoal retort kiln utilized in this study, as depicted in Fig. 1, was constructed from readily available components to ensure cost-effectiveness and practicality for community-scale applications. The primary components included: 1) Pyrolysis Chamber: A 200-liter steel drum was repurposed to serve as the main pyrolysis chamber, where biomass was contained and the carbonization process took place. The drum's robust structure and high-temperature resistance made it an ideal and cost-effective choice. 2) Combustion Chamber: A 5 x 5 inch steel pipe was integrated as the combustion chamber. This component was designed to facilitate the burning of auxiliary fuel and distribute heat efficiently into the pyrolysis chamber. 3) Flue and Gas Vent: A 1 x 1 inch steel pipe functioned as a flue, connecting the pyrolysis chamber to the combustion chamber. Its primary role was to channel smoke and exhaust gas from the pyrolysis process back into the combustion chamber for secondary combustion. This design feature was crucial for reducing smoke emissions prior to their release into the environment. 4) Thermal Insulation: To prevent heat loss and maintain a consistently high internal temperature, thermal insulation was applied around the steel drum and its lid. To monitor the thermal performance of the kiln, Type K thermocouples were strategically installed at multiple locations: the bottom, middle, and top of the pyrolysis chamber, inside the combustion chamber, and at the flue gas exit. This setup allowed for precise monitoring of temperature profiles throughout the carbonization process.

2.2 Carbonization process of charcoal

The production of wood charcoal is a carbonization process, a specific form of pyrolysis. Pyrolysis is the thermal breakdown of complex molecular structures into simpler molecules in a restricted-oxygen environment. This heat-induced decomposition produces carbon and other chemical byproducts, a process known as carbonization. While the primary product is charcoal, byproducts like pyroligneous acid, wood gas, tar, and acetic acid are also generated. These byproducts are typically not harvested; instead, they are incinerated to provide the heat necessary to sustain the carbonization process. The critical parameters influencing this process are the wood's moisture content, the kiln's architecture, and the control methodology. To simulate pyrolysis under controlled laboratory conditions, the carbonization process was divided into four distinct stages:

Step 1 Drying Stage: The process begins by thermally treating the biomass to eliminate inherent moisture content. This is a critical preliminary step, as excessive moisture can negatively affect both the efficiency of the carbonization process and the quality of the final charcoal product [19]. After the eucalyptus wood feedstock (prepared as described in Section 2.3) was loaded, the kiln lid was sealed to minimize air infiltration. Heat was then applied by igniting the combustion chamber with waste diesel engine oil, maintaining a consistent temperature to ensure effective moisture removal from the raw material.

Step 2 Decomposition Stage: Once the drying phase was complete, the temperature was gradually increased to initiate the thermal decomposition of hemicellulose, cellulose, and lignin. This process was evidenced by the emission of volatile compounds and tar [20]. These compounds were recirculated to the combustion chamber via the gas outlet for re-combustion. At this point, the external fuel supply was ceased, and the generated gas became the sole fuel source for the process.

Step 3 Carbonization Stage: The kiln temperature was further elevated to above 400°C and maintained to ensure complete carbonization. This stage was identified by the gradual cessation of gas emissions from the gas vents. As carbonization progressed, the remaining volatile compounds were expelled, and the biomass matrix was transformed into solid carbon [21]. Thermal conditions were carefully regulated by adjusting the air inlets and using insulation materials to minimize temperature fluctuations.

Step 4 Following the completion of the carbonization period, the kiln was sealed to cut off the oxygen supply. This allowed for a gradual cooling process over 12–16 hours, which was essential to prevent spontaneous combustion when the charcoal was later exposed to atmospheric oxygen. The lid was then carefully removed once the kiln temperature had dropped below 100°C, and the resulting charcoal was extracted for analysis.

Throughout all stages, Type K thermocouples connected to a data logger were used to ensure accurate thermal profiling. The entire carbonization cycle was conducted in triplicate to verify the reproducibility of the results.

2.3 A commercially available 200-liter vertical charcoal kiln and charcoal feedstocks

A commercially available 200-liter vertical charcoal kiln, based on a modified design from the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy, Thailand, was procured from a local distributor in Rayong Province. The structural configuration of this kiln aligns with the specifications detailed in Section 2.1. It was externally insulated with a 0.5-inch thick layer of ceramic fiber. Insulation is essential for this type of kiln to achieve the necessary temperatures for the carbonization process. Preliminary testing confirmed that operating the commercial kiln without any insulation was not feasible, as it failed to retain sufficient heat to reach the required carbonization temperature. This resulted in incomplete pyrolysis and excessive fuel consumption, highlighting the necessity of insulation for baseline operation. This specific charcoal kiln was used for comparative testing against a modified version equipped with an auxiliary temperature control device, and its performance was further evaluated by comparing various insulation types of equivalent thickness.

This study utilized eucalyptus wood as the biomass feedstock to investigate the kiln's efficiency. The eucalyptus wood was prepared with an approximate diameter of 5 cm and cut into 20 cm sections. It was then dried to a moisture content below 10% for experimental use. Each test employed a consistent mass of 60 ± 5 kg of eucalyptus wood. The drying process involved a combination of sun drying and adequate ventilation over a period of 10–14 days. Subsequently, samples were collected to determine their moisture content using a UNI-T UT377A wood moisture meter.

