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Research article

Energy performance, safety and durability of charcoal cooking stoves commonly used in West Africa: Benin case study

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Abstract: The use of inefficient cooking stoves puts great pressure on the forests, as well as poorly secured cookers pose health risks to the users. Improving the energy efficiency of cookstoves reduces biomass consumption and thus the anthropogenic pressure on forests. This work aims to identify the best charcoal cooking stove(s) in terms of energy performance, safety and sustainability. The proposed approach combines the combined study of the energy performance, safety and durability of charcoal cooking cookers. A representative sample of five types of charcoal stoves commonly used in Benin is tested according to the requirements of the ISO 19867 standard. These are the square cooking stove, the circular cooking stove, the clay cooking stove, the rim cooking stove and the Nansu cooking stove. The results show two stoves with the best performance: The Nansu stove with a total energy efficiency of 27.44% and an output of 0.9 kW and the clay stove with a total energy efficiency of 25.11% and an output of 0.71 kW. These two stoves are made of clay, while the other three are made of metal. The clay stove offers the best safety with an overall average rating of 71.5 compared to 66.5 for the Nansu stove. The Nansu stove has better durability than the clay stove. This study thus contributes to the preservation of the environment and health through the recommendation of efficient, safe and durable charcoal cookers to be promoted.

Keywords: sector cooking stove; charcoal; energy performance; safety; durability

1. Introduction

Energy is at the heart of all human development. To this end, Sustainable Development Goal 7 (SD Goal 7) to ensure access for all to reliable, sustainable and modern energy services at an affordable cost is defined by the United Nations. However, millions of people around the world live in energy poverty, marked by lack of access to modern energy sources and lack of access to clean cooking energy [1]. About 40% of households worldwide cook on open stoves or inefficient biomass cooking stoves. A World Bank study conducted in 2015 indicates that 81% of households in Sub-Saharan Africa use solid fuels for cooking energy needs [2]. Recently, the special report Africa Energy Outlook 2019 published by the International Energy Agency (IEA), shows that about 850 million people in Sub-Saharan Africa still use wood energy as their main source of energy.

In Benin, according to the 2017 report of the Energy Information System of the Ministry of Energy, wood energy (firewood and charcoal) accounts for nearly 50% of the national energy balance, followed by hydrocarbons (about 47%) and electricity accounts for about 3%. A recent study indicates that out of a sample of 640 households surveyed in Benin, 76.48 percent depend on fuelwood and 18.18 percent on charcoal [3]. Charcoal is mainly used in urban and peri-urban areas, while fuelwood is used in rural areas. The dependency of populations on solid fuels increases anthropogenic pressure on vegetation cover. This is exacerbated by inefficient charcoal burning techniques and the use of very inefficient wood or charcoal cooking stoves. The use of inefficient stoves has many environmental, health and economic impacts on households. Inefficient or inefficient stoves cause users to consume much more wood or charcoal than is needed for the same level of use. Better still, forests are constantly being called upon to provide fuelwood or charcoal, which creates environmental problems. GHG emissions are no longer captured because trees are cut down in an uncontrolled manner. Emissions generated by the combustion of biomass also contribute to the GHG emissions responsible for global warming. Several studies are being conducted to improve the energy efficiency of cooking stoves by looking at the technology of cooking stoves or the geometry of charcoal or the emissions generated by the combustion of biomass. In this sense, Zhao et al. (2020) have shown that reducing the size of coal has improved thermal efficiency and reduced pollutant emissions [4]. The same source recalls that residential use of coal has been recognized as a major source of air pollutants [5,6], including carbon monoxide (CO), nitric oxide (NO), hydrogen sulfide (H_2S), sulfur oxides (SOX), methane (CH_4), black carbon (BC), primary particulate matter (PM), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and greenhouse gases. Exposure to pollutant emissions and indoor pollution causes several negative health effects in households [4]. Households are susceptible to respiratory, cardiopulmonary, and other health problems, which are responsible for an estimated 1.1 million premature deaths in China, for example [7]. In addition to the adverse health and environmental effects, the economic losses are not negligible [4]. In Benin, the carbonisation technique is that of the traditional millstone with a low mass yield (generally less than 15%) [8,9]. It thus takes on average 6 kg of wood to produce 1kg of charcoal. Energy management is one of the surest ways to achieve Sustainable Development Objective 7 (SDO7). It is therefore important to identify the equipment with the best aptitudes from an energy, environmental and safety point of view.

Thus, this study focuses on assessing the energy performance, safety and durability of charcoal cooking stoves commonly used by households in Benin. Indeed, previous studies carried out in Benin have focused on determining the technical performance of cooking stoves used in Benin by the boiling water technique [10,11]. This work is devoted to the study of the influence of the type of cooking stove on performance, as well as the savings that can be achieved with the different cooking stoves. These authors prove that wood/charcoal combination cooking stoves have better performance than protected charcoal cooking stoves. Segbefia et al. in Togo, carry out comparative studies between clay improved cookstoves and traditional (Malagasy) stoves using the water boiling test technique [12]. Based on the results relating to specific boiling time, thermal efficiency, and specific fuel consumption, they prove that clay improved stoves are more efficient. However, very few studies have been carried out in accordance with the requirements of an international standard.

The combined study of the energy performance, safety and durability of cooking stoves is very little addressed in Benin and in the sub-region. This article therefore evaluates the energy performance, safety and durability of charcoal cooking stoves according to the ISO 19867 standard. A combined analysis of these indicators as well as the economic aspect makes it possible to highlight the cooking stoves with the best performances to be promoted.

2. Literature review

There are 2.8 billion people or 38% of the world's population and nearly 50% of the population in developing countries who live without access to modern sources of cooking energy to cook food [1]. In Africa, the number of people without access to modern sources of cooking energy exceeded 900 million in 2018. This situation forces people to rely mainly on traditional solid fuels (firewood and charcoal) [13]. The cooking stoves used by households are not always efficient and pose serious environmental and health problems. Indeed, traditional three-stone cookstoves are mostly used in rural areas. Traditional cooking stoves are most commonly used by low-income households. This type of traditional cooking stove is generally identified as a very inexpensive or free device, which may include a simple open fire, built on the ground with three stones to support a pot, or a basic ceramic, clay or metal stove. It is characterized by very low efficiency, unlike improved cookstoves, which have better performance [1]. Traditional cooking stoves in Africa have average energy efficiency scores ranging from 18% to 21% for wood-burning stoves and 21% to 24% for charcoal stoves [1]. Meanwhile, these scores are much higher for improved cookstoves. Several works are therefore being carried out to implement improved cookstove technologies to improve household health and economy. Many cookstove models have been implemented in many countries around the world [14]. These different programs have had mixed but generally unsatisfactory results. These authors recommend that cookstove designers consider smoke and heat removal and fuel availability before other factors in cookstove design. Several studies show that improved cookstoves save not only wood or charcoal, but also cooking time and cooking drudgery [15–17]. Some studies suggest "rocket" technologies for cookstove design [15]. The improved cookstove is a cooking appliance with higher energy efficiency than the traditional cookstove. There are different types of improved cookstoves in different countries and regions. It is known by different names taken from local languages (such as sakkanal and diambar in Senegal, sewa in Mali, Kenyan jiko in Kenya, Nansu in Benin, ouaga métallique in Burkina, etc.) [18]. Different materials are used in the design of improved cookstoves including: clay, cow dung, sheet metal, ceramic materials etc. [18].

