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Enhancing the energy efficiency of traditional brick kilns through sustainable insulation with rice husk ash and wood ash

Sopa Cansee*[1)], Nuntawat Butwong[1)], Sarawut Saenkham[1)], Teerasad Kanasri[2)], Shenghua Hu[3)] and Worawut Promtown[1)]

[1)]Faculty of Engineering, Mahasarakham University, Maha Sarakham 44150, Thailand
[2)]Faculty of Liberal Arts and Science, Roi Et Rajabhat University, Roi Et 45120, Thailand
[3)]Faculty of Electrical and Mechanical Engineering, Qingyuan Vocational High School, Lishui, Zhejiang, 323800, China

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Abstract

This study investigates the use of rice husk ash (RHA) and wood ash (WA) as sustainable thermal insulators to enhance the energy efficiency of traditional brick kilns. As readily available byproducts of agricultural and biomass combustion processes, RHA and WA are low-cost materials that support circular economy practices. Their favorable physical properties, including low thermal conductivity, high porosity, and reactive silica content, make them suitable for use as insulation for kiln walls. Experiments were carried out using a scaled-down downdraft open-top kiln to evaluate the thermal performance across various wall thicknesses and compaction levels. The results indicated that WA, particularly in a 15 cm loose-fill configuration, achieved the lowest heat loss (23.24 MJ) and the highest thermal efficiency (54.42%), representing a 15.09% improvement compared to the control. This approach to insulation also reduced the unit energy cost per brick from 0.00487 to 0.00414 USD, yielding an estimated annual fuel saving of 588 USD and a payback period of 1.47 years (~20 batches). In addition to energy savings, the reuse of RHA and WA reduces landfill waste, mitigates reliance on virgin insulation materials, and contributes to emission reductions, potentially lowering the CO_2 output by up to 750 kg per year for small-scale kilns. These findings confirm that incorporating RHA and WA into kiln construction is a viable, cost-effective strategy for improving sustainability in artisanal and semi-industrial brick production. The results are scalable and adaptable to various geographical and climatic contexts, thereby supporting broader adoption in developing regions.

Keywords: Rice husk ash, Wood ash, Brick kiln, Thermal efficiency, Sustainable insulation

Nomenclature

W_a	Amount of water absorbed (%)
W_s	Saturated wet weight of the brick (kg)
W_d	Dry weight of the brick (kg)
L_T	Total thickness of the composite (m)
K_T	Overall thermal conductivity of the composite (W/m·K)
L_i	Thickness of the *i*-th layer (m)
K_i	Thermal conductivity of the *i*-th layer (W/m·K)
Q_t	Total energy consumption (MJ)
m_f	Mass of LPG consumed (kg)
LHV	Low heating value of LPG (MJ/kg)
Q_{wall}	Kiln wall heat loss (kJ)
A	Area of kiln wall (m²)
ΔT	Temperature difference across the kiln wall (°C)
ΔX	Kiln wall thickness (m)
dt	Time interval
i and *j*	Indices for summation (specific meaning not clearly defined in the text)
Q_{kiln}	Accumulated heat in the kiln (kJ)
m	Mass of insulator (bricks, RHA, WA) in kiln units (kg)
c_p	Specific heat of insulator (kJ/kg·°C)
Q_{stack}	Stack heat loss (kJ)
$\dot{m}$	Air flow rate for the stack (kg/s)
c_{pair}	Specific heat of air through the stack (kJ/kg·°C)
Abbreviations	
LPG	Liquid Petroleum Gas
RHA	Rice Husk Ash
WA	Wood Ash

1. Introduction

Clay bricks are among the most widely used construction materials globally. Approximately 87% of the 1.5 trillion clay bricks produced annually are made in Asia, of which over 20% are produced in South Asia [1, 2]. These bricks are highly valued for their durability [3], thermal insulation properties, and fire resistance. Several studies have reported the thermal conductivity of clay bricks as ranging from 0.6 to 1.0 W/mK [4, 5], while their resistance to fire and adverse weather conditions has been well documented [5-8]. In developing countries, brick production continues to rely predominantly on traditional artisanal and small-scale kilns, using processes which have remained technologically stagnant for decades [9]. Several classifications of brick kilns have been reported [10-12]; of these, intermittent clamp kilns exhibit an efficiency of 10–15% [2], open-top kilns achieve values of 20–30% [13], and downdraft kilns operate with an efficiency of 35–50% [9].

*Corresponding author.
Email address: sopa.c@msu.ac.th
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In Latin America and Asia, where artisanal brickmaking is widespread, energy inefficiency remains a significant challenge [14, 15]. Traditional kilns are typically constructed using clay bricks combined with clay mud [16]; although conventional insulation materials, such as firebricks and refractory cement, provide some thermal protection, they are often inadequate in terms of minimizing energy waste to acceptable levels [13]. The specific energy consumption (SEC) of various kilns has been widely documented. In clamp kilns and other batch kilns in Asia, the SEC ranges from 2.0 to 4.5 MJ/kg of fired brick, with coal consumption varying between 32 and 71 tons per 100,000 bricks [17], while open-top updraft kilns, which primarily use firewood, consume approximately 4–5 MJ/kg of fired brick [18]. In intermittent kilns, where bricks are fired in batches, the SEC reaches a maximum of 3.85–5.35 MJ/kg of fired brick, whereas in downdraft kilns, it is significantly lower, at 2.37 MJ/kg of fired brick [19, 20]. However, traditional kilns suffer from substantial heat loss due to inadequate insulation, leading to excessive fuel consumption, increased operational costs, and environmental degradation [2, 12, 19]. Valdes et al. [12] have reported that to address these challenges, various measures have been implemented to improve the energy efficiency of traditional brick kiln operations, including adding roofs to clamp kilns, insulating kiln walls with mud or biomass residues, and increasing the kiln height. Although moderately effective, these modifications have prompted further research aimed at optimizing energy consumption and minimizing heat loss through improved kiln design [2].