2.4 Improving Temperature Control Devices

Building upon the study of a commercially available 200-liter vertical charcoal kiln with built-in 0.5-inch ceramic fiber insulation, a key observation was the significant temperature variation across different locations within the kiln. This thermal heterogeneity often led to inconsistent charcoal quality within each production batch. In response, the researchers developed an auxiliary temperature control device, as shown in Fig. 2, specifically designed to achieve a more uniform temperature distribution. The device consists of a series of fins fabricated from 6 mm thick flat steel. These fins are mounted radially at a 45-degree downward angle inside the exhaust pipe of the combustion chamber. Specifically, three flat steel fins, each measuring 4.39 inches in length, 1 inch in width, and 6 mm in thickness, were arc-welded to a central steel core plate (1 inch wide, 31 inches long, and 6 mm thick). When viewed from above, this configuration forms an "X" cross-sectional pattern. This design is intended to promote turbulence and prolong the heat exchange between the hot gases and the kiln wall. By inducing rotational airflow and increasing heat residence time, the device aims to reduce vertical thermal gradients and thereby improve the overall thermal uniformity of the kiln.

2.5 Influence of Heat Insulation

A study was conducted to investigate the influence of thermal insulation on charcoal kiln efficiency by examining three different insulation materials: ceramic fiber, sand, and black rice husk. All materials were applied at a consistent thickness of 1 inch to allow for a direct comparative analysis. These three materials were selected based on their contrasting properties: (1) Ceramic Fiber: Ceramic Fiber: A commercially manufactured high-temperature insulator composed primarily of alumina (Al_2O_3) and silica (SiO_2). This material, with fiber diameters between 2–5 µm, has a nominal thermal conductivity of 0.12 W/(m·K) at 600°C. It was chosen for its superior insulation properties and exceptional heat resistance, capable of withstanding temperatures up to 1,260°C [27]. (2) Black Rice Husk: An abundant agricultural byproduct in rural Thailand. Its structure, composed of amorphous silica and carbon within a porous matrix [28], gives it a thermal conductivity coefficient of 0.073 W/(m·K), which is comparable to common thermal insulation materials [40]. (3) Sand: This material was used as a baseline due to its low cost and wide availability. Although it provides thermal buffering, sand has a relatively high thermal conductivity (~0.25–0.35 W/(m·K)), making it a less effective insulator [29].

Initially, prepared eucalyptus wood (as detailed in Section 2.3) was loaded into the charcoal kiln, and the lid was securely sealed to prevent air leaks. The three different insulation types were applied around the kiln and its lid for each test. The combustion chamber was then ignited using an initial load of 0.5 liters of used diesel engine oil. Subsequently, additional fuel was incrementally fed at an average rate of 0.6–0.7 liters per hour, controlled by a valve. Air for combustion was supplied through the combustion chamber, operating on the principle of thermodynamic air circulation: hot air rises and is replaced by cooler air. The kiln's design ensured sufficient airflow into the combustion chamber for thorough and complete combustion. All tests were conducted under similar environmental conditions to ensure result comparability. The fuel combustion released thermal energy, which was then transferred to the pyrolysis chamber. In the oxygen-limited environment of the pyrolysis chamber, the eucalyptus wood underwent thermal decomposition. As a result, steam, volatile compounds, and tar were released from the wood and channeled through the gas vent into the combustion chamber for secondary combustion. This process continued until carbonization was complete. Throughout the entire process, temperatures at various locations within the charcoal kiln were recorded every 10 minutes to monitor the thermal profile.

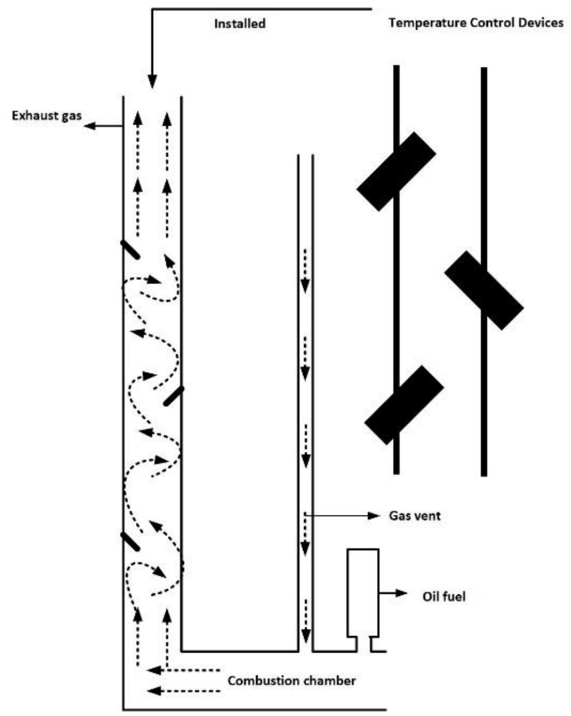

Fig. 2 An auxiliary temperature control device design.

2.6 Charcoal kiln efficiency

The efficiency of the charcoal kiln was a key indicator of the carbonization process's success. This efficiency was quantified by analyzing the physicochemical properties of the charcoal produced, specifically its moisture content, volatile matter, ash, and fixed carbon, in accordance with ASTM D7582-15 [22]. Furthermore, the calorific value of the charcoal was determined following the standards outlined in ASTM D5865-10 [23].

