Scientific Research Publishing

Journal of Sustainable Bioenergy Systems, 2026, 16(3), 70-83
https://www.scirp.org/journal/jsbs
ISSN Online: 2165-4018
ISSN Print: 2165-400X

Experimental Investigation of Thermal Energy Storage Using Inert Materials for Enhancing the Energy Performance of Biomass Cookstoves: Influence of Cooking Pot Size

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How to cite this paper: Sawadogo, G.L., Ouedraogo, D., Gounkaou, Y.W., Sana, A. and Igo, S.W. (2026) Experimental Investigation of Thermal Energy Storage Using Inert Materials for Enhancing the Energy Performance of Biomass Cookstoves: Influence of Cooking Pot Size. *Journal of Sustainable Bioenergy Systems*, **16**, 70-83.
https://doi.org/10.4236/jsbs.2026.163004

Received: June 22, 2026
Accepted: August 11, 2026
Published: August 14, 2026

Abstract

This study builds upon previous work on the thermo-energy optimization of improved biomass cookstoves. It analyzes the impact of thermal storage using inert materials on the thermo-energy performance of improved biomass cookstoves operating on charcoal. The main objective is to evaluate the effect of integrating materials with high thermal inertia, particularly granite and clay, on overall energy efficiency and the reduction of heat losses. Experiments were conducted according to the Water Boiling Test (WBT) protocol using two pot sizes (number 2 and number 3). The thermo-physical properties of the adobe bricks used in the cookstove construction were also characterized to assess their heat storage capacity. The results show that the addition of inert materials significantly improves the energy stored in the bricks and clay, promoting a gradual release of heat and better thermal stability. The overall thermal efficiencies obtained with the charcoal + inert material mixture reached 31.26% ± 0.81% for pot size 2 and 32.90% ± 0.66% for pot size 3, compared to approximately 14.5% with charcoal alone. The integration of inert materials thus reduces heat loss, improves energy efficiency, and decreases fuel consumption. These results confirm the potential of integrated thermal storage in improved cookstoves as a sustainable solution for domestic cooking in sub-Saharan Africa.

Keywords

Storage, Thermal, Energy, Overall Efficiency, Granite

1. Introduction

The use of wood fuels and charcoal for domestic cooking remains widespread in developing countries, particularly in sub-Saharan Africa, due to their accessibility and low cost [1]-[4]. However, the use of traditional stoves is characterized by low thermal efficiencies (5% - 15%), high biomass consumption, and significant pollutant emissions, with direct impacts on health and the environment. The work of Jetter and Kariher (2009) and Sutar *et al.* (2015) has shown that improving biomass stoves is an effective solution for reducing energy losses and harmful emissions [5] [6]. More recently, several authors have demonstrated that the thermal and energy performance of stoves is highly dependent on the geometry of the combustion chamber, the type of fuel, the air supply conditions, and the thermophysical properties of the constituent materials. Mengsi Deng *et al.* (2023) synthesized these parameters and showed that thermal insulation and material selection are among the most decisive factors in improving efficiency [7]. Similarly, Boafo *et al.* (2013) showed that the combustion chamber material directly influences specific fuel consumption and thermal efficiency, with ceramic materials exhibiting the best performance due to their high thermal inertia [8]. The present work follows directly from our previous research. In an initial study dedicated to the comparative analysis of the thermal performance of improved cookstoves using charcoal and wood as a function of pot size, we highlighted the significant effect of the container diameter on heat transfer, boiling time, and efficiency during the different phases [9]. These results showed that adapting the cookstove geometry to the pot size optimizes heat exchange between the hot gases and the bottom of the container. In a second study on improving the energy efficiency of cooking stoves through the integration of inert materials: a comparative experimental study, we observed that the addition of bricks and clay reduced heat loss, increased heat retention time, and improved the thermal stability of the system [10]. These observations are consistent with the findings of Yunusa *et al.* (2023), Aier *et al.* (2024), and Mengsi Deng *et al.* (2023), who emphasize the crucial role of sensible heat storage in modern improved stoves [7] [11] [12].