Improving energy efficiency is therefore crucial for brick manufacturers seeking to optimize business operations and sustainability [20-23]. Despite advancements in kiln design, existing insulation methods remain insufficient in regard to reducing the substantial heat loss that occurs during the brick-firing process [6, 20]. Moreover, conventional insulation materials are often costly and resource-intensive, making them impractical for small-scale and artisanal brick manufacturers in developing regions. This gap in extant research and practical solutions highlights the need for low-cost, sustainable alternatives that are both thermally efficient and environmentally friendly. This study explores the potential of rice husk ash (RHA) and wood ash (WA), both of which are byproducts of the brick-firing process, as viable solutions for improving the thermal insulation of brick kilns [24]. These materials, which are widely available and underutilized, offer sustainable and cost-effective alternatives to conventional insulation materials, and can potentially reduce the heat loss and enhance the energy efficiency of brick production [23].

RHA is derived during the milling process from the outer coverings of rice grains, which constitute approximately 20% of the 500 million tons of paddy rice produced globally each year [25]. With a high calorific value of approximately 4000 kcal/kg, rice husks are traditionally used to generate heat for various applications, including small-scale vapor generators and brick kiln firing. During the firing process, RHA is formed as a byproduct and is rich in silica, with a content of between 80% and 95% depending on processing conditions, making it highly resistant to chemical etching and thermal shocks, while its low thermal conductivity enhances its effectiveness as a thermal insulator [23]. Its thermal conductivity ranges from 0.44 to 0.70 W/mK, with a porosity of 65% to 8%, corresponding to an apparent density of 350 to 950 kg/m³ [23, 26]. Similarly, WA, a byproduct of wood combustion in brick kilns, has been shown to improve the porosity of insulating materials, thereby enhancing their heat-retention capabilities [27]. Tibrewal et al. [28] reported the total energy consumption for brick production in India in 2017 with its distribution based on kiln technology and fuel type. Firewood accounted for 18% of the total biomass consumption**,** which amounted to approximately 25 million tons per year (Mt/year). Typically, the ash content from wood combustion ranges between 0.5% and 6% of the original dry weight of the wood [29], meaning that burning one ton (1,000 kg) of dry firewood can produce approximately 5 to 60 kg of wood ash. The thermal conductivity depends on the chemical composition, temperature, and structure of the ash [30]. Muia and Gaitho [31] have reported the thermal conductivity of WA as ranging from 0.03 to 0.068 W/mK, depending on grain size and porosity.

These properties suggest the strong potential of RHA and WA as cost-effective and sustainable alternatives to conventional kiln insulation methods, thereby addressing the urgent need for improved energy efficiency and waste management in brick production. The incorporation of RHA and WA into kiln wall insulation offers significant benefits, not only in terms of energy efficiency but also in environmental sustainability. The use of these waste materials is aligned with the principles of the circular economy, as it repurposes agricultural and industrial byproducts, thereby reducing the environmental burden of waste disposal and conserving natural resources [25]. RHA and WA can enhance the insulation of kilns, which can significantly reduce fuel consumption and lower the overall carbon footprint of brick production [28, 32]. This reduction in energy use also translates into lower operational costs for brick manufacturers, particularly those in small-scale and artisanal operations.

By addressing the problems of environmental degradation and economic inefficiency, the use of RHA and WA offers a viable solution to the challenges associated with traditional brick kiln operations. The application of agricultural residues such as RHA and WA as thermal insulators represents a promising approach to enhancing kiln energy efficiency while contributing to sustainable waste management practices. This study investigates the effectiveness of RHA and WA in reducing heat loss in brick kiln walls, with the aim of providing a sustainable, cost-effective solution for artisanal and small-scale producers facing both economic and environmental challenges.

2. Materials and methods

The methodology involved the selection of materials, the construction of a rectangular downdraft open-top kiln unit, experimental design and testing, as well as laboratory experiments. The experiments included: (1) a sieve analysis, (2) specific gravity testing, (3) a Brunauer–Emmett–Teller (BET) analysis for raw material characterization, (4) water absorption testing, and (5) thermal performance testing of the rectangular downdraft open-top kiln unit.

2.1 Materials

2.1.1 Green and fired bricks

Four-hole green bricks, with dimensions of 6.5 cm in width, 15 cm in length, and 6.5 cm in height, were supplied by Ban Khum Ngoen Brick Enterprise and Thai Pottery Factory in Roi-Et province (N15° 39’ 16” E104° 05’ 55”). These green bricks were produced using a standard extrusion machine. The initial moisture content averaged 7.80% wet basis (w.b.) after natural drying for about 5 days, with an average sample weight of 1 kg per piece. The fired bricks had a bulk density of 1,750 kg/m³ and were of the same type as the green bricks, which were used to construct the rectangular open-top kiln unit.

2.1.2 Wood ash

WA was sourced from Ban Khum Ngoen Brick Enterprise and Thai Pottery Factory, which produce about 100 tons of WA annually from 12,000 tons of firewood.

2.1.3 Rice husk ash

RHA was sourced from an open brick kiln at Red Brick (Noknid Brick Factory) in Changhan District, Roi Et (N16° 13’ 15” E103° 38’ 06”). In this kiln, rice husk was burned at a high temperature, and was the only material used as fuel for the brick-burning process. The RHA collected from the kiln was free of debris, and consisted of particles of varying sizes.

2.2 Rectangular downdraft open-top kiln unit

The rectangular downdraft open-top kiln, adapted from a traditional downdraft kiln with a dome, was previously introduced as a model designed to improve performance and management. This kiln model, developed by Ban Khum Ngoen Brick Enterprise and Thai Pottery Factory, is widely used in brick enterprises across Thailand. Ban Khum Ngoen Brick Enterprise has over 30 years of experience in this industry, and specializes in three main areas: bricks, pottery, and machinery related to clay brick production. For further details of the rectangular downdraft open-top kiln, the reader is referred to Promtow et al. [19]. The kiln was 4 m in width, 8 m in length, and 2.5 m in height, with a total volume of 80 m³. The walls, built with clay bricks and reinforced with muddy clay for strength, had a thickness of 0.45 m to prevent heat loss and cracking at high temperatures. The walls were insulated with mud and clay brick material. The kiln had a capacity of approximately 50,000 to 80,000 clay bricks, depending on the size and type of bricks loaded. The main components of the rectangular downdraft open-top kiln included: (1) a dual burner, (2) a high-pressure blower, (3) kiln walls, (4) a firing room, (5) a temporary door in one of the walls, and (6) chimneys. The firing process was as follows: green bricks were loaded through the temporary door and stacked in rows from bottom to top, leaving spaces between the rows to allow the flow of hot gases. The top layer of bricks was arranged tightly, and sand was applied to the surface to seal it and to prevent the escape of hot air. The temporary door was designed for easy opening and closing during the loading and unloading of bricks.