The real problem in developing countries is that some cookstoves come onto the market and are marketed as improved cookstoves without prior testing and studies having been carried out on these cookstoves. The other problem often encountered is that cookstoves improved for energy performance are not durable and do not offer sufficient safety to users and are therefore not economically viable. Energy performance should not be separated from safety and durability. It is therefore this gap that this study fills by studying the performance (safety, energy efficiency and durability) of the different cookstove technologies available on the Beninese market.

The study of the energy performance and safety of cooking stoves has been addressed in previous research work. These studies, although they did not address the combined analysis of the two parameters of energy performance and cookstove safety, have attempted to study them separately. In fact, the energy performance of cooking stoves has long been a concern for the various researchers in the field because of the close link between them and the consumption of solid fuel, the preservation of the environment and the household economy. In Benin, for example, the performance of cookstoves has been evaluated by the water boiling technique [10]. This study revealed that losses are higher for metal and clay stoves. Another study reveals that in Benin, fossil fuel stoves have the best economic performance, but the very low cost of wood fuels gives them an advantage [11]. A comparative study of two types of traditional improved cookstoves (clay cookstoves and Malagasy cookstoves) indicates that the clay improved cookstove performs better than the Malagasy cookstove [12]. Chica and Pérez designed and evaluated a biomass improved cookstove for developing countries [19]. The actual cookstove is a rocket stove. Water boiling tests conducted on this cookstove revealed an average energy efficiency of 20.9% with a boiling time of 31.6 minutes. The thermal and emission performance of biomass stoves is being tested in Nigeria [20], water boiling tests (WBT) and food cooking tests (rice and beans) have been carried out. The results indicate that of the 15 charcoal stove samples tested, 62% met the minimum Tier 2 standard, while 51% of the 10 firewood stove samples tested met the minimum Tier 2 standard. The star rating of a biomass stove is determined by the value of the stove's thermal efficiency level. Stoves available in local markets in Nigeria do not have a star rating. Water boiling tests conducted on aluminum stoves in Ghana indicate that the thermal efficiency of the stove compared to the traditional stove is much improved [21]. According to another study in Ghana [22], wood-burning stoves have an energy efficiency of 12.2 ± 5.00%, charcoal stoves 23.3 ± 0.73%, and Gyapa charcoal stoves 30.00 ± 4.63%. These authors recommend switching to and adopting Gyapa charcoal cookstoves to increase efficiency and reduce emissions.

As seen above, there is a lot of work being done to improve the energy efficiency of cookstoves and reduce solid fuel consumption, but the safety and durability of cookstoves has long been overlooked. Thus, for developing countries, Johnson and Bryden (2015) sought to reduce injuries and other incidents created by the use of cooking stoves on household members by proposing ten (10) safety guidelines for solid fuel cooking stoves [23]. The authors' Cooking Stove Safety Rating Grid will serve as a reference or decision support tool for designers of improved cookstoves and users. Other authors have evaluated cookstove safety protocols in low-income and middle-income countries [24]. These authors sought to assess whether the ten tests proposed by the biomass stove safety protocol (BSSP) are reliable and meet the requirements. They sought to determine whether this test will produce repeatable safety scores over a series of tested cookstoves. The results show that significant differences are obtained for each tester. It is concluded that the BSSP is an important starting point for the evaluation of safety tests but that some of its aspects need to be improved. The different cooking stoves commonly used in households in Benin and in the West African sub-region have not been the subject of a scientific study taking into consideration the combined analysis of energy performance, safety and durability of these cooking stoves. It is therefore this gap that this study fills by focusing initially on the most commonly used charcoal cooking stoves in the Republic of Benin.

3. Materials and method

3.1. Materials

In order to carry out this study, several pieces of equipment are required. We present them in this section.

3.1.1. Description of the sample of charcoal cooking stoves studied

A representative sample of five types of charcoal cooking stoves produced in Benin is used. Most of them are designed by craftsmen in environments where the level of control and technological mastery is not very high. The five models of cooking stoves are described in the following paragraphs. Each stove model represents a family of similar charcoal cooking stove models.

(1) The charcoal circular cooking stove

For this traditional charcoal cooking stove, very often, the sheet metal used in the construction of this type of stoves are the carcasses of abandoned cars or scrap metal. The coal chamber is circular with holes distributed over the bottom. The stove is covered with a thin coat of paint for aesthetics. The following Figure 1 describes this type of cooker.

Figure 1. Circular charcoal cooking stove.

(2) Square charcoal cooking stove

Usually manufactured by welders from metals (usually iron), it is widespread and mainly used in households and in food service locations. This type of cooking stove (see Figure 2) is widely available throughout the country.

Figure 2. Square charcoal cooking stove.

(3) Charcoal cooking stove made of baked clay

In keeping with rural uses and practices, this stove is made from a local material available in the environment: fired clay (see Figure 3). It is used because of its resistance to weather conditions such as heat, wind, rain, insulation capacity etc. (see Figure 3). This stove allows a good part of the energy to be contained in the material due to the thermal properties of clay.

Figure 3. Clay charcoal cooking stove.

(4) Nansu charcoal cooking stove

Made from metal (iron or aluminum) and clay, the Nansu stove, shown in Figure 4, is a clay stove with a metal lining. The upper part consists of a ceramic core for the fuel, two handles used to lift the stove and three triangular metal rod supports on which the pot rests. The lower part of the stove rests on a pedestal and has a door at the front of the stove to control air flow and remove ashes.

Figure 4. Nansu charcoal cooking stove.

(5) Rimmed charcoal cooking stove

Also made by welders, it is widely used by good ladies who sell food and scrubland. This cooking stove rests on three iron legs (see Figure 5). The coal chamber is formed by the wheel rim of a salvage vehicle and the kettle can rest directly on three rectangular-shaped supports. An opening on the side of the stove allows air circulation.

Figure 5. Rimmed charcoal cooking stove.

Table 1 below summarizes the average measured characteristics of each of these different charcoal cooking stoves.

Table 1. Characteristics of the cooking stoves studied.

Cooking stove	Height (cm)	Diameter/Side (cm)	Mass (kg)
Circular cooking stove	22	30.5	1.339
Squared cooking stove	25	28.5	3.167
Clay cooking stove	24.8	26	7
Nansu cooking stove	25	30.5	9
Rimmed cooking stove	54.5	36.5	12

To perform the tests, several other equipments are used. These are mainly:

(1) A cooking vessel

Cooking stoves are tested with a cooking vessel similar to those readily available on the market. This is a medium-sized aluminium pot with a diameter of 23.5 cm.

(2) Fuel (charcoal)

The selection of charcoal with the best physico-chemical properties was made following characterization. We chose charcoal with a high Lower Calorific Value (LCV) of 26820 kJ/kg and a moisture content of 6%. This type of coal is easily found on the local market and is widely used by households who appreciate it because it does not smoke much and burns quickly. As the stoves are not designed to hold the same amount of charcoal, we have set the initial mass at 700g. This mass is the same that is used for all the stoves so that the test results are comparable.

