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The Efficiency of a Designed and Constructed Improved Wood Burning Stove

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ABSTRACT

A study on Testing the Effectiveness of a Designed and Constructed Fuel wood Stove for Domestic Energy Consumption have been carried out in Gombe State. The general linear model for Analysis of Variance (ANOVA) and the Two Sample t-test shows significant difference between energy used in 20 households before and after intervention with t-calculated greater than t-tabulated. A two hole Multipot improved wood burning stove was designed and constructed using locally available materials. Fuel wood and Cornstalk were used as the available energy sources. Three types of fuel wood (namely mahogany, mark and tifirmi) and cornstalk were used as energy sources in comparative tests of the designed stove and the traditional stove. Three tests were carried out- Kitchen Performance Test (KPT), Water Boiling Test (WBT) and Controlled Cooking Test (CCT). The KPT compares the performance of the designed stove over and against the traditional stove. WBT determines the amount of fuel wood consumed in raising the temperature of a given quantity of water from ambient temperature to its boiling point and the time taken, while the CCT was used to determine the specific fuel consumption, time taken to cook some food samples and the amount of fuel wood used. A 3-day Kitchen Performance Test (KPT) was conducted on a single household using fuel wood and cornstalk as source of energy for both the designed stove and the traditional stove. The results indicated an average daily consumption of 231.47 MJ and a per capita consumption of 43.52 MJ with a standard deviation 13.0 between the two energy sources for traditional stove against 194.67 MJ and 36.65 MJ and a standard deviation of 5.1 between the two energy sources for the improved stove. Thereafter, 20 households were randomly selected and the same repeated. The result obtained indicates great fuel wood saving using the improved stove because the per capita daily energy consumption of households varies from 14.4 to 25.60 MJ with an average daily consumption of 19.40 MJ giving a fuel wood savings of about 50 % (44.60%).

Keywords: Stove, Energy, Efficiency, Fuelwood, Biomass and Traditional.

1.0 Introduction

Man has used fuel wood for domestic cooking for so many centuries. However, the efficiency of such traditional cooking stove has been so low and a lot of fuelwood is wasted (Danshehu and Sambo, 1993).

Fuelwood is the most readily available and utilized cooking fuel for the majority of Nigerians (Danshehu and Atiku, 2003). However, the un-coordinated felling of trees to supply the required quantities of wood without systematic replacement has encouraged desert encroachment and soil erosion. The traditional open fire method of cooking which have been used for centuries has some advantage, in that the devices are simple and cheap (Danshehu and Sambo, 1990). However, the methods leave considerable room for improvements, because they are very inefficient as only 7 % to 15 % of the potential energy in the fuel wood is utilized in the cooking process.

Several sources indicate that fuelwood is the most widely used domestic fuel Adinoyi (2009). Hall *et al.*, (1982) reported that about half of the world's population cooks with biomass fuel for all or some of their meals. The dependence on fuelwood by the rural dwellers of most developing countries including Nigeria is estimated at about 100 %, while the annual consumption of fuelwood in Nigeria is estimated at about 70 million cubic meters (Adinoyi, 2009).

The effective utilization of energy in all forms in a sustainable manner has been a global concern over the years, also the links between energy production and utilization and its consequent effects on the environment have also been a global concern. This means that the more energy is produced or used, the more the environment becomes degraded by emissions of products such as CO_2, CO, NO_2, NO, SO_2 and particulate matter that are harmful to human life and plants. The solution to this is for us to compromise and select alternative energies that have low pollution tendencies in an integrated energy management system. Fuel wood is the most readily available and utilized cooking fuel for the majority of Nigerians (Atiku and Danshehu, 2003). However, the un-coordinated felling of trees to supply the required quantities of wood without systematic replacement has led to desert encroachment and soil

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erosion. The traditional open fire methods of cooking which have been used for centuries has some advantage, in that the devices are simple and cheap (Danshehu and Sambo, 1993). However, the methods leave considerable room for improvements, because they are very inefficient as only 7 % to 15 % of the potential energy in the fuel wood is utilized in the cooking process.