Within this framework, the present study aims to analyze the contribution of thermal storage using inert materials to improving the energy performance of biomass cookstoves, simultaneously considering the type of fuel, the size of the cooking pot, and the energy stored in the bricks and clay. This approach is also supported by recent studies highlighting the importance of sensible heat storage and refractory materials for improving the thermal performance of biomass cookstoves. Rathore *et al.* (2022) [13] demonstrated the significant contribution of heat storage to cooking efficiency, while Mengsi Deng *et al.* (2023) [7] identified thermal storage and material selection as key design parameters for next-generation biomass cookstoves.

The central hypothesis is that the heat stored in inert materials during the combustion phase can be gradually released during low-power and simmering phases, thus reducing fuel consumption, increasing overall thermal efficiency, and improving cooking comfort. The results obtained will contribute to the optimization of high-performance, energy-efficient domestic cookstoves adapted to the realities of the Sahel.

2. Material and Methods

2.1. Materials

The experiments were conducted with the following equipment:

- An improved charcoal stove, designed for use with charcoal and adapted for thermal performance testing;
- A quantity of charcoal and inert materials, such as granite, is placed in the combustion chamber to improve thermal inertia and the gradual diffusion of heat;
- Two metal pans, sizes 2 and 3, used for the comparative evaluation of the stove's thermoenergetic performance;
- The size 2 and 3 cookings pots, commonly used in domestic culinary practices;
- In Burkina Faso, have respective diameters of 24 cm and 27 cm, corresponding;
- to nominal capacities of 3 L and 4 L [14];
- Water, used as the test fluid according to the Water Boiling Point (WBT) test protocol;
- Each test was repeated three times to ensure the reproducibility of the results. The values presented are the experimental averages. Temperatures were measured using an infrared thermometer with an accuracy of ±0.5˚C, and masses were determined using an electronic balance with an accuracy of ±0.01 kg (**Figure 1**);
- A stopwatch, allowing for the precise measurement of boiling time and the different cooking phases;
- A metal tray, used to hold the charcoal and inert materials during the tests;
- A device for measuring ambient conditions, to record the outside temperature during the tests (**Figure 2**).

Figure 1. Fuels used: (a) coal combined with inert material; (b) coal alone.

Figure 2. Experimental setup with charcoal combined with an inert material (granite).

✓ **Characterization of adobe bricks**

The materials used to characterize our bricks manufactured for the construction of the hearth are described below. The objective of this study is to determine the main thermo-physical properties of the adobe bricks used for the construction of the hearth, in order to evaluate their capacity for heat storage and transmission in improved hearth applications. The parameters studied are density, thermal conductivity, thermal diffusivity, and specific heat capacity.

✓ **Materials used for the characterization of adobe bricks**

- The thermal characterization of the bricks was carried out at the Laboratory of Chemistry and Renewable Energies (LaCER) of Nazi Boni University in Bobo-Dioulasso. The equipment used for this study included:
- A hot-wire probe, used to measure the thermal conductivity of the samples; A hot-wire ring probe used to determine thermal diffusivity;
- A computer for acquiring, processing, and displaying the experimental data. The hot-wire method was chosen because of its reliability and widespread use for the thermal characterization of porous building materials such as adobe bricks. Figure 3(a) and Figure 3(b) show the hot-wire probe and the hot-wire ring probe,
- respectively. The complete experimental setup used for the measurements is illustrated in Figure 3(c).