(3) The decameter and the ruler

They are used to measure dimensions.

(4) A hygrometer

For the measurement of relative humidity and room temperature during experiments, a two-channel USB data logger is used (EL-USB-2+).

(5) An anemometer

Throughout the tests, the wind speed must be less than 1 m/s. The anemometer allowed us to measure and control this parameter.

(6) An electronic scale

With an accuracy of 1g, it allowed the measurement of 2.558 kg of water and 0.7 kg of coal for each of the stoves during the energy performance tests. The mass of water used in the tests (2.558 kg) is the same for all the tests and all the cookstoves studied.

The characteristics of the charcoal used for the tests are summarized in the following Table 2. The immediate analysis was carried out according to the following standards. ISO 18134-3 for moisture content, ISO 1213 for volatile matter content, ISO 18122 for ash content and ISO 18123 for fixed carbon content. The ultimate analysis is carried out according to ASTM D5373.

(1) Cloth, rag or loose clothing.
(2) Stick chalk to sketch the stove, floor and wall.
(3) Thermometer for measuring air temperature.
(4) Infrared thermocouple for measuring surface temperatures of cookers and the environment.

Table 2. Immediate and elemental charcoal analysis.

	Parameters	Scores (%)
	Fixed carbon rate	78.84
Immediate charcoal analysis	Volatile matter content	19.81
	Moisture content	6
	Ash content	1.35
	%C	52.7
Elemental analysis	%H	5.85
	%O	40.72
	%N	0.73

3.1.2. Description of the acquisition system

With the help of an Arduino assembly, a temperature recorder was placed in the kettle every 30 seconds. This is an Arduino Uno plate which allowed us to do the wiring and to program the temperature recorder. A type K thermocouple (on the right in Figure 6) is the temperature sensor used. Arduino Genuino software version 1.8.6 is used to write the program (see Appendix 1 for the code). The thermocouple is associated with the MAX 6675 which is a digital K thermocouple converter with cold junction compensation (0℃ to +1024℃) see Figure 7.

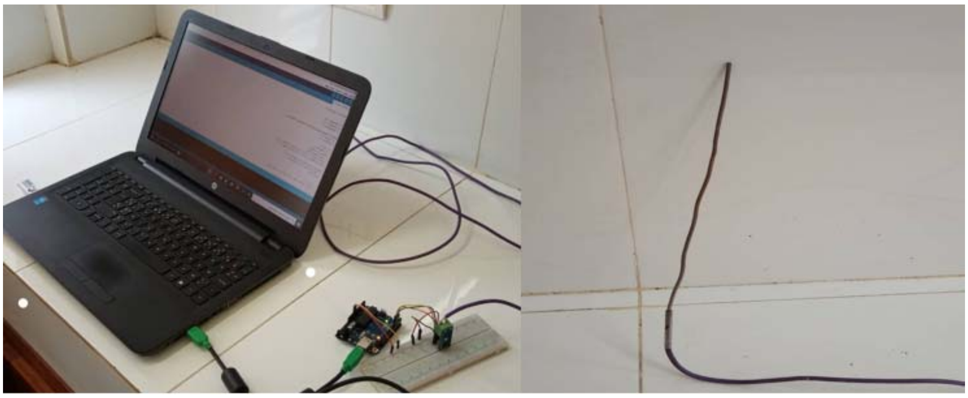

Figure 6. Data acquisition system + thermocouple.

Figure 7. MAX 6675.

The following Figure 8 gives a brief description of the experimental device used for each type of stove.

Figure 8. Experimental device.

3.2. Method

The methodology used to assess the energy performance, safety and durability of charcoal cooking stoves is described in ISO 19867. Several parameters are determined for this purpose. For all the operating conditions tested, spot measurements of temperature, wind speed, relative humidity, water mass and charcoal were regularly taken.

3.2.1. Energy performance of cooking stoves

Energy efficiencies are the ratios of the amount of useful energy to the amount of energy supplied to the water in the pot by burning the fuel (charcoal). Each model of cooking stove is tested three times under the same temperature and humidity conditions. The measurements made allow the calculation of the different efficiencies.

The tests last 60 minutes. The ambient temperature must remain between 5 and 40°C, the masses of water and charcoal respectively noted G1 and B, are weighed at the beginning. The charcoal is burnt using kerosene. The quantity is 5% (by mass) of the mass of the fuel. The tested cooking stoves do not have an air control device, so they are all tested at a single power level.

The cooking vessel containing water must be placed on the cooking stove after the oil flames have been extinguished (this usually takes 4 min to 6 min). Once this time has elapsed, the temperature sensor (thermocouple K) must be placed in the cooking vessel. The pressure of the medium is atmospheric pressure (101325 Pa), the local boiling point of the water is 100℃. Water temperature measurements and time are recorded by our data acquisition system every 30 seconds.

If the local boiling point temperature is reached before 60 min, the corresponding time is recorded. However, if the boiling point temperature has not been reached after 60 minutes, the time and the water temperature are recorded. The test ends when the water temperature falls to 5℃ below the boiling point reached. Then the remaining masses of water and carbon are weighed, giving G2 and C respectively.

The results of the cooking power are expressed in Watts. After these tests, the important parameters are determined as follows:

Useful energy delivered is the energy transferred to the contents of a cooking vessel including sensible heat energy that raises the temperature of the contents of the cooking vessel and the latent heat of evaporation of water from the cooking vessel. It is determined by the formula:

$$\boldsymbol{Q_1 = C_P \times G_1(T_2 - T_1) + (G_1 - G_2)\gamma} \quad (1)$$

where Q_1 is the useful energy delivered in kJ; C_P is the specific heat of water, 4.18 kJ/kg.K; G_1 is the initial mass of water in the cooking vessel, kg; G_2 is the final mass of water in the cooking vessel, kg; T_1 is the initial water temperature in the cooking vessel, ℃; T_2 is the temperature of the local boiling point or the highest temperature reached in the cooking vessel, ℃; γ is the latent heat of vaporization of water at the local boiling point, kJ/kg.

Cooking power is the average rate of energy delivered to the contents of a kettle over a selected period of time during a cooking sequence.

$$\boldsymbol{P_C = \frac{Q_1}{t_3 - t_1}} \quad (2)$$

where P_C is the cooking power in kW; Q_1 is the useful energy delivered, kJ; t_3 is the final time at the end of a test phase, s; t_1 is the initial time at the beginning of a test phase, s.

Energy efficiency results are expressed in terms of thermal efficiency. This is the ratio of useful energy supplied to fuel energy used.

Without taking into account charcoal residues, we get:

$$\boldsymbol{\eta_C = \frac{Q_1}{B \times LHV} \times 100\%} \quad (3)$$

where η_C is the thermal efficiency of cooking without taking into account the charcoal residue, %; Q_1 is the useful energy delivered, kJ; B is the mass of fuel supplied to the cooking stove, kg; LHV is the lower calorific value of the fuel introduced, kJ/kg.