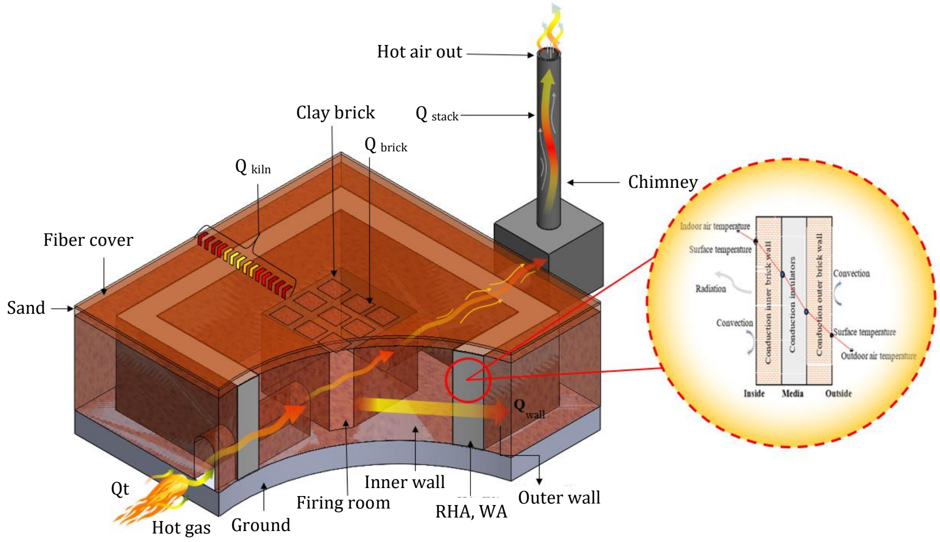

Figure 1 Heat transfer across the composite kiln wall of a regular open-top brick kiln unit.

The rectangular downdraft open-top kiln unit used for testing was a scaled-down version at a ratio of approximately 1:500 with respect to the full-size kiln, as shown in Figure 1. The inner dimensions of the scaled-down kiln were 0.4 m in width, 0.4 m in length, and 0.5 m in height, resulting in a total volume of 0.08 m³. A gas burner was installed at the front of the kiln unit to provide reliable control of fuel and heat. Hot gases naturally flowed into the firing room and exited through a chimney located at the back of the kiln unit. The kiln walls, which were 0.45 m thick, were constructed from clay bricks and bound with muddy clay. The kiln wall unit had extended wall spaces on all four sides, as shown in Table 1, which were filled with RHA and WA media. Heat transfer through the kiln walls and media was assumed to occur only through the side walls via conduction, as the bottom of the kiln was set into a groove in the ground, and the top was covered with a thick layer of sand and fiberglass to prevent heat loss. Heat loss due to convection inside the kiln was compared with the conduction heat loss [33].

2.2.1 Experimental planning and testing

RHA and WA were used as insulation by filling the spaces between the brick walls at distances of 10 cm and 15 cm. The filling method was varied, with three levels of compaction: loose, medium compact, and densely compacted. After filling, the density was calculated to give the values shown in Table 1. Twelve tests were conducted and compared with a control, in which a traditional insulated brick kiln wall was used. Samples of four-hole green bricks (6.5 cm wide, 15 cm long, and 6.5 cm high) were fired for testing in this study.

Table 1 Experiment planning and conditional factors

Run No.	Code	Insulator	Thickness (cm)	Compaction
	Control*	–	–	–
1	10RHAL	RHA	10	Loose
2	10WAL	WA	10	Loose
3	10RHAD	RHA	10	Dense
4	10WAD	WA	10	Dense
5	10RHAM	RHA	10	Moderate
6	10WAM	WA	10	Moderate
7	15RHAL	RHA	15	Loose
8	15WAL	WA	15	Loose
9	15RHAD	RHA	15	Dense
10	15WAD	WA	15	Dense
11	15RHAM	RHA	15	Moderate
12	15WAM	WA	15	Moderate

*: The kiln unit was uninsulated with a 0.45 m thick wall and used as the control.

A preliminary data collection process was conducted three times on the kiln unit, and the data were used to plan the testing of green brick samples for the experiment. Approximately 200 green bricks were placed in the kiln unit, with adequate space to allow heat to circulate throughout the firing chamber. The bricks were arranged using the same technique as in an open-top downdraft brick kiln, with those near the top insulated with sand to retain heat. The temperature of the hot gas was measured using type-K thermocouples at four different points in the kiln: (1) the burner room, (2) the firing room (inner wall), (3) the outer walls of the brick kiln on all four sides, and (4) the chamber exit. The velocity of the exhaust gas was measured with a vane anemometer (Digicon model DA–42). The temperature data were digitized and stored using a multichannel data logger. The brick firing process consisted of three main steps. The initial drying process involved removing moisture by adjusting the gas flow to a rate of 0.10–0.15 kg/h and maintaining a temperature range of 200–250°C. The gas weight and temperature changes were recorded every 30 min over a period of 6 h. Following the drying process, the firing process began, in which the structure of the bricks was altered by increasing the liquid petroleum gas (LPG) flow to a rate of 1.0–1.11 kg/h, giving temperatures of 800–900°C over 8 h. After the firing process, the LPG gas was turned off, and the tempering phase commenced. To prevent a sudden temperature drop, which could damage the structure of the bricks, clay mud was applied to the entrance of the gas burner during the cooling phase. The tempering process lasted 12 h. Once the bottom layer of bricks had reached 250°C, the firing room was opened, and the fired bricks were removed.