In view of the above, the researcher proposes the use of improved wood-burning stoves with higher efficiency for use in Gombe State. The objective is to have increased efficiency in the use of energy, conservation and the expanded use of alternative energy sources as essential goals for effective future energy plans. It is important to note that more efforts has to be geared towards the development of an efficient and reliable energy saving stoves especially for our rural communities that constitute over 70 % of the Nigerian population (World Bank/UNDP, 1993).

Langa and Ododo (2011), discovered that most households in Gombe State (93 %) patronize fuel wood for domestic cooking. Gombe State is one of the frontline States bedeviled by desertification and most forest reserves have disappeared because of farming activities and over grazing since the State is agrarian in nature. Oral interviews conducted during this research work have indicated that people have a mindset to use fuel wood even if other alternative sources abound. In addition, as good as all the current available improved wood stove designs could be, the cost, accessibility and reliability matters. This prompted the decision to use locally available materials in this study to embark on the design of a modified improved wood-burning stove that will be within reach (in terms of construction materials) by the common man and will be readily affordable. Also, designing and construction of an improved vented mud stove with improved efficiency could reduce the quantum of fuelwood used by different households for domestic cooking thereby reducing deforestation, thereby controlling deforestation, hence controlling desertification.

This present study is designed to investigate the efficiency of a designed and constructed improved stove for domestic use in Gombe State, Nigeria. The objective of this study is to survey and examine the various existing stove designs and then improve on them by way of increasing the thermal efficiency for efficient and reliable use by entire citizenry. This will reduce the quantity of wood consumed thereby introducing some level of conservation on our forest resources.

2.0 Materials and Methods

Area of Study

Gombe State, which was created on October 1, 1996, is located in the Northeast sub-region of Nigeria. It is bounded in the north by Yobe State, in the south by Taraba and Adamawa States, in the East by Borno State and in the west by Bauchi State. It has a population of about 2.4 million people (NPC, 2006) and occupies a total landmass of 36,542.14 km^2. Although Gombe State is in Northern Nigeria and is one of the states in the northeast region, no such studies have been conducted so far. In view of the fast rate of small and medium scale industry development in the young state, there is the dire need to have a study such as the one being undertaken by the researcher. Moreover, exhaustive literature searches did not indicate the existence of any detailed domestic energy consumption survey of Gombe State; this has obviously created a need for this study.

2.1 Materials

The materials used for the construction of the improved wood-burning stove were purchased locally in Gombe, the capital of Gombe state. These include: the design mould, a special local clay, a wire mesh, binding material (Millet/Rice husk), separator (millet ash), a 3 inch metal pipe, a granulated powder of broken pots (Grog), a wooden spatula, scissors, and a ½ inch metal flat bar. These materials are discussed as follows:

i. Clay: Is the main ingredient of the construction,
ii. Millet/Rice husk: Serves as binding materials in the clay,
iii. Ash: This is a separator between the clay, hand and mould,
iv. Grog: This serves as an anti-cracking agent in the clay mixture,
v. Moulds: Two (2) moulds required for this design. The first Mould is the top of the stove which is a flat rectangular wood (or metal). The base is 80 cm in length and 36 cm in breath. It has three (3) openings of diameter, 28, 24 and 6 cm respectively. The first and second holes stands for the two (2) pots, while the last one is an opening for the chimney. The second mould is called the chimney mould which is hollow and cylindrical in shape. Results for the three (3) energy sources: mahogany (*Khaya senegalenses*), mark (Annogeissus leoicarpus) and Tifirmi (*Combretum nigricans*) were collated as indicated on Tables 1 – 6.

2.2 Methods

i. The clay with rice and millet husk in the ratio of 2:1, were mixed very well to ensure an even distribution of binding material in the clay. Water was added to make the clay pastry and soft enough to be cut and molded in different shapes without the clay sticking to the hand after touching the separator.
ii. Small quantity of ash was sprinkled on the mould and thereafter placed on the mould flat form clay.