Taking into account the charcoal residue, we have:

$$\boldsymbol{\psi_C = \frac{Q_1}{(B - C)LHV} \times 100\%} \quad (4)$$

where ψ_C is the "real" cooking thermal efficiency, taking into account charcoal residues; Q_1 is the useful energy delivered, kJ; B is the mass of fuel supplied to the cooking stove, kg; LHV is the lower heating value of the fuel, kJ/kg; C is the mass of charcoal remains after cooking, kg.

3.2.2. Safety tests of cooking stoves

This is the ability of a cooking stove to operate at an acceptable level of risk to users. Certain features of cooking stoves can be potential safety hazards, causing fires, burns and cuts. The design and evaluation of stoves must necessarily include a safety assessment. The method of safety evaluation is suggested by the standard referred to above. It consists of the analysis of key aspects of improved stoves as described below.

(1) Sharp edges and points

Sharp edges and tips can entangle clothing and cause the stove to overturn. Therefore, the outer surfaces of a stove must not catch or tear clothing or risk cutting your hands during normal use.

a) Gently rub a cloth over the entire outside surface of the stove to find areas that catch or tear the fabric.

b) Record the number of areas on the surface of the stove that catch or tear the cloth. Depending on the number of areas detected, refer to the following Table 3:

Table 3. Grading grid for sharp edges and points.

Number of zones detected	Evaluation	Score
Four or more	Poor	1
Three	Fair	2
One or Two	Good	3
None	Best	4

(2) Tilting the cooking stove

The cooking stove must be stable to maintain a vertical orientation when in operation. Burning charcoal can be expelled from the firebox or spilled when the stove tips over. This can cause eye burns and lead to fires. The following Figure 9 shows cooking stove position.

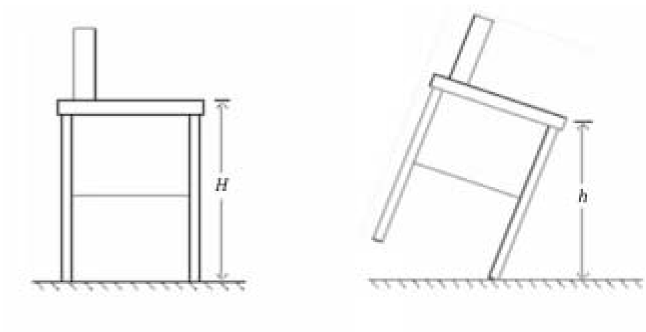

Figure 9. Cooking stove position.

H: standing height, measured before tilting; h: tipping height, measured after tipping.

For each round, divide the tilted height (h) by the standing height (H) to find the ratio. The highest ratio of all rounds is the maximum ratio (R), which is used to identify the score in the following Table 4.

Table 4. Grading grid for tilting the cooking stove.

Maximum ratio R	Evaluation	Score
>0,978	Poor	1
0,961 < R ≤ 0,978	Fair	2
0,940 < R ≤ 0,961	Good	3
≤0,940	Best	4

(3) Obstructions near the cooking surface

The areas surrounding the cooking surface should be flat so that cooking vessels moved from the stoves do not collide with protruding parts and spill boiling contents onto hands or children.

The difference in height between the cooking surface and any protrusions closely surrounding it must be determined.

a) Inspect the cooking stove for the presence of a skirt (a skirt is present if the cooking vessel is partially inserted into an extension of the range). This test is not performed if the cooking stove has a skirt. In this case, the cooking stove is rated “Good”.

b) Do not perform this procedure for solar cookers. Solar cooking stoves are rated “Best”.

c) Measure the height of the cooking surface.

d) For each obstruction closely surrounding the cooking surface, measure the height of the obstruction in cm. Obstructions may include small but solid obstacles such as handles perpendicular to the grid.

e) For each obstruction, calculate the difference in height between the cooking surface and the obstruction. The maximum height difference (Δhmax) is used to find the rating and score.

The rating system for obstructions near the cooktop is shown in the following Table 5:

Table 5. Rating grid for obstructions near the cooking surface.

Maximum height difference	Evaluation	Score
$\Delta h_{max} > 4$	Poor	1
$2,5 > \Delta h_{max} \geq 4$	Fair	2
$1 > \Delta h_{max} \geq 2,5$ (cooking stove with a skirt)	Good	3
$\Delta h_{max} \leq 1$	Best	4

(4) Fuel containment

Burnt fuel must not fall out of the cooking stove when spilled.

a) Fill the cooking stove with fuel, but do not light it.

b) All lids and/or utensils in the cooking stove remain in their normal position.

c) Place the cooking vessel on the burner surface.

d) Visually inspect for exposed areas through which fuel can be seen (often on the sides or through the fuel loading chamber).

e) Measure the area of each exposed area. Select the appropriate formula based on the shape of the gap.

f) Calculate the sum of all individual exposed areas, which will be the total area of fuel exposed, A.

Refer to the following Table 6 for scoring:

Table 6. Grading grid for fuel containment.

Exposed area A (cm²)	Evaluation	Score
$A > 250$	Poor	1
$150 < A \leq 250$	Fair	2
$50 < A \leq 150$	Good	3
$A \leq 50$	Best	4

(5) Surface temperature

The importance of this test is that it protects children and women from burns as children tend to touch cooking stoves and women are likely to come into contact with cooker surfaces during normal use. A child's touch can be 0.9 m or less. Conversely, adults are assumed to be susceptible to accidental contact at heights less than 1.5 m. Therefore, heights above this level are considered out of range and are not tested.

(6) Heat transfer to the environment

Large amounts of heat transferred to the environment can ignite fuels or the household structure in the vicinity of the cooking stove. The following procedures are used if the stove is placed within 10 cm of a fuel or has a combustion chamber within 5 cm of the floor. If the stove is located outside of these limits, it is given a "Best" rating.

(7) Handle temperature

This test measures the parts of the cooking stove that are affected during regular operation.

a) Ensure that the cooking area is shaded during the evaluation.

b) Record the air temperature.

c) Draw very thick lines on the cooking chamber at heights of 0.9 m and 1.5 m, if the cooking chamber reaches these heights measured from the ground.

d) Chalk a grid of 8 cm × 8 cm on the surface of the cooking chamber below the 0, 9 m line and between the 0, 9 m and 1, 5 m lines, if applicable. The grid must cover the entire target area of the cooking chamber with lines spaced 8 cm apart vertically and horizontally.

e) Horizontal cooking surfaces, such as burners or hobs, are excluded for tests relating to surface temperature and heat transfer to the environment.

f) Light the fuel and wait until the stove has reached its maximum temperature (about 20 min to 40 min) before proceeding, adding fuel if necessary.

g) Record the temperature data using the thermocouple at each grid intersection.

h) Begin wall and floor measurements by moving the cooking stove away from the oven for up to 1 minute, then return the oven to its initial position for at least 5 minutes, take the surface temperature and manipulate the temperatures during this time. Repeat step g) until all data points have been checked.