2.3 Laboratory experiment and thermal calculation

2.3.1 Sieve analysis test

A sieve analysis for WA and RHA was conducted as specified in ASTM C136 [34]. After drying the media to an air-dry state in the laboratory, the material was sieved, using a series of sieves with apertures of 0.85, 0.425, 0.250, 0.150, and 0.075 mm, to obtain a non-aggregated sample (<0.25 mm) [35].

2.3.2 Specific gravity and porosity

A specific gravity test for both WA and RHA were performed in accordance with ASTM D854 [36], and porosity was characterized via a BET analysis using a Micrometrics TriStar II Plus to determine the surface area, volume, and porosity of the particles.

2.3.3 Water absorption

Water absorption of the final fired bricks was evaluated in accordance with ASTM C67-07. Bricks were first dried in an oven at 105°C for 24 h, and the dry weight (W_d) was obtained. They were then immersed in water for a further 24 h and the saturated wet weight (W_s) was measured. The amount of water absorbed (W_a) by the brick was subsequently calculated as shown in Equation (1) [37]. An average value was calculated for five bricks.

$$W_a = \frac{W_s - W_d}{W_d} x100 \quad (1)$$

2.3.4 Thermal heat calculation

The thermal conductivity and specific heat of the fired bricks (kiln wall unit), RHA, and WA are shown in Figure 2, and were used to evaluate the heat loss of the brick kiln unit. The kiln unit was constructed with clay bricks, with improved insulation provided by the addition of RHA and WA (see details in Figure 1). This research focuses on the factors outlined in Table 1, although the thermal conductivity may be influenced by a number of other factors, including composition, particle size and distribution, density and porosity, compaction, moisture content, temperature, impurities, and heat treatment. In this case, the heat loss through the brick kiln walls was primarily determined based on the temperature under each condition.

The thermal conductivity of composite materials can be calculated using a series model. For materials arranged in series (layered one after another), the overall thermal conductivity (k_T) is obtained as shown in Equation (2) [38].

$$\frac{L_T}{k_T} = \sum_{n=1}^{n}\left(\frac{L_i}{k_i}\right) \quad (2)$$

where L_T is the total thickness of the composite material, k_T is the overall thermal conductivity of the composite material, L_i and k_i are the thickness and thermal conductivity of the i-th layer, respectively, and n represents the number of layers in the composite material.

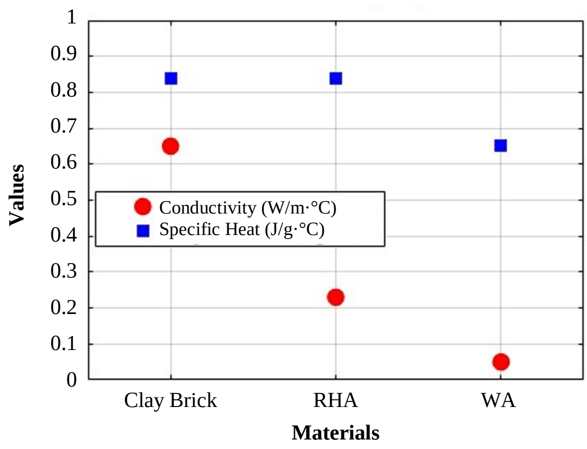

Figure 2 Values of the thermal conductivity and specific heat for the insulators considered in this research [23, 26, 31, 39].

(1) Total heat energy

The total energy consumption of LPG in the brick kiln unit (Q_t) is determined by the total mass of LPG consumed during each brick firing process, as shown in Equation (3) [10].

$$Q_t = m_f \times LHV \tag{3}$$

where Q_t is the total heat energy consumed (MJ), m_f is the mass of LPG consumed (kg), and LHV is the low heating value of LPG, which is 46.1 MJ/kg.

(2) Heat loss through the kiln wall

The energy lost through the kiln wall (Q_{wall}) is obtained based on the difference in temperature between the inner and outer surfaces of the kiln wall, as given by Equation (4) [38].

$$Q_{wall} = \sum_{i=1}^{n} \left[\sum_{t=1}^{j} \left(A k_T \frac{\Delta T}{\Delta X} dt \right)_t \right]_i \tag{4}$$

where Q_{wall} is the heat loss through the kiln wall (kJ), A is the area of the kiln wall (m²), k_T is the overall thermal conductivity of the kiln wall (W/m·°C), ΔT is the temperature difference across the kiln wall (°C) at each time interval dt, ΔX is the thickness of the kiln wall (m), t is the time step over the range considered, and i represents the specific wall sections. j represents the time intervals over which the heat loss is measured. The total heat loss through the kiln walls is calculated by summing the energy lost through each wall section (i) and over the entire duration of the firing process (j). The temperature difference ΔT is averaged over each time period using the formula $\left[\frac{T_j + T_{j+1}}{2}\right]$, where T_j and T_{j+1} are the temperatures at successive time intervals.

(3) Accumulated heat of the kiln

The amount of heat accumulated in the kiln during the firing process represents the heat absorbed by the structural materials of the brick kiln, from the beginning of the firing process until completion. The accumulated heat (Q_{kiln}) is calculated as shown in Equation (5) [10].

$$Q_{kiln} = \sum_{i=1}^{n} \left(m c_p \Delta T \right)_i \tag{5}$$

where Q_{kiln} is the total accumulated heat in the kiln (kJ), m is the mass of the insulators (bricks, RHA, WA) within the kiln unit (kg), c_p is the specific heat capacity of the insulators (kJ/kg·°C), and ΔT is the difference between the initial temperature of the material at the start of the process and the maximum temperature reached during the brick firing process (°C).