To determine the moisture content, a test specimen was placed in a pre-weighed crucible and its initial mass (W) was recorded. The specimen was then dried in an oven at a temperature of 107±3°C. The moisture content was calculated using Equation (1), where B represents the mass of the test specimen after drying.

$$M = \left(\frac{W-B}{W}\right) \times 100 \quad (1)$$

Volatile matter, or gaseous material, directly influences the combustion characteristics of charcoal, affecting both the efficiency and intensity of the fire. The volatile matter content was calculated using Equation (2), where C represents the mass of the test specimen after the volatile matter test.

$$V = \left(\frac{B-C}{B}\right) \times 100 \quad (2)$$

Ash content was determined by measuring the mass of the residue remaining after burning the charcoal specimen at a temperature of 750°C. The ash content was calculated using Equation (3), where F is the mass of the crucible and ash residue, and G is the mass of the empty crucible.

$$A = \left(\frac{F-G}{W}\right) \times 100 \quad (3)$$

Fixed carbon is a calculated value representing the mass percentage of carbon remaining in the charcoal. It was determined by subtracting the percentages of moisture, ash, and volatile matter from 100, as shown in Equation (4). This equation standardizes all variables to the same moisture reference basis.

$$FC = 100 - (M + A + V) \quad (4)$$

The charcoal yield analysis involved determining the proportion of charcoal produced (M_c) relative to the initial biomass input (M_w), as described by Equation (5).

$$\text{Charcoal yield} = \frac{M_C}{M_W} \quad (5)$$

The calorific value, or the heat generated by the fuel, was determined using a bomb calorimeter in accordance with ASTM D5865-10. This apparatus was employed to measure the heat released from the combustion of a fuel sample and oxygen at a constant volume.

2.7 Comparison and data analysis

This research conducted a direct comparative analysis between a commercial charcoal kiln and a modified charcoal kiln equipped with an auxiliary heat control device to assess the thermal uniformity within the kiln. Temperature was measured using K-type thermocouples installed at three distinct locations: top, middle, and bottom. Subsequently, three different insulating materials—ceramic fiber, black rice husk, and sand—were tested in the modified kiln under controlled conditions. Each insulation material was applied uniformly at a thickness of 1 inch to ensure a direct and accurate comparison of their thermal efficiency and insulation properties. To ensure reproducibility, three charcoal production cycles were performed for each experimental condition. The final charcoal products were then subjected to physicochemical analysis to determine their yield, moisture content, volatile matter content, fixed carbon content, and calorific value.

Data from each experiment were analyzed using IBM SPSS Statistics 28 software. The statistical analysis included a one-way analysis of variance (ANOVA). The significance of the differences between pairs of means was assessed using Tukey's Honestly Significant Difference (HSD) test. Pairs with a p-value less than 0.05 ($p<0.05$) were considered statistically significant. All results are presented as the mean and standard deviation (SD) from the three replicates of each experiment.

This comparative methodology allowed for the quantification of improvements or drawbacks associated with each modification, with particular attention paid to the influence of temperature control and insulation materials on both the thermal behavior and the properties of the resulting charcoal. This rigorous comparison facilitates the identification of the most appropriate kiln configuration to maximize carbonization efficiency and charcoal quality.

3. Results and discussion

3.1 Temperature Control in the Kiln

The thermal behavior and temperature distribution within 200-liter vertical charcoal kilns were investigated to evaluate the efficiency of the carbonization process under two distinct conditions: (1) a conventional kiln with integrated 0.5-inch ceramic fiber insulation and (2) a modified kiln featuring both the aforementioned insulation and an auxiliary temperature control device. Temperatures were measured at three specific vertical positions—top, middle, and bottom—in each kiln. The collected data provided critical insights into the dynamics of heat transfer, the initiation and progression of pyrolysis, and overall kiln performance.

Fig. 3 illustrates the temperature profile over time for the conventional 200-liter vertical charcoal kiln. Data was collected from the top, middle, and bottom layers. The top section's temperature increased rapidly, reaching a peak of approximately 655.67 ± 6.65 °C at 200 minutes. This rapid increase suggests an excessive accumulation of combustion gases and heat in the upper region, likely due to upward convection of hot air and limited structural insulation. Following this peak, a sharp temperature drop was observed, declining to below 250 °C by the end of the carbonization cycle at 300 minutes. This behavior is indicative of either uncontrolled heat loss or the depletion of combustible volatiles in the upper biomass layers. In contrast, the middle section exhibited a slower, more linear temperature increase, peaking at approximately 569.43 ± 15.53 °C around 260 minutes. The bottom section displayed the lowest temperatures, reaching a maximum of only 522.04 ± 19.18 °C after 280 minutes. The significant lag and lower peak temperature in the bottom region imply inefficient heat penetration from the top to the base. This stratified heating pattern suggests incomplete or uneven pyrolysis, particularly in the lower part of the kiln, which leads to a heterogeneous product in terms of carbon content and moisture [24].

Furthermore, the premature peak and subsequent drop in the top layer may have initiated early charring and a potential loss of volatile matter, which would adversely affect charcoal yield and calorific value [25-26]. The pronounced temperature gradients between sections also reflect poor thermal regulation, likely resulting from inefficient heat distribution. These shortcomings align with known limitations of traditional batch kilns, which often experience uneven heating zones and inconsistent charring rates along the vertical axis.

Fig. 4 presents the temperature profile for the modified kiln, which was equipped with an auxiliary temperature control device. This kiln demonstrated a more uniform and sustained thermal behavior throughout the carbonization period. The top section showed a gradual and controlled temperature increase, peaking at approximately 688.30 ± 7.02 °C at 220 minutes, followed by a smooth decline to approximately 400 °C at 300 minutes. Unlike the conventional kiln, this modified design maintained elevated temperatures for a longer duration, a condition crucial for complete devolatilization and carbon stabilization. The middle section reached a higher peak temperature (633.36 ± 12.53 °C) than in the conventional kiln and followed a thermal trend closely aligned with the top section. Most notably, the bottom section showed a substantial improvement, reaching a peak of 532.74 ± 12.97 °C and following a more synchronized trend with the other zones.