The cooking chamber is away from its initial position. After the data logging period, place it in its initial position for a period of at least 3 minutes to give the surfaces time to warm up.

i) Find the maximum temperature for each surface below/above 0.9 m in height (the child line) for metallic and non-metallic surfaces, for the floor and walls, and for the temperatures of the non-metallic handle.

j) Fireplaces that have no components that need to be touched during use receive a "Best" rating for the wrist temperature test.

It is important to note that this test applies only to wrists and other parts that are touched during normal use, but the surface temperature test applies to surfaces that could be inadvertently touched.

Depending on the results of the surface temperature test, refer to the following Table 7:

Table 7. Grading grid for surface temperature.

Surface	Temperature difference ΔT	Evaluation	Score
Below the child line (<0.9 m) metallic	$\Delta T > 50$	Poor	1
	$44 < \Delta T \leq 50$	Fair	2
	$38 < \Delta T \leq 44$	Good	3
	$\Delta T \leq 38$	Best	4
Below the child line (<0.9 m) non-metallic	$\Delta T > 58$	Poor	1
	$52 < \Delta T \leq 58$	Fair	2
	$46 < \Delta T \leq 52$	Good	3
	$\Delta T \leq 46$	Best	4
Above the children's line (≥0.9 m) metallic	$\Delta T > 66$	Poor	1
	$60 < \Delta T \leq 66$	Fair	2
	$54 < \Delta T \leq 60$	Good	3
	$\Delta T \leq 54$	Best	4
Above the children's line (≥0.9 m) non-metallic	$\Delta T > 74$	Poor	1
	$68 < \Delta T \leq 74$	Fair	2
	$62 < \Delta T \leq 68$	Good	3
	$\Delta T \leq 62$	Best	4

With regard to the test for heat transfer to the environment, Table 8 states the following. For the handle temperature test, see Table 9.

Table 8. Grid for heat transfer to the environment.

Surface	Surface Temperature difference (between the stove and the ambient air) ΔT	Evaluation	Score
Ground	$\Delta T > 65$	Poor	1
	$55 < \Delta T \leq 65$	Fair	2
	$45 < \Delta T \leq 55$	Good	3
	$\Delta T \leq 45$	Best	4
Wall	$\Delta T > 80$	Poor	1
	$70 < \Delta T \leq 80$	Fair	2
	$60 < \Delta T \leq 70$	Good	3
	$\Delta T \leq 60$	Best	4

(8) Chimney protection

This test evaluates the risk of contact with the chimney shield, the methodology specifies that for cooking stoves without a chimney, consider the evaluation as "Best". This is the case for the tested cooking stoves.

Table 9. Grading grid for wrist temperature.

Surface	Temperature difference (between the cooking stove and the ambient air) ΔT	Evaluation	Score
Metallic	$\Delta T > 32$	Poor	1
	$26 < \Delta T \leq 32$	Fair	2
	$20 < \Delta T \leq 26$	Good	3
	$\Delta T \leq 20$	Best	4
Non-Metallic	$\Delta T > 44$	Poor	1
	$38 < \Delta T \leq 44$	Fair	2
	$32 < \Delta T \leq 38$	Good	3
	$\Delta T \leq 32$	Best	4

(9) Flames surrounding the cooking vessel and emerging from the fuel chamber

Flames that touch the cooking vessel must not come into contact with hands or clothing. This prevents the risk of burns to people in the vicinity.

(a) If the cooking stove has concentric rings that can be removed, these must be removed for the test.

(b) Maintain the fire in the fully lit cooking stove.

(c) Place the cooking vessel in the cooking position.

(d) Observe the uncovered flames surrounding the cooking vessel for 5 minutes. Measure the maximum height of the flame, and if less than 4 cm, more than 4 cm, or if the flames reach the top of the cooking vessel and the handles.

e) Cooking stoves that completely enclose all the flames (such as cooking stoves that use a cooktop) receive a "Best" rating (because there is no danger from a stray flame).

If, during testing, all stoves completely close all flames, i.e., there is no danger from a stray flame, then the affected stoves receive a "Best" rating and a score of 4.

Table 10 below provides information on the scoring system:

Table 10. Grading system for the flames surrounding the cooking vessel.

Flames surrounding the cooking vessel	Evaluation	Score
The entire container and/or handles	Poor	1
Part of the cooking vessel, without the handles	Fair	2
Less than 4cm from the sides of the container, without handles	Good	3
None	Best	4

(a) Remove the cooking vessel from the cooking stove.

(b) Maintain the fire in the cooking stove at a high operational level.

(c) Visually inspect the amount of flame exiting the firebox, if any.

(d) The rating is "poor" if the flames are protruding and "better" if the flames are contained.

The scoring system for testing the flames exiting the combustion chamber is provided in the following Table 11:

Table 11. Grading system for the appearance of flames.

Appearance of the flames	Evaluation	Score
Salient flames	Poor	1
Flames contained	Best	4

The flames coming out of the combustion chamber are either contained or protruding. Nevertheless, in the case of the tested stoves, in the absence of real "flames", we consider that at the level of the combustion chamber, the flames are contained. All of the stoves tested therefore receive the "Best" rating for this test and therefore score 4.

To calculate the overall safety score, the scores for each of the 7 procedures are multiplied by a weighting factor based on the system provided in the standard and then added together to obtain an average total score.

3.2.3. Durability of cooking stoves

Durability methods are intended to evaluate aspects of the design of improved cooking stoves that may affect the quality of use by consumers. For this purpose, a point based rating system is used to enable countries and organisations to select levels according to their priorities. Cooking stoves may be exposed to rough handling and treatment, including transportation, falling of the cooking stove, dropping of other objects on the cooking stove and overturning of the cooking stove. These aspects are taken into account in the durability criteria for improved cookstoves. The order in which the durability tests are performed has been established because some tests require the stove to be fully assembled while others are performed on specific components. We will limit ourselves to those tests that do not require destructuring or possible degradation of the improved stove. These include the leakage test. Firing stoves can reach extremely high temperatures, at which point the materials may begin to degrade and no longer perform their function. Due to the high combustion temperatures and relatively cold cooking temperatures of many cooking modes, there is a risk of sudden temperature changes. This thermal shock can crack or break many components of the cooking stove. Prior to the test, a detailed visual inspection of the cooking stove is conducted. The pan is then filled to within 1 cm of the edge. The cooking stove must be in operation for 1 hour. An extra 1 litre of water is quickly poured into the pan, causing water to overflow into the stove. Once dried, the same process is repeated twice, for a total of three attempts. The observations made after the test, as well as the photos taken, are recorded.

3.2.4. Economic analysis

An economic analysis based on the evaluation of the gains (in terms of charcoal saved and in terms of financial savings) generated by the transition from a traditional stove to an improved one. This analysis uses the notion of energy efficiency of cooking stoves and the notion of payback time. These two parameters are evaluated as follows.