(4) Stack heat loss through the chimney stack

The heat loss through the chimney stack was calculated based on the temperature and flow rate of the air exiting the chimney during the firing process, continuing until the end of the firing process. The temperature was averaged over each time period by taking the mean of successive temperature measurements. The heat loss is calculated using Equation (6) [10]:

$$Q_{stack} = \sum_{t=1}^{i} \dot{m} c_p \Delta T dt \tag{6}$$

where Q_{stack} is the heat loss through the stack (kJ), $\dot{m}$ is the mass flow rate of air through the stack (kg/s), ΔT is the difference between the airflow temperature and the ambient temperature outside the stack (°C), c_p is the specific heat capacity of the air passing through the stack (kJ/kg·°C), and dt represents the time interval over which the measurements are taken.

(5) Heat transferred to bricks

The heat energy transferred to the bricks is calculated as the difference between the heat energy from the total firewood used during the firing process and the total heat energy lost during the firing process, as given in Equation (7).

$$Q_{brick} = Q_t - (Q_{wall} + Q_{kiln} + Q_{stack}) \tag{7}$$

3. Results and discussion

3.1 Physical properties of RHA and WA

Table 2 and Figure 3 show the results for the particle size distribution and key physical properties of RHA and WA, obtained from a brick kiln. These values are consistent with findings from prior studies. In this study, both materials were sieved in accordance with ASTM C136 [33], yielding mean particle sizes of 0.35 mm for RHA and 0.24 mm for WA, and bulk densities of 351.32 kg/m³ and 925.93 kg/m³, respectively. Their specific gravities were measured as 2.349 for RHA and 2.594 for WA, values that align well with their corresponding bulk densities.

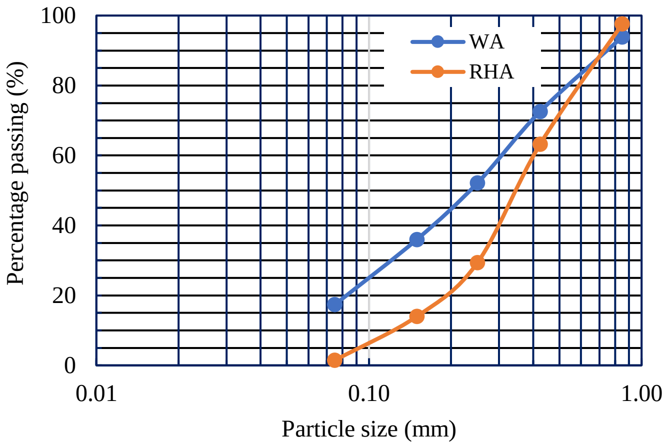

Figure 3 Particle size distributions for RHA and WA.

The higher density of WA is likely to be due to residual soil and sand contamination from firewood combustion directly on earthen surfaces, an observation that is consistent with other studies involving open-burning processes [23]. De Silva and Perera [25] reported similar values for the particle size and bulk density for RHA (0.32 mm and 380 kg/m³), whereas Raheem et al. [27] found WA particle sizes in the range 0.20–0.30 mm and bulk densities of 900–960 kg/m³, all of which are in agreement with our findings. These physical parameters, especially the bulk density and particle size, play a critical role in thermal conductivity, as they influence the ability of the material to retain heat when used as insulation in brick kilns.

One important aspect is that RHA has a high silica content, typically ranging from 80% to 95%, of which a substantial fraction exists in the amorphous (reactive) form. This reactive silica, confirmed by De Silva and Perera [25] and Gonçalves and Bergmann [23], is known to possess low thermal conductivity and high thermal stability, enabling efficient heat retention and resistance to thermal shock at elevated temperatures. Its porous microstructure and relatively high BET surface area (6.115 m²/g in this study) further contribute to its insulating effectiveness by trapping air and limiting conductive heat transfer. WA is composed mainly of metal oxides and carbonates, and has even lower thermal conductivity values, reported as being between 0.03 and 0.068 W/mK [31]. Its fine particle size and granular morphology allow it to achieve dense compaction within wall cavities, thereby limiting thermal bridging and improving insulation. The measured BET surface area of WA was 33.850 m²/g, with a pore volume of 0.03691 cm³/g, indicating its high capacity for heat retention.

Table 2 Characteristics of RHA and WA

Sieve size (mm)	Percentage passing (%)	
	RHA	WA
0.850	97.61	93.88
0.425	63.29	72.61
0.250	29.36	52.13
0.150	14.01	36.02
0.075	1.46	17.39
Pan	0	0
Physical property		
Bulk density* ($kg.m^{-3}$)	351.32	925.93
Specific gravity (-)	2.349	2.594
Mean particle size (mm)	0.35	0.24
BET surface area (m^2/g)	6.115	33.850
Pore volume (cm^3/g)	0.01159	0.03691
Porosity (%)	61.071	45.273

* Loosely packed in cylinders of 200 cm^3 volume, 5 cm diameter with five replicates.

In terms of environmental performance, both RHA and WA offer significant advantages. Their reuse as insulation materials supports the principles of the circular economy by valorizing biomass combustion waste, thus reducing the demand for high-emission construction materials such as cement, ceramic fiber, or firebricks. According to Andreola et al. [32] and Gonçalves and Bergmann [23], the integration of RHA into construction applications can substantially offset carbon dioxide emissions by acting as a substitute for cementitious or mined insulators. A life cycle assessment (LCA) conducted by De Silva and Perera [25] demonstrated that clay bricks incorporating RHA achieved a 15–25% reduction in overall carbon footprint compared to conventional fired bricks without recycled content. Although full LCAs of WA are limited, its potential to contribute to emission savings is supported by Raheem et al. [27], who found that the use of WA used in masonry products improves thermal efficiency and indirectly reduces fuel consumption. Since both materials are generated on site in brick kilns, their reuse eliminates transport emissions and disposal burdens, further reinforcing their environmental advantages.

In summary, the physical properties of RHA and WA, such as their particle size, bulk density, porosity, and surface area, directly contribute to their thermal performance. Coupled with their environmental benefits and widespread availability, these materials offer a viable, low-cost, and sustainable insulation solution for brick kiln operations [25, 27].