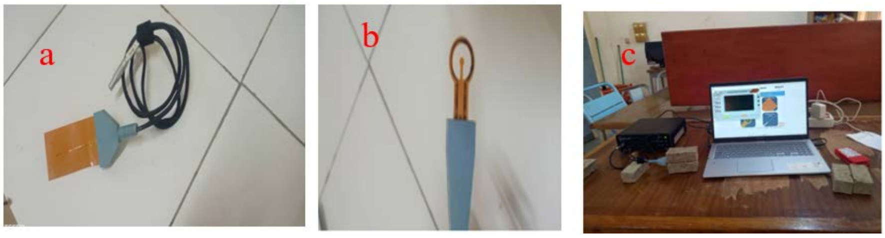

Figure 3. Materials used for brick characterization: (a) hot wire probe; (b) hot ring probe; (c) final measurement.

2.2. Methods

Several tests were carried out with 0.45 kg of charcoal and 0.45 kg of granite. The tests were performed with water masses of 3 kg and 4 kg respectively, in size 2 and 3 pots. Table 1 shows the total mass of bricks and clay used.

Table 1. Mass of brick and clay used.

Mass of a brick	Number of bricks	Total mass of brick (en kg)	Mass of clay used (kg)
1.8	21	37.8	34

We report in Table 2 the heat capacity of granite and the latent heat used.

Table 2. The heat capacity of granite and the latent heat.

Heat capacity of granite (J/kg·K)	799 [15]
latent heat of vaporization of water (kJ/kg)	2260 [16]

Equations (1)-(4) respectively calculate Heat storage by brick, Heat storage by clay, Heat storage using inert materials (granite) and the total thermal efficiency.

✓ **Heat storage by brick**

It is given by relation (1) [13] by:

$$Q_B = n \times M_B \times C_p \times \left(T_{fB} - T_{iB}\right) \tag{1}$$

✓ **Heat storage by clay**

This is the heat stored by the clay within the hearth. It is calculated using the following Equation (2) [13]:

$$Q_{ar} = M_{ar} \times C_p \times \left(T_{ff} - T_{if}\right) \tag{2}$$

✓ **Heat storage using inert materials (granite)**

It is expressed by the following relation (3) [13]:

$$Q_C = C_{pc} \times M_c \times \left(T_{cf} - T_{ci}\right) \tag{3}$$

✓ **Total thermal efficiency**

The total efficiency (η_t) is the ratio between the amount of heat received, estimated from measurements of the amount of water evaporated, and the total amount of heat produced by the combustion of the fuel during the boiling and simmering phases. It is expressed by the following Equation (4) [17] [18]:

$$\eta_t = \frac{\left[M_i(T_{ébl} - T_i) + M_i^{mj}(T_{fmj} - T_{imj})\right]C_{pe} + \left(M_{ev}^{ébl} + M_{ev}^{mj}\right)L_v}{\left(M_b^{ébl} + M_b^{mj}\right)PCI} \tag{4}$$

3. Results and Discussion

Table 3 shows the results of our experiments on characterization.

Table 3. Thermo-physical properties of construction materials.

Density ρ (kg·m^{-3})	Thermal diffusivity α (m^2·s^{-1})	Thermal conductivity λ (W·m^{-1}·K^{-1})	Specific heat capacity C_p (J·kg^{-1}·K^{-1})
1774.4940	3.32×10^{-7}	0.832	1412.25

The measured density, on the order of 1774.4940 kg·m^{-3}, indicates that the studied bricks have a relatively compact structure, characteristic of slightly or moderately lightweight adobes. This value is slightly closer to that reported by Čáchová*et al.* [19], who found a density of 1880 kg·m^{-3} for dried clay bricks. This density gives the material good mechanical strength, which is advantageous for use in fireplaces. The thermal conductivity obtained (0.832 W·m^{-1}·K^{-1}) is higher than that generally observed for highly fibrous or lightweight adobes, whose conductivity typically varies between 0.4 and 0.6 W·m^{-1}·K^{-1} [20]. This value reflects a moderate heat transfer capacity, suitable for fireplace applications where the objective is not only thermal insulation but also controlled heat diffusion. The relatively low thermal diffusivity indicates that heat spreads slowly within the material. This property is particularly advantageous for fireplaces, as it limits sudden temperature fluctuations and contributes to greater thermal stability during operation. The specific heat capacity, estimated at approximately 1412.25 J·kg^{-1}·K^{-1}, demonstrates that these bricks possess good thermal storage capabilities. Compared to industrial refractory bricks, whose specific heat capacity is often between 800 and 1100 J·kg^{-1}·K^{-1} [21], the studied adobes exhibit a higher heat storage capacity, although their resistance to very high temperatures is lower. **Table 2** presents the meteorological conditions.