The energy efficiency of a charcoal cooking stove is given by the following relationship.

$$\eta_f = \frac{Useful\ energy}{Mass\ of\ charcoal \times LHV} \quad (5)$$

The payback time (IRR) is determined as follows.

$$IRR = \frac{Investment\ cost}{Profit} \quad (6)$$

4. Results and discussions

4.1. Results

4.1.1. Tests to assess the energy performance of charcoal stoves

The results obtained indicate that the Nansu and clay stoves have the best energy performance followed by the square, circular and rimmed stoves respectively (Table 12). In terms of useful energy output, cooking power and thermal efficiency of cooking with or without residual charcoal, the Nansu stove has the highest scores. This is followed immediately by the clay stove, which also scores well. The other stoves are less efficient in terms of the above characteristics. The highest cooking power (0.9 kW) is achieved with the Nansu stove followed by the clay stove with a score of 0.71 kW, while the lowest (0.43 kW) is achieved with the rim stove. The other stoves have intermediate ratings of 0.59 kW and 0.63 kW for the circular and square stoves respectively.

Table 12. Energy performance results.

	Cooking power Pc (kW)		Residue-free cooking heat yield (%)		Total Cooking Heat Efficiency (%)	
	Mean	Incertitude	Mean	Incertitude	Mean	Incertitude
Circular cooking stove	0.59	0.06	11.35	0.013	24.64	0.013
Squared cooking stove	0.63	0.05	12.14	0.012	23.19	0.009
Rimmed cooking stove	0.43	0.027	8.23	0.008	10.58	0.013
Clay cooking stove	0.71	0.03	13.72	0.009	25.11	0.014
Nansu cooking stove	0.90	0.05	17.34	0.017	27.44	0.015

Figure 10 describes the water temperature versus time for each cooking stove. On this graph, it can be seen that the Nansu cooking stove is the one that reaches the local boiling temperature (100°C) most quickly after 24 minutes. The clay stove and the square stove are the second fastest to reach the local boiling point after about 32 minutes. The circular stove reaches the local boiling point after about 46 minutes. The rim stove does not reach local boiling point at the end of the test. The average maximum temperature reached is 87.75°C obtained after 27.5 minutes. The Nansu and clay stoves therefore burn better than the other stoves.

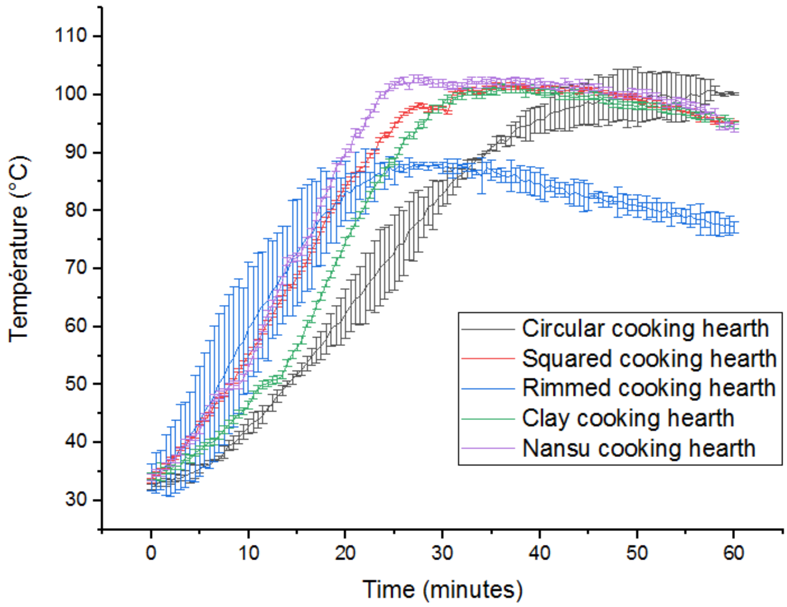

Figure 10. Evolution of water temperature as a function of time for each cooking stove tested.

Ambient conditions are monitored during testing. For example, Figures 11 and 12 describe the variation in wind speed and the variations in relative humidity and temperature in the environment, respectively. The analysis of Figure 11 shows that throughout the tests, the wind speed never reached 1 m/sec. It always varied between 0 and 0.8 m/s. Figure 12 shows that the ambient temperature varied between 29 and 34.8°C and the relative humidity varied between 55% and 80%. Overall the ambient conditions have remained within the limits suggested by the ISO 19867 standard used. As a result, the test environment did not influence the results obtained.

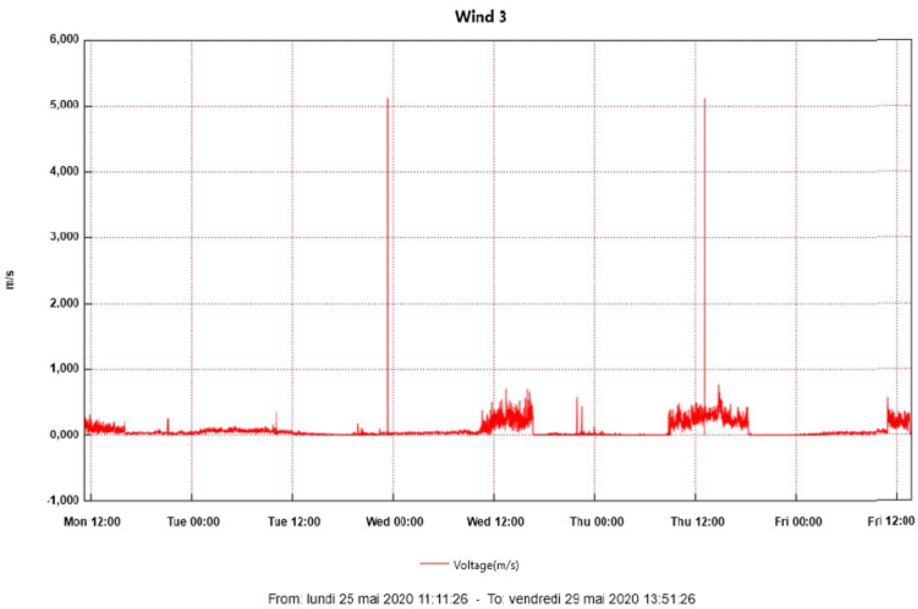

Figure 11. Evolution of the wind speed during the tests.

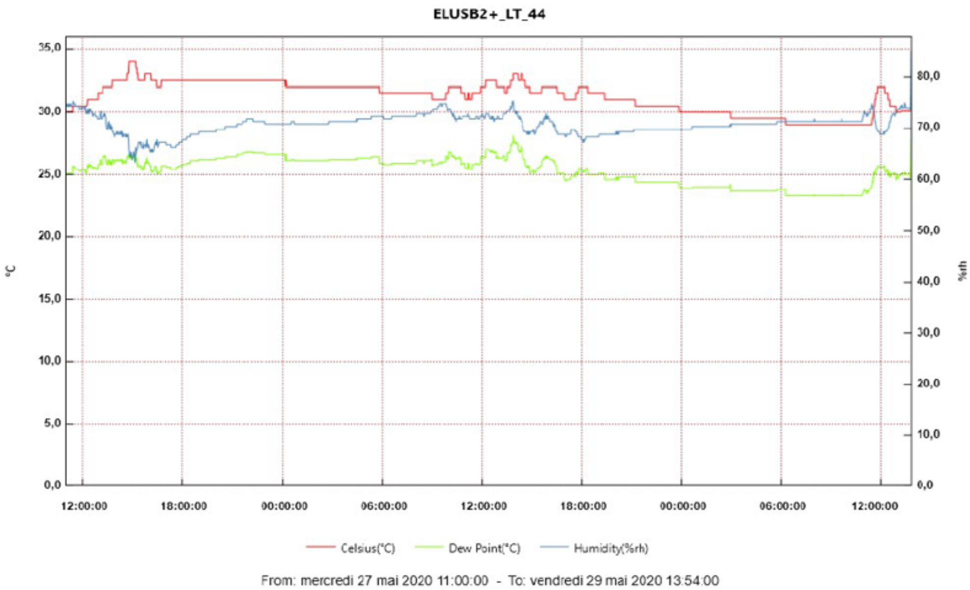

Figure 12. Evolution of the ambient temperature and relative humidity during the test period.