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iii. Three (3) sides walls of the stove were erected, with length of 18 cm, leaving the side of the bigger pot
iv. A fire box by measuring 16 cm x 16 cm was erected to serve as the fire box opening (or inlet).
v. A cover was constructed with a sheet of metal inserted between the chimney hole and the chimney collar at the end side.
vi. The chimney was constructed by casting the prepared clay around the cylindrical mould that was sprinkled with ash. The mould is then removed leaving the cast chimney; about 3-4 numbers of such was constructed for one stove.
vii. The hole covers were constructed to fit the pot holes.
viii. The casted stove was allowed to dry over night and was turn upside down to allow for further drying.
ix. A chimney cover and damper were constructed separately using an iron sheet.

The constructed two-hole Improved Vented Mud Stove (IVM) was then dried and fired in a locally made kiln and thereafter used in the Water Boiling Test (WBT) using three varieties of wood source viz: Mark, Mahogany and Tifirmi. The data so obtained from these tests was used to determine the stove efficiecy, stove deleivery power, burning rate and Annual Saving Potential (AES). Controlled cooking test (CCT) was performed using three varieties of available wood sources, namely; Mark (marke local name), Tifirmi (local name), and mahogany (madachi local name).

3.0 Some Stove Parameters so Determined were:

a) Annual saving potential of the stove (AES) can be computed as:

$$AES = B_{ysaving} \times NCV_{fuelwood} \quad (1)$$

$$AES = B_y \times \left(1 - \frac{\eta_{old}}{\eta_{new}}\right) \times NCV_{fuelwood} \quad (2)$$

Where,

B_y is the quantity of fuelwood used by a household that rely on the traditional 3-stone open fire,
η_{old} is the efficiency of the traditional 3-stone stove,
η_{new} is the efficiency of the new stove, (IVM) stove, and
NCV is the net caloric value of fuelwood = 0,015 TJ/ton (or 4,167 kWh/ton.

b) The Fuel burn rate per cycle, F, may be determined by:

$$F = \frac{Amt}{t_{cycle}} \quad (3)$$

Where:

F = Fuel burn rate per cycle,
t_{cycle} = Duration of fuel burn cycle,

c) The firepower (the ratio of the energy content of the fuel consumed during a test or phase to the duration of the test or phase) is calculated as follows:

$$P - \frac{m_f h_f^o - m_c h_c^o}{T} \quad (4)$$

Where,

P is the average fire power (kJ),
m_f is the mass of fuel (kg),
h_f^o is the enthalpy of combustion of the fuel (kJ/kg),
m_c is the mass of the charcoal remaining (kg),
h_c^o is the enthalpy of combustion of charcoal (kJ/kg), and
T is the test duration.

The equivalent mass of fuel burned, on an energy basis (with reference to the unburned wood), can then be calculated in the following manner: (http://www.cookstove.net/others/fuel-economy.html)

Efficiency,

$$\eta = \frac{M_{wo} C_{pw} (T_W - T_{amb}) + (M_{wo} - M_w) H_{vw} + m\Delta T}{(M_c - M_{co}) H_{vc}} \quad (5)$$

Where,

M_{wo} is the initial weights of water,
M_w, is the final weights of water,
m, is the mass of water in the second pot,
T_w is the water temperature,
T_{amb} is the water ambient temperature,
C_{pw} is the specific heat of water,
H_{vw} is the latent heat vaporization of water;
M_{co} is the initial weights of charcoal,
M_c is the final weight of charcoal,
H_{vc} is the heat value of charcoal, and
ΔT is the temperature rise in the second pot.

The specific fuel consumption for CCT can be expressed as:

$$SFC = \frac{Mass\ of\ fuel\ consumed}{Total\ mass\ of\ cooked\ food} \quad (6)$$

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Specific fuel consumption can also be expressed as:

$$SFC = \frac{\left\lfloor W_f(1-m) - 1.5M_c \right\rfloor}{M_w} \qquad (7)$$

Where,

W_f is the final mass of fuel wood at the end of the test,
m is the moisture content of the fuel wood in (%),
M_c is the mass of charcoal and
M_w is the mass of water.