Table 4. Weather conditions for conducting the tests.

External conditions	Cold start	Hot start	Simmering
	For the pot size 2		
Ambiantes Temperatures (˚C)	27.2	27.1	26.7
	For the pot size 3		
Ambiantes Temperature (˚C)	27.2	26.4	25.9

Table 4 presents the different energy storage methods used by bricks and clays in the two improved stoves. These materials have an average thermal capacity, allowing the stoves to retain heat without transfer by conduction to the outside.

Table 5. Energy values stored in materials.

Fuels	Stored energy from bricks (kJ)	Stored energy from clays (kJ)
	For the pot	**size 2**
Coal + inert material	3293.512 ± 125.4	3058.651 ± 79.8
Coal	1572.455 ± 95.83	1460.323 ± 79.25
	For the pot	**size 3**
Coal + inert material	4141.457 ± 157.46	3725.12 ± 96.9
Coal	2543.702 ± 128.26	2287.986 ± 96.36

Table 5 highlights the influence of fuel and the addition of inert material on the energy stored in the bricks and clay for different sizes of cooking pots. The results

clearly show that using a mixture of coal and inert material leads to a significant increase in stored energy compared to using coal alone. This difference reflects an improvement in the overall thermal properties of the system, particularly the heat capacity and thermal inertia of the materials. For size 2 cooking pots, the energy stored in the bricks reaches 3293.512 kJ with the coal and inert material mixture, compared to only 1572.455 kJ with coal alone. This increase of over 100% demonstrates that adding an inert material promotes the accumulation and retention of heat within the cooking pot structure. Similarly, in the clay, the stored energy increases from 1460.323 kJ to 3058.651 kJ. These results indicate that the inert material acts as a thermal reservoir capable of limiting energy loss to the outside. For the size 3 pot, the same behavior is observed. The energy stored in the bricks increases from 2543.702 kJ to 4141.457 kJ when the inert material is added. In the clay, the values increase from 2287.986 kJ to 3725.12 kJ. This improvement confirms that inert materials increase the thermal storage efficiency of the system regardless of the pot size. From a physical perspective, this improvement can be explained by the increase in the specific heat capacity of the mixture. Inert materials generally possess good thermal stability and low thermal conductivity, which reduces rapid heat transfer to the environment. As a result, a larger fraction of the energy produced by combustion remains trapped in the bricks and clay as internal energy. This energy is then released gradually during firing. The results obtained are consistent with the work of Bhattacharya and Salam (2002), who showed that improving the thermal insulation of cooking hearths reduces heat loss and increases energy efficiency [22]. According to these authors, refractory and inert materials significantly improve the thermal efficiency of domestic stoves. Furthermore, the observations agree with the studies by Bailis *et al.* (2007), which indicate that the use of materials with high thermal inertia in improved stoves allows for better heat retention and reduced fuel consumption [23]. The authors also point out that refractory bricks and stabilized clays are effective materials for thermal storage.