4.1.2. Safety tests of charcoal cooking stoves

This section describes the different results obtained for the safety tests. Figure 13 describes the overall safety scores obtained for each stove tested. The clay stove and the Nansu stove have the highest overall safety scores, while the other three stoves have lower scores. The safety assessment of the individual stoves tested shows that the clay stove has the highest overall average safety score (71.5) followed by the Nansu stove (66.5). The other three stoves have overall scores of around 62. The clay stove and Nansu therefore offer the best safety for users.

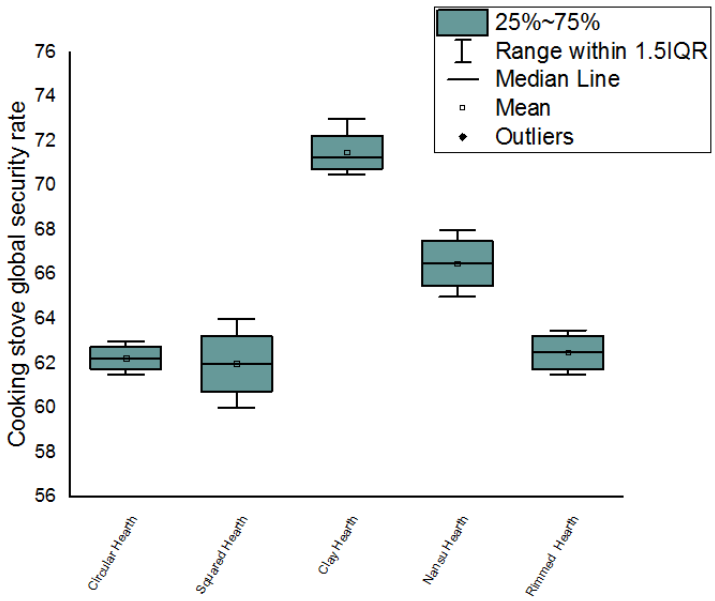

Figure 13. Boxed Diagram of the Global Safety Scores of the different box stoves tested.

4.1.3. Durability tests of charcoal cooking stoves

To assess the durability of the cooking stoves, we observe for each of the tested cooking stoves the plausible damage after testing.

For the circular stove, following the durability test, we can observe a degradation of the combustion chamber (Figure 14), the paint, surely of poor quality, which gradually peels off. The smell of burnt paint is toxic and unbreathable. This constitutes a risk to human health but also a danger to the environment. This stove will therefore deteriorate quickly under the influence of climatic hazards and under severe conditions of use. Given that the majority of households have their kitchens outside and knowing the culinary practices in Benin, this stove is not very sustainable. In view of this, the risk factor presented by this stove is 5.

Figure 14. Observations made at the circular cooking stove level.

The square and rimmed cooking stove (Figure 15) show no obvious degradation. They have remained as they were before the durability tests. However, due to the metal used, some rust is noticeable. Thus exposed to the weather, these stoves could be altered. These two stoves present a risk factor of 1.

Figure 15. Square door (left) and rimmed stove (right) after durability test.

As for the Nansu and clay stoves, no particular changes were observed as can be seen in Figure 16.

Figure 16. Clay (left) and Nansu (right) stoves after durability test.

However, the durability of these stoves cannot be judged solely on the basis of this test. Other durability tests require, among other things, that the stove be dropped. Taking this into account, the agile stove is fragile and will break quickly if it is dropped suddenly or if too much force is exerted on it. Food preparation techniques are often brutal in Benin, especially when it is necessary to prepare maize paste or maïzena or even yam cossette paste. Taking these aspects into account means that the clay stove is not very durable because of its fragility. It is less durable than the Nansu stove, for example, whose metal coating protects the clay interior. The risk factor is therefore 0 for the Nansu and 5 for the clay stove.

4.2. Discussion

In this section, we present a discussion of our findings in relation to previous work. It must be said that few studies have addressed the study of the laboratory performance of the charcoal cookers described in this paper. In South Africa, a study carried out to assess the emissions and thermal performance of three improved charcoal cookers (the charcoal cookers of Zambia, Kenya Jiko and Madagascar) revealed that the Zambian model failed in terms of fire power, while the Kenyan Jiko and Malagasy models succeeded, with an average fire power of between 3 and 5 kW [25]. A similar study [26] carried out on four domestic cookers reveals that the clay cooking stove has an efficiency of 17.06% while the metal cooker has a thermal performance of 20.02%. The same source reveals that the clay cooker took the shortest time to bring water to the boil. This compares to our results where the clay cookers were the first to reach the local boiling temperature (100℃) fastest after 24 minutes and 32 minutes. Amiebenomo, Igbesi and Omorodion, have also shown that improving the thermal performance of cooking stoves requires insulation around the combustion chamber to reduce heat loss through the combustion chamber walls [27]. This result makes it possible to understand that the presence of clay (a good insulator) in the Nansu technology played a remarkable role in the energy performance obtained.

4.2.1. Combined analysis of energy performance, security and sustainability

The summary of the test results and the purchase price of each type of stove are summarised in the following Table 13. In terms of energy performance, the Nansu stove leads the way with 27.44%, followed by the clay stove with 25.11%. The square and circular stoves have good scores of 24.64% and 23.19% respectively. The rim stove is the most inefficient of all the stoves tested with an average total thermal efficiency of 10.58%. We note that the Nansu and clay stoves with the best energy performance are made with clay, while the other three very inefficient stoves are made of either iron or aluminium (metals). It can be deduced that the presence of clay made the difference. Clay is indeed a good thermal insulator capable of retaining heat. Several studies show that clay-based materials can reduce the energy consumption of buildings [28]. In the same sense, studies show that clay is an ecological material because of its thermal properties reducing energy consumption [29]. In summary, materials with clay baits have low thermal conductivities, thus limiting heat gains and losses [30]. In the specific case of the studied stoves, the presence of clay reduced the energy losses of the clay and Nansu stoves. The other three stoves are made of metals, which are very good thermal conductors, thus increasing the energy loss from charcoal combustion. In a previous study conducted by the International Energy Agency, it is mentioned that the energy efficiency of modern charcoal burning stoves for West Africa is on average 32%. As for traditional stoves, it is 23% [1]. Based on this information, it is understandable that the Nansu cooking stove has characteristics similar to those of modern cooking stoves. All in all, the Nansu and clay stoves are more energy-efficient than traditional stoves. Based on the results, we can identify two stoves that perform satisfactorily with a few nuances. The Nansu stove and the clay stove have the highest scores in terms of thermal efficiency and safety. In the data sheet on improved stoves in Benin published by the Ministry of Environment and Living Environment [31], the Nansu cooking stove has very good energy performance and excellent durability as well as excellent safety. In terms of durability, the Nansu cooking stove is the best while the clay cooking stove has poor durability. The Nansu charcoal stove was among the top 5 improved stoves selected for extension by the Ministry of Environment and Living Environment [31]. The best cooking stove is therefore inferred to be the Nansu stove. The clay stove also has some interesting features, but its technology needs to be improved to increase its durability.