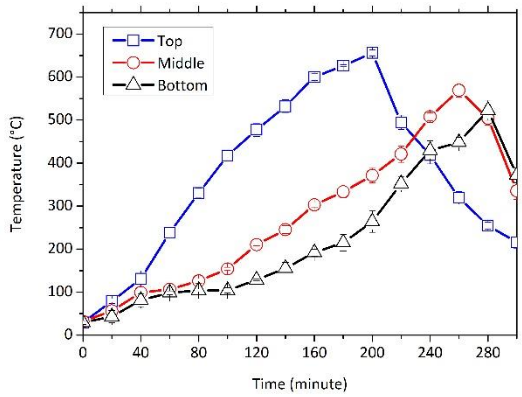

Fig. 3 Temperature profile over time in a commercial 200-liter vertical charcoal kiln with 0.5-inch ceramic fiber insulation. Data collected from top, middle, and bottom layers.

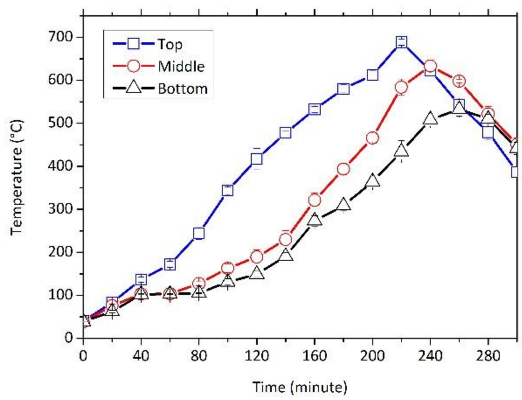

Fig. 4 Temperature profile over time in a commercial 200-liter vertical charcoal kiln with 0.5-inch ceramic fiber insulation and an auxiliary temperature control device. Data collected from top, middle, and bottom layers.

This near-parallel increase and decline across all three regions indicate a significant improvement in heat distribution and retention. This is likely attributable to the temperature control mechanism, which regulated air intake and fuel combustion, in combination with improved kiln insulation. This uniform thermal distribution effectively reduced the temperature differentials between the top and bottom sections. A decrease in these temperature gradients not only leads to more even pyrolysis but also enhances overall process efficiency, resulting in a higher yield of fixed carbon, lower ash content, and greater charcoal production. Additionally, the prolonged maintenance of high temperatures in the middle and bottom sections likely facilitates the cracking of tar and the generation of more producer gas, which reduces residual volatiles and boosts the product's energy content. These observations are consistent with the findings of Supin et al. [12], who reported that controlled thermal conditions enhance the quality and uniformity of charcoal, particularly in biomass systems with vertical stratification.

3.2 Effect of Thermal Insulation

The regulation of internal temperature within charcoal kilns is a critical parameter that directly influences both the efficiency of the pyrolysis process and the physicochemical properties of the resulting charcoal. To optimize these factors, an auxiliary temperature control device was installed within the combustion chamber. This device was designed to improve thermal efficiency, facilitate more uniform heat distribution, and maintain a stable thermal environment throughout the pyrolysis duration. Furthermore, reducing heat loss from the pyrolysis chamber was considered essential for sustaining temperatures within the optimal range required for the effective thermochemical conversion of biomass into charcoal. For consistency and reliability, all improved kiln experiments were conducted with standardized 1-inch insulation layers across all materials tested. This allowed for a direct comparison of their thermal performance under equivalent structural and operational conditions. This study conducted a comparative evaluation to investigate the effects of three different insulation materials—ceramic fiber, black rice husk, and sand—on the internal temperature dynamics of the charcoal kiln. The aim was to determine how each material influenced the thermal profile and, consequently, the uniformity and completeness of biomass carbonization across different vertical sections of the kiln.

Among the insulation materials tested, the 1-inch ceramic fiber exhibited superior thermal performance. As illustrated in Fig. 5, the maximum temperatures achieved were 695.45 ± 7.03 °C at the upper section (after 220 minutes), 647.39 ± 2.10 °C at the middle section (after 240 minutes), and 548.97 ± 7.92 °C at the lower section (after 260 minutes). The relatively narrow temperature differentials across the kiln layers are attributed to the intrinsic properties of ceramic fiber, which include its ability to withstand extremely high temperatures (ranging from 1200–1400 °C) and its composite structure predominantly composed of alumina (Al_2O_3), silica (SiO_2), and kaolin-based fibers. These characteristics enabled the ceramic fiber to retain heat effectively, minimize conductive and convective losses, and promote uniform heat distribution. Consequently, the pyrolysis reactions—namely, devolatilization, gasification, and carbonization—proceeded in a more complete and consistent manner throughout all kiln sections.

For the kiln insulated with 1-inch black rice husk (Fig. 6), slightly higher peak temperatures were demonstrated at all levels: 718.26 ± 14.77 °C at the upper section, 696.20 ± 4.61 °C at the middle, and 591.56 ± 12.37 °C at the lower section. Despite these elevated temperatures, the internal thermal gradients remained relatively uniform, thereby enabling synchronized thermochemical processes across the kiln. These findings corroborate previous studies by Jofrishal et al. [28], which highlighted the insulating potential of black rice husk as a bio-based, environmentally sustainable material. The high carbon and silica content of rice husk, along with its fibrous and porous structure, contributed to its capacity to reduce heat loss while simultaneously minimizing environmental impact.

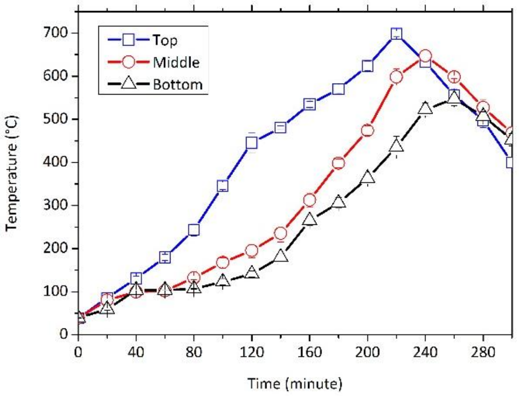

Fig. 5 Temperature profile in the kiln with 1-inch ceramic fiber insulation and an auxiliary temperature control device. Data collected from top, middle, and bottom layers.