3.2 Firing temperature behavior and heat loss

The principles of heat transfer, and specifically Fourier's law of heat conduction, mean that as the temperature difference between the inside and the outside of the kiln wall becomes higher, the rate of heat loss becomes greater. According to this law, the rate of heat transfer through a material is proportional to the temperature difference across the material and its thermal conductivity, and is inversely proportional to the thickness of the material, as shown in Equation (4). A higher temperature difference therefore results in a higher rate of heat transfer, meaning that more heat is lost through the kiln walls. Conversely, a lower temperature difference results in less heat loss. When the fuel combustion rate is increased to 1.0–1.11 kg/h, as shown in Figure 3, the increase in temperature during brick firing causes changes in the structure of compounds in the clay. At around 300–600°C, organic materials present in the clay decompose, which may affect the color and strength of the brick. Over the temperature range 400–900°C, any remaining organic materials and iron compounds oxidize. This step can change the color of the bricks, often turning them red due to the formation of iron oxides.

Figures 4a and 4b show the temperature changes for WA insulators at thicknesses of 10 cm and 15 cm, respectively. At a thickness of 15 cm with loose compaction, a lower temperature was found than for moderate and dense compaction, due to the higher rate of heat loss through the kiln wall. The maximum temperatures for loose, moderate, and dense compaction of WA at a wall thickness of 15 cm were 532°C, 561°C, and 597°C, respectively. Figures 3c and 3d show the temperature changes for RHA insulators, which behaved similarly to WA. The maximum temperatures for loose, moderate, and dense compaction of RHA at a wall thickness of 15 cm were between 576°C and 648°C. Hence, the heat stored in a brick kiln increases as the thickness of the insulation wall increases and becomes more densely compacted. RHA retains heat less effectively than WA due to its higher thermal conductivity, as reflected in the heat energy values shown in Figure 4.

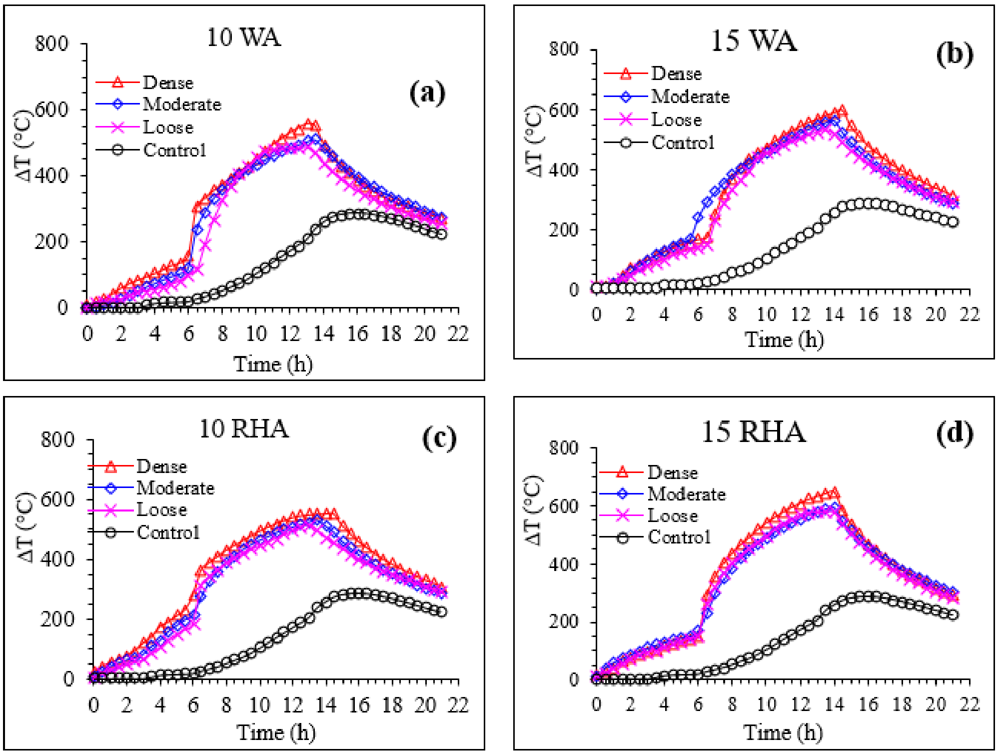

Figure 4 Differences in firing temperature between the inner and outer kiln walls under varying conditions.

Figure 5 shows the total heat loss through the brick kiln wall unit in each condition compared with the control. The total heat loss through the four side walls of the brick kiln was calculated using Equation (4). The total thermal conductivity was determined based on the data in Figure 2 and Equation (2), along with the differences in temperature across the brick kiln wall as shown in Figure 4. It was found that under each condition, adding insulation reduced the heat loss through the wall compared to the control (97.47 MJ). The use of RHA insulation resulted in a higher heat loss than WA insulation due to differences in physical characteristics (as shown in Table 2) and the higher thermal conductivity of RHA compared to WA. This disparity led to greater heat loss in RHA-insulated kilns. Compaction of each of the insulating materials (RHA and WA) resulted in slightly different heat losses: the heat losses for 10RHA and 10WA insulation ranged from 62.55 to 70.88 MJ and 26.11 to 31.03 MJ, respectively. As the thickness of the insulating wall increased, the heat loss decreased, since the rate of heat transfer through a material is proportional to the temperature difference across it and inversely proportional to its thickness [40].

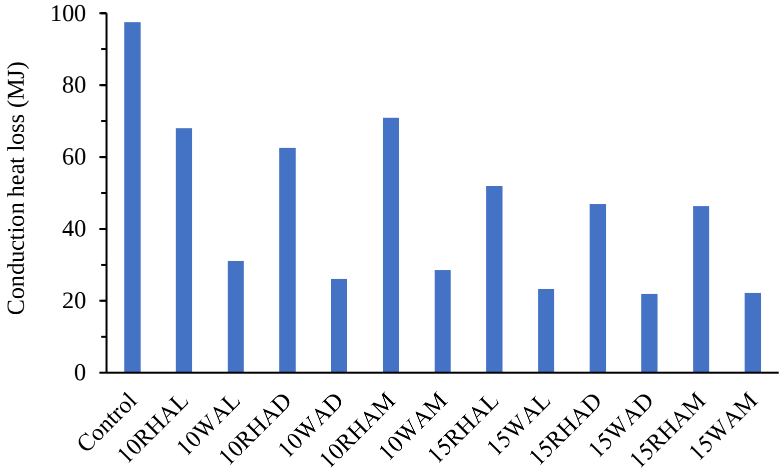

Figure 5 Total heat loss through the walls of the brick kiln unit under each condition.