The Nansu stove, although expensive to purchase compared to the other stoves studied, has an excellent price/performance ratio [31]. Indeed, the clay stove, although four (04) times less expensive than the Nansu stove, is not good value for money because it breaks easily and frequently and requires households to repeat the purchase several times in a year.

Table 13. Summary table of tests carried out and purchase price of stoves.

	Circular cooking stove	Square cooking stove	Rim cooking stove	Clay cooking stove	Nansu cooking stove
Thermal efficiency (%)	23.99	23.03	11.04	24.96	26.82
Overall Security Score	62	62	62.5	71.5	66.5
Sustainability risk factor	5	1	1	5	0
Purchase price in FCFA	1000	2000	3500	900	4000

4.2.2. Economic analysis

This section seeks to determine the gains from moving from other stoves to the Nansu Stove. Coal gains and payback times are estimated. As a reminder, 1 kg of charcoal saved corresponds to at least 6 kg of wood saved. For a household using a charcoal cooking stove other than Nansu, switching to Nansu will require an investment equal to the purchase price of Nansu (4000 F CFA). Taking into account the price per kilogram of charcoal on the local market (150 F CFA/kg) and the savings in charcoal generated, the financial savings and payback time will be determined. The following Table 14 shows that the investments made by households are recovered after about two (02) months at the earliest and about 12 months. The Nansu cooking stove has an average lifespan of 3 to 5 years [32]. It is therefore concluded that the Nansu stove is economical, cost-effective and therefore beneficial to households.

Table 14. Summary of economic analysis.

	Charcoal cooking stoves			
	Circular cooking stove	Square cooking stove	Rim cooking stove	Clay cooking stove
Coal savings per month in kg	2.55	3.87	15.36	2.12
Financial savings per month in FCFA	382	580	2300	318
Return on investment time	10 months and 14 days	6 months and 26 days	1 month and 22 days	12 months and 17 days

4.2.3. Socio-economic and environmental impacts

There are many environmental and socio-economic benefits to using the Nansu improved stove. Indeed, a reduction in charcoal consumption implies a reduction in the use of wood for carbonization and thus a reduction in anthropogenic pressure on the environment. Although the emissions from cooking stoves could not be studied within the framework of this work, the environmental scope of this study is all the more relevant since it contributes to the preservation of forest resources and implies a decrease in greenhouse gases (GHG).

We propose a small simulation to estimate the quantities of charcoal and wood that will be saved by promoting the Nansu-type stove that has been shown to be the most energy efficient. Suppose that a household uses a low-efficiency charcoal cooking stove with an energy efficiency score of 10.58% for example and wants to switch to a more efficient stove such as the Nansu with an energy efficiency of 27.44%. Assuming that with the inefficient stove the household uses 25 kg of charcoal per month, let us assess the savings in charcoal and wood.

The monthly useful energy of the household is given by:

$$Useful\ energy = Efficiency_{inefficient\ stove} * m * LCV \tag{7}$$

with: m the mass of charcoal (25 kg); LCV is the lower calorific value of charcoal; A switch to the Nansu improved cooking stove allows us to have a new mass of charcoal m'.

$$Efficiency_{Nansu} = \frac{Efficiency_{inefficient\ stove} * m}{m'} \tag{8}$$

It comes that:

$$m' = \frac{Efficiency_{inefficient\ stove} * m}{Efficiency_{Nansu}} \tag{9}$$

$$m' = \frac{0.1058 * 25}{0.2744} = 9.64\ kg$$

The saving in charcoal is therefore worth:

$$Saving_{Charcoal} = m - m' = 25 - 9.64 = 15.36\ kg$$

In summary, the household saves 15.36 kg of charcoal per month or 184.32 kg per year by switching to an improved cooking stove. Knowing that it takes on average in Benin 6 kg of wood to produce 1 kg of charcoal [8,9], then it is six times the mass of charcoal that is saved in terms of wood. The wood saving is therefore worth 92.16 kg per month or about 1,106 kg of wood per year for the household alone. This is a considerable saving, which is why energy policies need to be more oriented towards the promotion and popularization of improved efficient cookstoves. This study contributes to the promotion of low-carbon sustainable development by highlighting the best charcoal stove technologies that are recommended for their energy and therefore environmental performance as well as their safety and durability. The results obtained make it possible to understand that the promotion of efficient technologies has a positive impact on the environment and the economy of households that will spend less on cooking energy supply.

A reduction in the amount of charcoal used by a household as a result of adopting the Nansu improved cooking stove results in a reduced workload for women and children. Indeed, women spend on average 1.4 hours per day [1], sometimes up to 5 hours of their time per day collecting energy sources (Rysankova et *al.*, 2014) cited in [32]. This time spent collecting the energy source can be used to carry out income-generating activities for women and will allow children to spend more time studying. Several studies indicate that access to electricity improves education [33–35]. Indeed, learners spend a lot of time collecting the energy source, which prevents them from spending time studying. Also noteworthy is the reduction in cooking hours (improved energy efficiency). The resulting financial savings can be used by households to improve the standard of living and quality of life.

5. Conclusions

Through the present study, we have managed to show that among the five types of charcoal cooking stoves commonly used in Benin, only two present interesting energy performances and safety. These are the Nansu and clay stoves respectively. However, the study revealed that only the Nansu cooking stove has excellent durability with a lifespan of between 3 and 5 years. The improved stove technology should include the use of clay, as this study proves that the presence of clay improves the energy performance of the stoves. The adoption of the Nansu stove requires an initial investment of about 4000 F CFA which is recovered after 1 to 15 months depending on the type of stove used by the household. Switching to the Nansu cooking stove is beneficial in several ways. The reduction of pressure on the forests, the improvement of the household economy and the reduction of the drudgery of collecting wood for women and children. It is desirable that the authorities in charge of energy and environment issues popularize the improved stoves as much as possible to subsidize their purchase. This study could not evaluate wood-burning cookstoves and could not measure emissions from cookstoves. The next stages of research will address not only these aspects but also the implementation of new improved stove technologies.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Evrard Karol Ekouedjen: Conception or design of the work, analysis, interpretation of data for the work, Drafting the work

Latif Adéniyi Fagbemi: Revising the work critically for important intellectual content; interpretation of data for the work, Final approval of the version to be published

Stephen Junior Zannou-Tchoko: Analysis, Revising the work critically for important intellectual content

Jihane Bakounoure: The acquisition of data, interpretation of data for the work

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