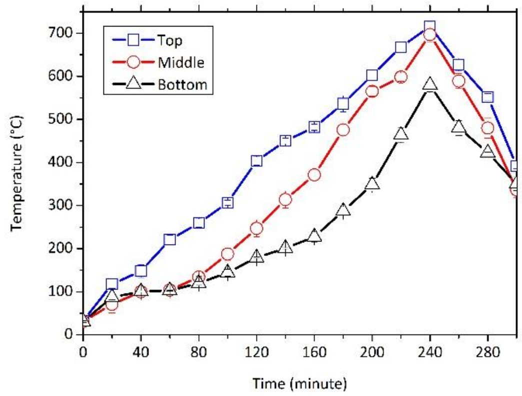

Fig. 6 Temperature profile in the kiln with 1-inch black rice husk insulation and an auxiliary temperature control device. Data collected from top, middle, and bottom layers.

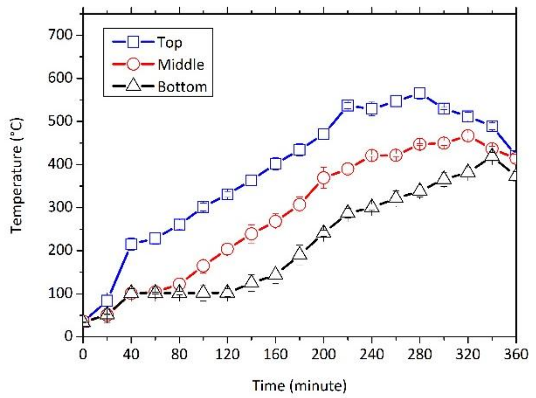

Fig. 7 Temperature profile in the kiln with 1-inch sand insulation and an auxiliary temperature control device. Data collected from top, middle, and bottom layers.

In stark contrast, the kiln insulated with 1-inch sand exhibited markedly inferior thermal performance. As shown in Fig. 7, the peak temperatures observed were significantly lower: 565.05 ± 13.23 °C at the upper section (after 280 minutes), 466.70±7.18 °C at the middle section (after 320 minutes), and 418.74±9.89 °C at the lower section (after 340 minutes). Not only were the achieved temperatures considerably lower than those with ceramic fiber and rice husk, but the rate of temperature increase was also significantly slower. These conditions led to extended carbonization times, especially in the lower kiln zones, where temperatures failed to reach the necessary thresholds for complete pyrolysis. The resultant charcoal exhibited suboptimal quality in terms of carbon content, structure, and combustion properties. This outcome is consistent with fundamental heat transfer principles, whereby sand, due to its relatively high thermal conductivity and compact granular structure, allows for rapid dissipation of heat to the environment [29].

The carbonization cycle for most kiln configurations—commercial, ceramic fiber, and rice husk—lasted approximately 5 hours (300 minutes) from ignition to sealing. However, the kiln insulated with sand required a prolonged duration of approximately 6 hours (360 minutes). This discrepancy is attributed to the lower thermal insulation capacity of sand, which resulted in slower heat buildup, extended heating times to reach pyrolysis thresholds, and delayed char completion in the lower layers. These variations in duration directly impacted fuel consumption and overall energy efficiency.

Effective temperature control and appropriate insulation within the charcoal kiln not only enhanced the quality of the produced charcoal but also contributed to reduced energy consumption and lower greenhouse gas emissions during production. These outcomes align with current trends in the development of sustainable and environmentally friendly charcoal production technologies. The findings of this study underscore the value of selecting suitable insulation materials, particularly ceramic fiber, due to its high thermal resistance and fibrous structure, which minimize heat loss. Similarly, black rice husk emerged as an efficient and eco-friendly bio-based insulation material. In contrast, sand insulation, characterized by high thermal conductivity, resulted in rapid heat dissipation and prolonged charcoal production time.

In conclusion, the strategic use of an internal temperature control device in combination with the selection of a high-performance insulation material is crucial for optimizing charcoal production efficiency and quality. These results provide practical guidelines for the development of sustainable charcoal production technologies.

3.3 Charcoal Yield and Quality

Table 1 presents the charcoal yield from five different kiln configurations. The kiln equipped with a temperature control device and insulated with 1-inch black rice husk exhibited the highest yield, producing 15.6 ± 0.50 kg of charcoal from an input of 60 ± 5.00 kg of biomass. This corresponds to a yield of 26.00 ± 0.50% and required the least amount of fuel oil (2.2 ± 0.50 L), indicating superior energy efficiency. According to the ANOVA and Tukey's HSD test, these values were significantly different ($p < 0.05$) from those of the other kiln types. This improved yield can be attributed to the low thermal conductivity and high insulation performance of black rice husk, which contributed to enhanced heat retention during the pyrolysis process. This finding is consistent with Thongsan et al. [30], who noted that biomass residues with porous structures are effective in improving thermal insulation and pyrolysis efficiency. In comparison, the conventional kiln with 0.5-inch ceramic fiber insulation but without a temperature control device produced only 10.9 ± 1.50 kg of charcoal (18.16 ± 1.50 % yield) while consuming 3 ± 1.00 L of fuel oil. Despite having a similar biomass input, the conventional kiln's lower thermal retention and uncontrolled combustion likely resulted in greater energy loss. The kiln with 0.5-inch ceramic fiber insulation combined with a temperature control device showed a modest improvement, producing 11.8 ± 1.20 kg of charcoal (19.33 ± 1.20 % yield) with a similar fuel input (3.1 ± 0.50 L). Increasing the ceramic fiber thickness to 1 inch further enhanced performance slightly, yielding 11.9 ± 2.00 kg (19.83 ± 2.00%). These results highlight the benefits of both insulation thickness and temperature regulation in improving pyrolysis efficiency. In contrast, the kiln insulated with 1-inch sand and equipped with a temperature control device demonstrated the lowest yield (17.33 ± 2.50 %) and consumed the most fuel oil (6 ± 2.00 L). The statistical tests confirmed that its fuel consumption was significantly higher and yield significantly lower compared to the black rice husk insulated kiln. Due to its high thermal mass, sand absorbed a substantial amount of energy before reaching the optimal pyrolysis temperature, which delayed the carbonization process and increased fuel demand [41].