4.0 Results and Discussion

Tables 1 to 3 indicate the Water Boiling Test (WBT) carried out using a variety of locally available wood sources namely: Mark, Tifirmi and Mahogany. The results show that the time taken to heat 2.5 liters (2250 cm^3) of water from 32.50 °C to 100.00 °C varies between 7.10 minutes and 16.80 minutes, and the energy required also varies from 1825.56 to 6984.25 kJ as shown. It indicates that we consume more wood in raising the temperature of water to its boiling point using Tifirmi and Mark and less wood when mahogany is used. This is because mahogany has high calorific value than both mark and tifirmi.

Moreover, Tables 1 to 3 indicates that an energy equivalent of 0.51 to 1.94 kWh is required to raise the temperature of water from ambient temperature to its boiling point. This amount of energy is more than enough for a day's use by an individual. This creates a dire need for a continuous search for increase in the efficiency of the wood burning in thus making it more efficient.

Tables 4 - 5 represent controlled cooking test (CCT) conducted using the modified improved stove that has been designed and constructed. A variety of available wood sources are used viz: Mark, Tifirmi and Mahogany. Some quantity of raw rice (0.5 kg) was used in each case. The results indicate that the duration varies between 18.50 minutes to 34.50 minutes to cook rice. The energy required or the quantity of wood used varies from 0.65 kg (13666.25 J) for mahogany to 1.20 kg (23946.00 J). This shows it requires more amount of wood to cook rice when using tifirmi than mahogany. The Tables 4 to 6 shows that we require 3.80 to 6.65 kWh of electricity to cook rice and 4.96 to 8.04 kWh of energy to cook beans. This quantum of electrical energy is enough for a 2 day's use for a family of 5 members. This also stresses the need for an efficient way of using wood burning stove to bring to the barest minimum energy wastages.

The Specific Fuel Consumption was calculated using equation (6) as:

For mark (20284 kJ) as the wood source, we have,
SC = 0.0031

This is value of SC for rice using mahogany as fuel source and for beans, the value of SC = 0.002 was obtained.

This implies that 0.0031 kg of wood is required to cook 1 kg of food (rice) and 0.002 kg of wood is needed to cook a kg of beans. Available data indicate that for traditional stove we require 0.95 kg of wood to cook a kg of rice, 1.07 kg to cook a kg of beans and an average of 2,52 kg of wood to cook all kinds of food (Wang *et al.*, 2009). It could observe that our design is better.

Table 1: Water Boiling Test (Wood Type- Mark, 20,284 kJ/kg)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
Mass of Pot B	1.78		
M_A+M_W	4.30		
M_B+M_W	4.00		
Stove Temp T_S	34.50 °C		
Stove Temp T_F	36.7 °C		
$\Delta t = t_f - t_i$	13.5 mins		
Temp of Water T_{wi}	34.00 °C		
Temp of Water T_{wf}	98.00 °C		
Temp of Water PotB	65.80 °C		
Mass of $Wood_i$	2.25	45,639.00	12.68
Mass of $Wood_f$	2.12	43,002.08	11.95
Mass of Wood used M_u	0.13	2,636.92	0.73
Initial mass of Charcoal M_{co}	0.00		
Final Mass of Charcoal M_c	0.046		

Source: Langa, H.B. (PhD Thesis)

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In the presentdesign, a Multipot massive wood stove with chimney was used. It was highlighted much earlier what was done especially to improved upon heat losses notably the one through the flue gas, a baffle was placed between the first and second pots to get more heat to the second cooking pot. For heat loss by convection and radiation from the stove body, a paste of ash was used to paint (2 cm thickness) the outside of the stove to reduce radiation loss. Tables 5 - 6 indicate that it reduces the temperature difference to less than 1 °C between the commencements of the cooking process to the final stage. Good air draft provided by the use of chimney height of 65 cm and appropriate opening for wood inlet complete combustion was achieved.