The difference observed between pots size 2 and 3 can be interpreted as the effect of system size on heat exchange. A larger pot generally has a greater exchange surface area and a higher thermal mass. This promotes the absorption of a greater amount of thermal energy. Thus, pot size 3 exhibits higher stored energy values than pot size 2. These results are also consistent with Fourier's theory of heat transfer. According to this theory, heat flux depends on the temperature gradient and the thermal conductivity of the material. Introducing an inert material reduces the overall thermal conductivity of the system, thereby limiting heat losses by conduction. Furthermore, the presence of the inert material can improve thermal homogeneity within the firebox. A more uniform heat distribution promotes more stable coal combustion, which increases the total amount of energy available for thermal storage. This thermal stability also contributes to improved cooking quality and reduced temperature fluctuations. The high energy values stored in the bricks demonstrate that they play a crucial role in the firebox's thermal behavior. Refractory bricks absorb a significant portion of the energy produced during combustion and release it slowly. This phenomenon is particularly desirable in improved cooking systems because it extends the heating time even after the flame has died down. The experimental results can also be compared to the work of Pandit *et al.* (2025), who demonstrated that improved fireboxes using refractory materials have higher thermal efficiencies than traditional fireboxes [24]. According to these authors, the increased thermal inertia directly contributes to reduced energy consumption. Finally, the overall analysis shows that adding inert material is an effective solution for optimizing the thermal performance of cooking fireboxes. This approach not only improves heat storage but also reduces energy losses and increases the overall efficiency of the thermal system.

For a typical experiment using 0.45 kg of charcoal (approximately 13 MJ of chemical energy), the total thermal energy stored in the bricks and clay ranged from about 6.35 MJ to 7.87 MJ, corresponding to approximately 49% - 60% of the fuel energy input. These values are physically realistic because the remaining energy is transferred to the cooking vessel and water or lost through flue gases, convection, and radiation. Therefore, the reported thermal storage values are fully consistent with the energy supplied by the fuel.

✓**Estimation of the thermal efficiency of the fireplace**

Figure 4 presents the results of the overall thermal efficiencies of the studied fireplaces, according to the different fuels used during the experiments.

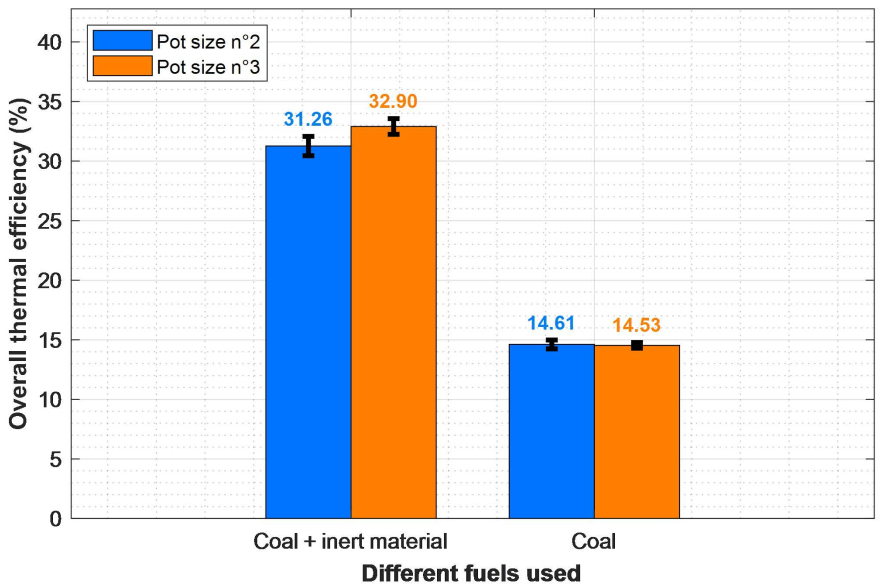

Figure 4. Comparison of overall thermal efficiencies with coal + granite and coal as a function of the size of pot 2 and 3.