For 15RHA and 15WA, the heat loss values ranged from 46.28 to 51.98 MJ and 21.87 to 23.24 MJ, respectively, with no statistically significant difference. Increasing the wall thickness to 15 cm resulted in a lower rate of heat loss compared to the 10 cm wall. The minimum value for the conduction heat loss was observed under the 15WA condition. In addition, 15WAL yielded superior thermal efficiency and cost-effectiveness, since a minimal quantity of WA was required as an insulating wall, making it a practical and efficient choice for improving kiln insulation.

The results from a comparison of heat loss between RHA and WA in this study are also supported those of previous research. In line with findings reported by Raheem et al. [27], the lower thermal conductivity of WA contributed to reduced heat loss when used as an insulator in the kiln. The level of compaction also influenced the thermal performance, with dense compaction resulting in lower heat loss compared to lose compaction for both RHA and WA. The 15 cm thick wall with dense WA insulation exhibited the lowest heat loss, confirming the effectiveness of WA as a superior insulator compared to RHA. Thus, the physical properties and heat insulation capabilities of RHA and WA obtained in this study are consistent with existing research, further validating the potential of these materials as cost-effective and sustainable alternatives for improving brick kiln insulation [23, 25, 27].

3.3 Improvement in heat utilization of the brick kiln

Table 3 compares the heat distribution in industrial-scale brick kilns, including the control unit and the 15WAL condition, and it can be seen that there is an improvement in thermal efficiency, as shown in Figure 6. A significant amount of firewood (approximately 10 tons per batch) was used in the industrial-scale kiln, which involved the conversion of 114,843 MJ of energy. In comparison, the control unit and 15WAL consumed 617.70 MJ and 487.17 MJ of LPG, respectively. Heat accumulation and heat loss were critical factors influencing the efficiency of thermal insulators [28]. This finding suggests that higher heat accumulation and lower conductivity heat loss contribute to improved thermal efficiency in brick kilns. The heat source balance is shown in Figure 6, where the values for the thermal efficiency of the industrial-scale brick kiln, control unit, and 15WAL condition were 39.33%, 43.63%, and 54.42%, respectively. This demonstrates that adding insulation resulted in an increase in the heat transferred to the bricks, with an increase from 39.33% to 54.42%. In other words, the insulation improved the thermal efficiency of the brick kiln by 15.09% compared to the uninsulated kiln.

Table 3 Comparison of heat kilns in an industrial-scale setting

Heat kiln (MJ)	**Condition**		
	Industrial-scale	**Control**	**15WAL**
Q_t	114,843.60	617.70	487.17
Q_{kiln}	43083.21	243.19	201.85
Q_{wall}	19893.54	97.39	23.24
Q_{stack}	6695.38	7.59	5.45
Q_{brick}	45171.47	269.53	265.11

The reuse of RHA and WA reduces landfill waste and mitigates the need for virgin insulation materials, thereby contributing to meeting the objectives of the circular economy. The substitution of conventional insulation with RHA/WA can indirectly lower the carbon footprint by reducing total fuel demand. A 15.09% improvement in thermal efficiency translates into a proportional reduction in CO_2 emissions, assuming constant fuel characteristics; this gives a potential reduction of up to 750 kg of CO_2 annually for small-scale kilns using firewood, as estimated by Weyant et al. [2] and Prasertsan et al. [18].

However, when evaluating the economic implications of using WA insulation in an industrial-scale brick kiln with a capacity of 40 m³ (dimensions: width 4 m × length 4 m × height 2.5 m), several key parameters must be considered. The kiln is designed to accommodate approximately 50,000 green clay bricks per batch, although this number may vary depending on the size, type, and stacking configuration of the bricks. Table 4 provides a practical breakdown of the associated expenses, particularly those arising from the construction of a double-layer kiln wall and the filling of the insulation gap with WA. The total volume of the external kiln wall is 5.81 m³, corresponding to 3,817 standard-sized bricks. The insulation gap to be filled with WA has a volume of 5.60 m³, translating to a total WA mass of 5,187.52 kg, based on a bulk density of 925.93 kg/m³. This high density is attributed to the presence of soil and sand particles accumulated from the combustion zone of the kiln. The material cost of the outer wall bricks amounts to 578.34 USD, whereas as a combustion byproduct, WA is classified as a low-cost waste material. However, the collection, transportation, and handling of WA incur associated costs, with the total material valued at 78.60 USD, corresponding to approximately 0.0152 USD per kilogram. The labor costs for installing the insulation were calculated as 20% of the material costs, giving a value of 131.39 USD. In total, the extended construction cost of the insulation system amounted to 867.16 USD, inclusive of materials and labor.

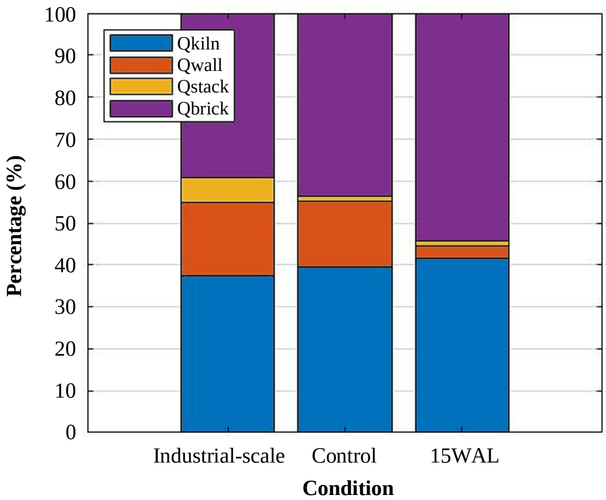

Figure 6 Percentage of heat energy in a brick kiln and efficiency improvement with insulation.