Table 2: Water Boiling Test (Wood Type- Tifirmi, 19,955 kJ/kg)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
Mass of Pot B	1.78		
M_A+M_W	4.30		
M_B+M_W	4.00		
Stove Temp T_S	34.40 °C		
Stove Temp T_F	36.20 °C		
$\Delta t = t_f - t_i$	16.80 mins		
Temp of Water T_{wi}	33.00 °C		
Temp of Water T_{wf}	98.00 °C		
Temp of Water Pot B	58.50 °C		
Mass of $Wood_i$	2.25	44898.75	12.47
Mass of $Wood_f$	1.90	37,914.50	10.53
Mass of Wood used M_u	0.35	6,984.25	1.94
Final Mass of Charcoal M_c	0.034		

Source: Langa, H.B. (PhD Thesis)

Table 3: Water Boiling Test (Wood Type- Red Wood- Mahogany, 21,025 kJ/kg)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
Mass of Pot B			
M_A+M_W	4.30		
M_B+M_W	4.00		
Stove Temp T_S	35.00 °C		
Stove Temp T_F	36.40 °C		
$\Delta t = t_f - t_i$	7 mins 10 s		
Temp of Water T_{wi}	32.50 °C		
Temp of Water T_{wf}	98.00 °C		
Temp of Water PotB	72.00 °C		
Mass of $Wood_i$	4.60	96,715.00	26.87
Mass of $Wood_f$	4.35	91,458.75	25.41
Mass of Wood used M_u	0.25	5,256.25	0.51
Final Mass of Charcoal M_c	0.042		

Source: Langa, H.B. (PhD Thesis)

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Table 4: Controlled Cooking Test (Wood Type-Mark, 20,284 kJ/kg) (Rice)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
M_A+M_W	4.30		
Stove Temp T_S	34.50 °C		
Stove Temp T_F	35.6 °C		
$\Delta t = t_f - t_i$	30.50 mins		
Temp of Water T_{wi}	34.00 °C		
Mass of $Wood_i$	2.12	43002.08	11.95
Mass of $Wood_f$	1.22	24746.48	6.87
Mass of Wood used M_u	0.90	18255.60	5.07
Mass of Raw Rice M_r	0.50		
Mass of Cooked Rice M_{cr}	3.80		

Source: Langa, H.B. (PhD Thesis)

Table 5: Controlled Cooking Test (Wood Type - Tifirmi, 19,955 kJ/kg) (Rice)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
M_A+M_W	4.30		
Stove Temp T_S	35.4 °C		
Stove Temp T_F	36.6 °C		
$\Delta t = t_f - t_i$	34.5 mins		
Temp of Water T_{wi}	32.50 °C		
Mass of $Wood_i$	2.12	42304.60	11.75
Mass of $Wood_f$	0.92	18358.60	5.10
Mass of Wood used M_u	1.20	23946.00	6.65
Mass of Raw Rice M_r	0.50		
Mass of Cooked Rice M_{cr}	3.80		

Source: Langa, H.B. (PhD Thesis)

Table 6: Controlled Cooking Test (Wood Type - Mahogany, 21,025 kJ/kg) (Rice)

Items	Quantity (kg)	Energy (kJ)	Energy (kWh)
Mass of Pot A	2.50		
M_A+M_W	4.30		
Stove Temp T_S	35.00 °C		
Stove Temp T_F	36.20 °C		
$\Delta t = t_f - t_i$	18.50 mins		
Temp of Water T_{wi}	33.00 °C		
Mass of $Wood_i$	2.50	52562.50	14.60
Mass of $Wood_f$	1.85	38896.25	10.80
Mass of Wood used M_u	0.65	13666.25	3.80
Mass of Raw Rice M_r	0.50		
Mass of Cooked Rice M_{cr}	2.02		

Source: Langa, H.B. (PhD Thesis)

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In the present design, a Multipot massive wood stove with chimney was used. It was highlighted much earlier what was done especially to improved upon heat losses notably the one through the flue gas, a baffle was placed between the first and second pots to get more heat to the second cooking pot. For heat loss by convection and radiation from the stove body, a paste of ash was used to paint (2 cm thickness) the outside of the stove to reduce radiation loss. Table 1 - 6 indicate that it reduces the temperature difference to less than 1 °C between the commencements of the cooking process to the final stage. Good air draft provided by the use of chimney height of 65 cm and appropriate opening for wood inlet complete combustion was achieved.