The charcoal quality under different insulation conditions is summarized in Table 2. The kiln insulated with 1-inch black rice husk and equipped with an auxiliary temperature control device not only delivered the highest yield but also produced charcoal of the highest quality. This product exhibited the lowest moisture content (3.05 ± 1.52%), lowest ash content (3.51 ± 1.14%), and lowest volatile matter (3.48 ± 1.03%), all of which are key indicators of high-grade charcoal. Statistical analysis demonstrated these parameters were significantly different ($p < 0.05$) from those of other kiln configurations. Furthermore, it yielded the highest fixed carbon content (89.96 ± 0.21%) and the highest calorific value (7,652.31 ± 1.25 kcal/kg), making it the most energy-dense product among the five configurations. According to Sugiarto et al. [32], high fixed carbon and calorific values are desirable characteristics in charcoal as they enhance combustion efficiency and energy output. The results from this study thus confirm the suitability of black rice husk insulation for producing high-quality charcoal. In contrast, the conventional charcoal kiln (without a temperature control device and with 0.5-inch ceramic fiber insulation) yielded charcoal with inferior properties, including high ash content (10.20 ± 1.20%) and volatile matter (8.76 ± 1.10%), along with a low fixed carbon content (72.19 ± 0.65%), contributing to a reduced calorific value of 6,170.94 ± 9.52 kcal/kg. These characteristics were statistically different from the black rice husk kiln results, suggesting a less complete carbonization process, possibly due to uncontrolled combustion and inconsistent temperature distribution. Similarly, the kiln insulated with 1-inch sand, despite being equipped with a temperature control device, produced charcoal with high moisture (8.01 ± 1.50%) and volatile content (10.59 ± 1.29%). Its fixed carbon content was moderate (74.77 ± 1.07%), and the calorific value remained low (6,166.71 ± 8.13 kcal/kg), all statistically different from the black rice husk kiln ($p < 0.05$). This reflects poor insulation performance and less efficient heat transfer due to the high thermal mass of sand. The kilns insulated with ceramic fiber showed intermediate charcoal quality. The 1-inch ceramic fiber kiln produced charcoal with a moisture content of 5.85 ± 0.48%, ash content of 5.86 ± 1.30%, and volatile matter of 6.29 ± 1.05%. Its fixed carbon was relatively high (79.42 ± 1.39%), and the calorific value reached 6,447.01 ± 2.81 kcal/kg, suggesting a more consistent carbonization process due to enhanced thermal insulation and controlled heating [31]. The 0.5-inch ceramic fiber kiln with temperature control showed similar trends but slightly lower quality metrics across all parameters compared to the 1-inch version.

The findings from this study demonstrate the importance of both temperature control and the selection of an appropriate insulation material in enhancing the efficiency and quality of charcoal production. Notably, bio-based insulating materials such as black rice husk not only improve the yield and quality of the final product but also offer a sustainable solution by utilizing agricultural waste. These results have practical implications for small- to medium-scale charcoal producers seeking to improve energy efficiency while reducing production costs.

3.4 Comparative Analysis with Commercial Kiln

A comparative assessment between the modified charcoal kiln and the conventional commercial 200-liter vertical kiln revealed substantial operational differences. While the traditional kiln suffered from non-uniform temperature distribution and lower energy retention, the modified kiln, particularly when equipped with an auxiliary temperature control device, demonstrated improved thermal performance and greater product consistency. The integration of thermal regulation mechanisms led to a more uniform heat distribution, reduced temperature differentials between kiln layers, and enhanced control over the carbonization process. These factors contributed to a higher fixed carbon content and calorific values in the resulting charcoal.

Additionally, the flexibility of pairing the temperature control device with various insulation materials allows users to adapt the system based on local resource availability. For instance, black rice husk, which is widely accessible in many agricultural regions, proved to be both effective and environmentally sustainable. In contrast, sand insulation, while easily sourced, delivered lower thermal performance.

Despite these demonstrated improvements in thermal uniformity, charcoal yield, and product quality, certain practical challenges remain that may affect the widespread adoption and scalability of the auxiliary temperature control device in rural settings. The device, while technically effective, involves fabrication using steel components, which may require specific welding skills and access to appropriate materials or workshops. Furthermore, routine maintenance of the charcoal kiln is essential to ensure sustained performance. Accumulated tar, ash, or corrosion due to prolonged exposure to high temperatures and pyrolysis gases may deteriorate the functionality of internal components, especially the auxiliary temperature control device. Regular inspection and cleaning are thus necessary, and this may place an additional burden on operators without technical support or standardized maintenance protocols.

To overcome these barriers, future research should explore the development of modular or prefabricated components that simplify installation and reduce maintenance frequency. Additionally, integrating local knowledge systems and providing training programs for community-based operators may enhance the long-term operability and resilience of the improved kiln technology. Overall, these findings support the continued refinement and field deployment of such systems in rural energy programs and carbon-neutral initiatives.