Table 4 Cost of investment for insulation in an industrial-scale brick kiln with a capacity of 40 m^3

Item	Units	Quantity
Brick production capacity	pieces	50,000
Outer wall volume	m^3	5.81
Number of bricks (wall construction)	pieces	3,817
Insulation fill volume	m^3	5.60
Weight of WA (insulation)	kg	5,187.52
Total brick cost (outer wall)	USD	578.34
Cost of WA	USD	78.60
Labor cost (20% of material cost)	USD	131.39
Annual maintenance cost (10%)	USD	78.83
Total extended insulation cost	USD	867.16
Fuelwood		
Fuel consumption per batch	kg/batch	9,455.00
Fuel price	USD/ton	25.76
Kiln operation frequency	batches/year	16
Annual fuel cost (traditional kiln)	USD	3,896.61
Annual fuel savings (15.09%)	USD	588.00
Economic evaluation		
Payback period	years	1.47
Equivalent to	batches	~20
Unit cost: Improved kiln (with WA)	USD/brick	0.00414
Unit cost: Traditional kiln	USD/brick	0.00487

Note: 1 USD equals 33 THB.

In practice, a kiln of this type only operates for approximately eight months per year, due to limitations such as the availability of labor and insufficient drying space during the rainy season. Consequently, the operational schedule consists of 16 firing batches per year. Each production cycle involves roughly one week of drying and two days of firing, followed by a cooling period before the bricks are sold. An increase in production frequency could expedite the return on investment. The addition of WA insulation improves thermal efficiency by 15.09%. Each firing cycle consumes approximately 9,455 kg of firewood, priced at 25.76 USD per ton, resulting in an annual fuel cost of 3,896.61 USD. With improved insulation, annual fuel savings are estimated as 588.00 USD. Fluctuations in fuel price are a significant determinant of the payback period; since firewood is in high demand for competing industries (e.g., biomass power plants and industrial stoves), its market price can range from 22.73 to 30.30 USD per ton. Furthermore, long-term operation of the insulated kiln requires consideration of maintenance costs due to the potential for wall cracking or degradation of the insulation ash. These risks will necessitate periodic repairs. An annual maintenance cost of 78.83 USD (equivalent to 10% of the initial material cost) was therefore incorporated into the analysis.

Based on these parameters, the payback period is estimated as 1.47 years, or approximately 20 firing cycles. This value may vary depending on factors such as the fuel quality, firing volume, and operational management practices [23]. The added cost of insulation represents approximately 16% of the overall capital investment for a kiln of this capacity. Since the installation of insulation is a one-time capital expense, while fuel and maintenance are recurring costs, the economic advantage of WA insulation becomes increasingly significant over time. Although a WA-insulated kiln yields immediate per-batch fuel savings, reducing the energy cost per brick from 0.00487 USD (traditional kiln) to 0.00414 USD (WA-insulated kiln), the full economic benefit is realized only after the payback period is complete; the total unit cost then becomes significantly lower, confirming the long-term cost-effectiveness and operational efficiency of WA insulation for small-scale brick kiln enterprises. This study clearly demonstrates the potential for favorable return on investment through the use of WA as a sustainable insulation material.

The results obtained from the scaled-down downdraft open-top kiln considered here can be reasonably extrapolated to full-scale traditional brick kilns, particularly in Southeast Asia, where similar kiln geometries, construction materials, and fuel sources are used. Brick kilns in these regions are often rectangular or dome-shaped, with wall thicknesses ranging from 30 to 50 cm and with firing capacities of 40,000 to 80,000 bricks per cycle. The rectangular downdraft open-top kiln used in this study reflects a common design in northeastern Thailand and neighboring countries, including Cambodia, Laos, and Vietnam [19].

In geographical regions with different climatic conditions, such as colder temperate zones or high-humidity coastal areas, the thermal behavior of the kiln may vary due to differences in ambient temperature gradients and moisture loss rates. However, the thermal insulation principles demonstrated here, such as the effectiveness of low-conductivity and high-porosity materials such as WA and RHA, remain valid. In colder climates, the benefit of insulation may be even more pronounced, as the greater temperature differential between the kiln interior and the environment increases the conductive heat loss. In high-altitude or arid regions where WA is abundantly available from biomass fuel, WA-based insulation can be particularly cost-effective and locally sourced.

Hence, while regional adaptation may necessitate minor modifications in kiln structure or operation, the core principles of insulation performance, energy efficiency, and cost-effectiveness demonstrated in this study remain broadly applicable to diverse geographical and climatic settings [32].

4. Conclusion

This study confirms that RHA and WA are viable, cost-effective alternatives to conventional kiln insulation materials, particularly for artisanal and small-scale brick production. WA demonstrated superior thermal performance, with loose compaction in a gap of 15 cm thickness (15WAL) achieving the highest temperature retention and lowest heat loss. The application of WA insulation improved thermal efficiency by 15.09% and reduced annual fuel consumption by 588 USD. A comparative analysis showed a decrease in unit production cost from 0.00487 USD/brick (traditional) to 0.00414 USD/brick (WA-insulated), with a payback period of 1.47 years.

In addition to energy savings, the environmental benefits are substantial. The reuse of RHA and WA diverts biomass waste from landfills, replaces high-emission insulating materials, and can reduce carbon emissions from small-scale kilns by up to 750 kg/year. These outcomes follow the principles of the circular economy and support low-carbon development targets. Furthermore, the findings are scalable to full-size kilns and are adaptable to various climatic regions, reinforcing their applicability in Southeast Asia and beyond. In conclusion, RHA and WA represent practical, scalable solutions for improving the thermal efficiency and sustainability of brick kiln operations, and offer economic and environmental advantages that support their widespread adoption.

5. Acknowledgments

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