4.1 The Result of the Stove Efficiency

The result of the stove efficiency (equation 5) were as follows

a. Data obtained from Water Boiling Test (WBT)

T_{amb} = 34.0 °C (307 K)
T_w = 98.0 °C (371 K)
M_{wo} = 1.80 kg
M_w = 1.74 kg
M_c = 0.046 kg
M_{co} = 0.00 kg
C_{pw} = 4200 J/kg K
H_{vw} = 2.26 MJ/kg
H_{vc} = 21.40 MJ/kg
M_{ws} = 1.78 kg
T_{ws} = 65.0 °C

Inserting the data into equation (5), we have;

$$\eta = 0.65446.$$

This formula has been used by many Researchers (VITA, 1982, Geller, 1981 and Bhatt, 1981)

Delivery Power

This quantity measures the amount of power delivered to the cooking pots, and in this case the first pot in the water boiling test. Here equation (4) is employed as:

b. Data

t = 430 seconds,
ΔT = (371 – 305.5) K = 65.5 K,
V = 0.225 m³

Inserting the given values P in kW was obtained as:

$$P = 2.56 \text{ kW}.$$

This is the amount of power delivered to the first pot during the water boiling test (WBT).

The burning rate of the fuelwood can be expressed as in equation (3) as

c. Data

X is the moisture content of the fuelwood (assumed to 20 % of fuelwood used)

X = 0.026 kg,
H_C = 21,400 kJ,
H_W = 20284 kJ,
M_w = 0.13 kg,
Mc = 0.046 kg, and
t = 7.0 minutes.

Inserting these values into equation (2.12), we obtain the burning rate as:

$$F = 1.326 \text{ kg/min}.$$

Thermal Efficiency

Recall equations (2.13) and (2.14), thermal efficiency was computed thus:

d. Data

Where,

C_w = 4,200 J/kg
C_p = 910 J/kg/K
L_v = 2,256, 000 J/kg
M_V = 1.78 Kg
C_F = 20,284,000 J/kg/K
M_W = 2.25 kg
M_F = 0.0252 kg
M_C = 0.046 kg
M_p = 2.50 kg
C_C = 21,400,000J/kg/K.
T_f = 100.0 °C
T_i = 34.5 °C

Inserting these values into equation (3), we obtain the percentage heat utilized (PHU) as:

$$PHU = 49.337\ \%.$$

The thermal efficiency, therefore becomes,

$$\eta_{th} = Burningrate \times PHU$$

$$= 65.42\ \%$$

Annual saving potential of the stove (AES) can be computed using equation (1) as:

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e. Data

NCV is the net caloric value of fuelwood = 0,015 TJ/ton (or 4,167 kWh/ton).
Now, with an average daily consumption of 10.03 kg of fuelwood for households who depends solely fuelwood,

B_y = 3610.8 kg

η_{old} = 0.25

η_{new} = 0.6545

Inserting these values into equation (1), we obtain AES as:

$$AES = 33.33 \times 10^9 \text{ J}$$

This implies that the new stove has a potential of saving 33.33 x 10^9 J of energy per annum for a household that rely solely on the traditional 3-stone stove for domestic cooking. In other words, the Improved Vented Mud (IVM) stove saves 33.33 x 10^9 J of energy per annum for a household.

5.0 Conclusions

The researchers have been able to achieve the following in this research work:

i. Designed and constructed a modified improved Multipot cook stove of two (2) holes,
ii. Determined the efficiency of the modified improved cook stove, which was found to be 65.45 %,
iii. Performed Water Boiling Test (WBT) using three wood samples Mark, Tifirmi and Mahogany and found that it takes between 7.00-16.8 minutes to boil (2250 cm^3) of water from 32.50 °C to 98.00 °C, and the energy required also varies from 1825.56 to 6984.25 kJ,
iv. The specific fuel consumption was found to be 0.0031 for mark and 0.002 for mahogany using rice as food sample,
v. The cost implication for unit of the modified improved stove is N3,700.00,
vi. Achieved an energy savings of about 24.12 MJ in a household,
vii. The repeated use of the same stove by different households may introduce some variations which were not taken into consideration in this research work.

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