Table 1 The charcoal yield of five types of charcoal kilns. A one-way analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) post-hoc test were performed to identify significant differences between the groups. Data with different superscript letters within the same row are statistically significant at the 0.05 level.

Kiln Type	Fuel Oil (L)	Initial Biomass (kg)	Charcoal (kg)	Yield (%)
Commercial charcoal kiln with built-in 0.5-inch ceramic fiber insulation	3 ± 1.00^{ab}	60 ± 5.00^{a}	10.9 ± 1.50^{b}	18.16 ± 1.50^{b}
Charcoal kiln with built-in 0.5-inch ceramic fiber insulation and an auxiliary temperature control device	3.1 ± 0.50^{ab}	60 ± 5.00^{a}	11.8 ± 1.20^{ab}	19.33 ± 1.20^{ab}
Charcoal kiln with built-in 1-inch ceramic fiber insulation and an auxiliary temperature control device	3.5 ± 1.00^{ab}	60 ± 5.00^{a}	11.9 ± 2.00^{ab}	19.83 ± 2.00^{ab}
Charcoal kiln with built-in 1-inch black rice husk insulation and an auxiliary temperature control device	2.2 ± 0.50^{b}	60 ± 5.00^{a}	15.6 ± 0.50^{a}	26.00 ± 0.50^{a}
Charcoal kiln with built-in 1-inch sand insulation and an auxiliary temperature control device	6 ± 2.00^{a}	60 ± 5.00^{a}	10.4 ± 2.50^{b}	17.33 ± 2.50^{b}

Table 2 Charcoal quality under different insulation conditions. A one-way analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) post-hoc test were performed to identify significant differences between the groups. Data with different superscript letters within the same column are statistically significant at the 0.05 level.

Parameter	Commercial charcoal kiln with built-in 0.5-inch ceramic fiber insulation	Charcoal kiln with built-in 0.5-inch ceramic fiber insulation and an auxiliary temperature control device	Charcoal kiln with built-in 1-inch ceramic fiber insulation and an auxiliary temperature control device	Charcoal kiln with built-in 1-inch black rice husk insulation and an auxiliary temperature control device	Charcoal kiln with built-in 1-inch sand insulation and an auxiliary temperature control device
Moisture (%)	8.85 ± 1.42^{a}	5.92 ± 0.89^{b}	5.85 ± 0.48^{b}	3.05 ± 1.52^{c}	8.01 ± 1.50^{a}
Ash (%)	10.20 ± 1.20^{a}	6.27 ± 1.10^{bc}	5.86 ± 1.30^{c}	3.51 ± 1.14^{d}	6.63 ± 1.94^{b}
Volatile Matter (%)	8.76 ± 1.10^{ab}	6.59 ± 0.87^{bc}	6.29 ± 1.05^{c}	3.48 ± 1.03^{d}	10.59 ± 1.29^{a}
Calorific Value (kcal/kg)	$6,170.94 \pm 9.52^{d}$	$6,485.23 \pm 3.25^{b}$	$6,447.01 \pm 2.81^{c}$	$7,652.31 \pm 1.25^{a}$	$6,166.71 \pm 8.13^{d}$
Fixed Carbon (%)	72.19 ± 0.65^{c}	78.22 ± 1.08^{b}	79.42 ± 1.39^{b}	89.96 ± 0.21^{a}	74.77 ± 1.07^{c}

3.5 Economic Evaluation

A preliminary economic evaluation was conducted to assess the practical viability of deploying the improved charcoal kiln system in commercial or community-level settings. The analysis compared the baseline cost and performance of a conventional 200-liter commercial kiln with the modified kiln, which was equipped with an auxiliary temperature control device and black rice husk insulation.

The additional investment required for the improved system primarily included the fabrication of the steel fin temperature control device (THB 550) and the application of rice husk insulation (THB 100), totaling an incremental capital cost of approximately THB 650 per kiln. On the benefit side, the improved kiln yielded a charcoal output of 26.00% compared to 18.16% for the conventional commercial kiln, representing a relative increase of 43.2% in production. Furthermore, the enhanced physicochemical properties of the improved charcoal, including higher fixed carbon content and calorific value, increased its market value by an estimated 20–25% in local markets. Assuming a single kiln processes 60 kg of biomass per batch and operates four cycles per week, the improved kiln would generate approximately 75.2 kg more charcoal per month. At an average market price of THB 30 per kg, this translates to an additional monthly revenue of THB 2,256. Under these assumptions, the payback period for the additional investment is approximately 0.29 months, after which the system begins to generate net economic benefits.

These findings suggest that the improved kiln design not only enhances energy efficiency and environmental performance but also presents a cost-effective solution for community-scale charcoal producers. The relatively short payback period and potential for higher income strengthen the commercial justification for adopting the improved system in rural contexts.

3.6 Sustainable Development of Charcoal Production

Sustainable development is recognized as a critical global framework aimed at balancing the economic, environmental, and social imperatives of human progress [33]. The development of commercial charcoal kilns using thermal control techniques is a technological innovation that aligns with sustainable development goals across multiple dimensions (Fig. 8).