Figure 3 presents highlight the evolution of the overall thermal efficiency of improved clay stoves depending on the fuel used and the size of the pots. The results clearly show that the use of the "coal + inert material" mixture leads to the best thermal performance, with efficiencies of 31.26% ± 0.81% for pot size no. 2 and 32.90% ± 0.66% for pot size no. 3. On the other hand, the use of coal alone results in significantly lower yields, of 14.61% ± 0.37% and 14.53% ± 0.24% respectively. This significant improvement in thermal efficiency in the presence of the inert material reflects the beneficial effect of the thermal inertia and the insulation provided by the refractory clay materials. Indeed, clay has a significant capacity for accumulation and gradual release of heat, which limits thermal losses by conduction and radiation to the external environment. Thus, a greater fraction of the energy from burning coal is transferred to the pot and used for useful heating. This behavior is consistent with the work of Valentim *et al.* (2022), who showed that refractory and insulating materials significantly improve heat conservation in biomass thermal systems [25]. The results obtained also demonstrate that the thermal efficiency of the fireplace using the coal + inert material mixture greatly exceeds that obtained with coal alone. This difference can be attributed to better temperature stabilization in the combustion chamber. The inert material acts as a thermal accumulator, allowing a more uniform and higher temperature to be maintained during cooking. Similar studies carried out on improved clay stoves have shown that refractory materials reduce specific fuel consumption while increasing the overall energy efficiency of the stoves (Haruna *et al.*, 2015) [26].

Furthermore, the thermal efficiencies obtained with the coal + inert material mixture (≈31% - 33%) fall within the range of performance reported in the literature for improved coal stoves. Asabie *et al.* (2025) report thermal efficiencies ranging from 28% to 35% for different models of improved coal stoves equipped with thermal insulation [27]. This consistency confirms the reliability of the energy performance of the stove developed in this study. The influence of the pot size remains relatively small, although a slight increase in efficiency is observed with pot size 3 when using the coal + inert material mixture. This improvement can be explained by better coverage of the active surface of the stove and more efficient heat transfer between the hot gases and the bottom of the pot. A larger exchange surface area does indeed promote the recovery of heat produced by combustion. In contrast, when using only charcoal, the low efficiencies observed indicate significant heat losses. These losses can result from rapid heat dissipation through the firebox walls, incomplete charcoal combustion, or poor containment of hot gases. According to Atajafari *et al.* (2024), traditional or poorly insulated stoves generally have thermal efficiencies below 20%, due to significant heat losses through convection and radiation [28]. The results obtained therefore confirm the importance of integrating refractory clay materials into the design of improved stoves. These materials not only improve thermal efficiency but also reduce charcoal consumption and the environmental impacts associated with the widespread use of biomass. This observation aligns with the findings of Dianda *et al.* (2025), who demonstrated that a stove equipped with clay refractory bricks significantly reduces charcoal consumption while increasing overall thermal efficiency [29] [30]. The stored energy values are significantly higher with the coal-inert material mixture, hich contributes to a gradual release of heat back to the pot, reducing heat losses and, consequently, improving overall thermal efficiency.

✓ **Comparison of results with certain studies in the literature**

The values obtained are also consistent with those of Teka Tesfaye Mengesha *et al.*, who evaluated the performance of a pyrolysis stove using the TEE. These authors reported maximum and minimum thermal efficiencies of 34.11% for a clay stove and 20.4% for an ELSA-type stove during the high-power start-up phase. At low power, efficiencies of 23.78% and 24.19% were obtained for the clay stove with two different fuels; these results corroborate our experimental findings [29]. Furthermore, the results of the present study are similar to those of Ebissa *et al.* [31], who evaluated the performance of an energy-efficient metal chulha using solid biomass as fuel. Using the TEE, the thermal efficiencies obtained are high, at 37%, 41%, and 46% respectively for the cold start, hot start, and simmer phases, for the improved stove compared to the traditional metal stove. The measured efficiencies are higher than those reported by Hari Bahadur Darlami *et al.* [32], who evaluated two improved raised earth stoves, with thermal efficiencies increasing from 17.99% to 24.7%. They are also comparable to the results of Gloria Boafo-Mensah *et al.* [8], who studied the performance of improved clay stoves, whose thermal efficiencies ranged from 11.7% to 35% for these different stoves. In addition, Kathleen Lask *et al.* [33] conducted a comparative study of two improved clay stoves using charcoal, for which the thermal efficiencies were 49.57% for a pyramidal stove and 13.49% for a rectangular stove. The efficiencies obtained in the present study, using charcoal combined with inert materials, are consistent with those of the pyramidal stove. For comparison, Hari Bahadur Darlamia *et al.* [32] evaluated the thermal performance of two improved clay stoves: the Nansu stove with a thermal efficiency of 27.44% and the terracotta stove with a thermal efficiency of 25.11%. Furthermore, Oketch *et al.* [34] conducted a study on the performance of local stoves, indicating yields of 23% for the Jiko stove, 43% for the stove using bioethanol gel and 13% for the 3-stone stove, during the hot start-up phase.