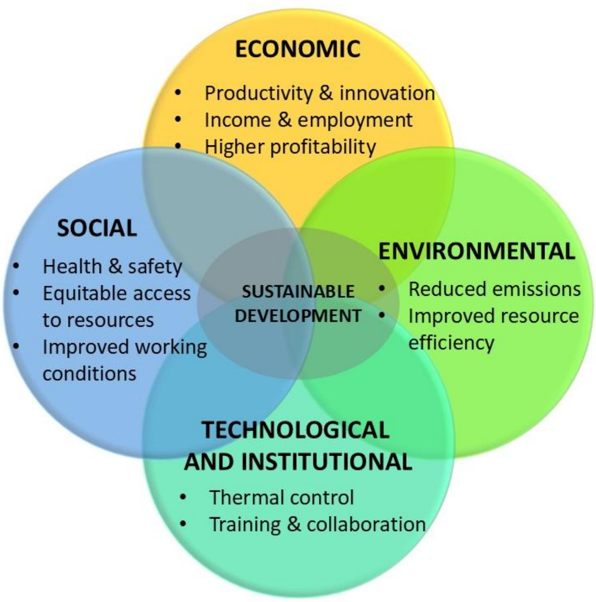

Fig. 8 Multidimensional framework of sustainable charcoal production. This includes environmental, economic, social, and institutional aspects aligned with SDG goals.

Environmental Dimension: Traditional charcoal production has been associated with significant environmental externalities, including deforestation, inefficient biomass use, and the release of greenhouse gases such as methane and particulate matter [34]. This research demonstrated that implementing improved temperature control and enhanced heat distribution in commercial kilns mitigates these harms by increasing carbonization yields and minimizing pollutant emissions compared to conventional kilns. The use of a feedback-controlled airflow system allows for better regulation of pyrolysis stages, thereby reducing smoke and toxic volatile emissions. These technological interventions support environmental sustainability objectives by lowering ecological footprints and improving the resource-use efficiency of biomass [35].

Economic Dimension: The improved kilns developed in this study facilitate increased output quality and quantity, directly enhancing economic outcomes for producers. By improving the carbon content and structural uniformity of the charcoal, the kilns enable higher market value and extended product durability. Furthermore, thermal control mechanisms reduce fuel waste and lower operational costs, thereby increasing profitability for stakeholders involved in the biomass supply chain. These outcomes align with the economic goals of sustainable development by promoting innovation-driven growth and strengthening local economies through value-added production [36].

Social Dimension: In traditional charcoal production, operators are often exposed to hazardous smoke, high temperatures, and unsafe working conditions [37]. This study addressed these issues by designing a kiln with insulated walls and controlled exhaust systems, which mitigates the release of harmful gases and particulates into the work environment. The efficiency and automation of the process also minimize the physical labor required, contributing to safer and more dignified employment. In this context, the technological upgrade supports the social dimension of sustainability by enhancing health, safety, and labor equity within rural settings.

Technological and Institutional Dimension: The implementation of thermal control systems reflects a critical innovation that integrates scientific research with engineering design to produce a sustainable charcoal production model. The successful deployment of these kilns relies on collaboration among academic institutions, local artisans, and government agencies. Institutional support, including training and knowledge dissemination, is crucial for the broader adoption and scaling of the technology. These results demonstrate the importance of capacity building and governance mechanisms in promoting the diffusion of sustainable practices [38].

In summary, the integration of thermal control techniques into commercial charcoal kiln design addresses key challenges across the environmental, economic, social, and technological dimensions of sustainable development. By increasing efficiency, reducing emissions, improving worker safety, and enhancing economic returns, this study serves as a model for sustainable biomass energy systems. Future work should emphasize scaling such innovations in alignment with international sustainability frameworks, including the United Nations Sustainable Development Goals (UN SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 12 (Responsible Consumption and Production) [39].

4. Conclusion

This study demonstrated that integrating thermal control mechanisms and effective insulation significantly improves the efficiency and quality of community-scale charcoal production. Enhancements to the kiln design, particularly the addition of an auxiliary temperature control device and the use of optimized insulation materials, were instrumental in achieving these improvements.

The conventional 200-liter vertical kiln with 0.5-inch ceramic fiber insulation exhibited notable internal temperature non-uniformity, which led to uneven pyrolysis and inferior charcoal characteristics. In contrast, the modified kiln achieved more uniform thermal profiles across all layers, reducing carbonization time and enhancing conversion efficiency. The selection of insulation material was also critical for maintaining optimal internal temperatures. Among the three materials tested, black rice husk insulation provided the most effective performance, sustaining high and uniform temperatures that enabled complete biomass carbonization. This configuration produced the highest charcoal yield (26.00 ± 0.50 %) and superior physicochemical properties, including a fixed carbon content of 89.96% and a calorific value of 7,652.31 kcal/kg. These gains were directly attributed to improved heat retention and uniform thermal distribution throughout the pyrolysis process. Additionally, the redesigned kiln's gas recirculation system redirected pyrolysis gases for secondary combustion, which not only improved thermal efficiency but also reduced visible smoke and harmful emissions, supporting more environmentally sustainable production practices.

Importantly, these technical improvements align with broader environmental and socioeconomic objectives. By enhancing energy efficiency and reducing pollutant emissions, the technology contributes to mitigating deforestation and air quality degradation. Economically, the increased charcoal yield and quality offer rural producers greater income opportunities and resource-use efficiency, fostering local livelihoods. Socially, the kiln's design improvements promote safer working conditions by minimizing operator exposure to heat and harmful emissions. These multidimensional benefits resonate with global sustainable development goals, such as UN SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), highlighting the potential for scalable, sustainable biomass energy solutions that integrate innovation with environmental stewardship and social well-being.

In summary, the integration of an auxiliary temperature control device and bio-based insulation presents a scalable and sustainable approach to advancing charcoal kiln technology. These findings offer practical guidance for improving rural biomass energy systems in alignment with clean energy and environmental sustainability goals, thereby contributing to a more resilient and equitable energy future.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of Generative AI and AI-assisted Technologies in Writing Process

During the preparation of this work, the authors used ChatGPT [https://openai.com/], Google Gemini [https://gemini.google.com/], QuillBot [www.quillbot.com], and Grammarly [www.grammarly.com] in order to improve only language and readability. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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