✓ **The limitations of the study**

One limitation of the present study is that it focused primarily on the thermo-energy performance and heat storage capacity of the improved biomass cookstove. Therefore, pollutant emissions such as carbon monoxide (CO), carbon dioxide (CO_2), particulate matter ($PM_{2.5}$), and smoke opacity were not measured during the experimental campaign. Although the improvement in thermal efficiency suggests a potential reduction in fuel consumption and associated emissions, these environmental benefits could not be quantitatively assessed within the scope of this work. Future studies currently under preparation will specifically address the characterization of gaseous and particulate emissions under different operating conditions. These investigations will provide a more comprehensive assessment of the environmental and health impacts of integrating inert materials into improved biomass cookstoves.

4. Conclusion

The results of this study demonstrate that integrating inert materials into improved biomass cookstoves is an effective strategy for enhancing the thermo-energy performance of domestic cooking systems. Thanks to their high thermal inertia, materials such as granite and clay promote the storage and gradual release of heat, thus reducing heat loss and improving the overall efficiency of the cookstove. The performance obtained with the charcoal + inert material mixture shows significant energy gains compared to using charcoal alone, with efficiencies exceeding 30% and improved thermal stability during the cooking and simmering phases. The study also highlights the influence of pot size on heat exchange and the system's energy efficiency. These results confirm that optimizing internal heat storage represents a relevant solution for reducing biomass consumption, limiting the environmental impacts associated with deforestation, and improving cooking conditions in households. However, further work on pollutant emissions, material durability and evaluation under real-world conditions would be necessary to consolidate the observed performance and promote large-scale dissemination of these improved stoves.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations and Acronyms

Q_B : Brick heat (J);
n : Number of bricks;
M_B : Masse d'une brique (kg);
C_p : Heat capacity of clay (J·kg^{-1}·K^{-1});
T_{fB} : Final brick temperature (K);
T_{iB} : Initial temperature of the brick (K);
Q_{ar} : Heat stored by the clay (J);
M_{ar} : Mass of clay used (kg);
T_{ff} : Final temperature inside the fireplace (K);
T_{if} : Initial temperature inside the fireplace (K);
Q_C : Heat stored by granite (J);
C_{pc} : Heat capacity of pebbles (granite) (799 J/kg·˚C);
M_c : Masse of pebbles (granite) (kg);
T_{ci} : Initial temperature of granites (K);
T_{cf} : Final temperature of the granites (K);
η_t : Total thermal efficiency (%);
M_i : Initial mass of water (kg);
$T_{ébl}$: Boiling of temperature (100˚C);
T_i : Initial water temperature (˚C);
M_i^{mj} : Mass of water at the beginning of simmering (kg);
T_{fmj} : Final simmering temperature (˚C);
T_{imj} : Temperature at the start of simmering (˚C);
M_{ev}^{mj} : Mass of water evaporated during simmering (kg);
M_b^{mj} : Mass of wood consumed during simmering (kg);
$M_{ev}^{ébl}$: Mass of water evaporated during the boiling test (kg);
L_v : Latent heat of vaporization of water (2260 kJ/kg);
$M_b^{ébl}$: Mass of wood consumed during boiling (kg);
C_{pe} : Specific heat capacity of water (in 4186 kJ/kg·˚C);
PCI : Lower heating value of coal (in 29,000 kJ/kg).