

Application of Statistical Design of Experiments to Performance Analysis of Charcoal Cooks Stoves

André Ndécky¹, Sébastien Gamache¹, Fabé I. Barro², Issakha Youm^{1,2}

¹Centre d'Etudes et de Recherches sur les Energies Renouvelables (CERER), Dakar, Sénégal

²Laboratoire des Semi-Conducteurs et d'Énergie Solaire (LASES), Département de Physique, Faculté des Sciences et Techniques, Université Cheikh Anta Diop de Dakar, Dakar, Sénégal

Email: andoondecky@yahoo.fr

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Abstract

The Design of Experiments (DOE) and the Analysis of Variance (ANOVA) are used to determine the effect of fuel type, fuel initial load, secondary air inlet and ventilation on thermal efficiency and CO emission of two biomass fire cookstoves during boiling or simmering. Analysis of variance with Fischer's statistical test (F-test) and Newman-Keuls test were applied to establish the influence of the independent parameters on the studied responses. The results of this study are useful to application of charcoal cooks stoves.

Keywords

Biomass Combustion, Charcoal Stove, Thermal Efficiency, Water Boiling Test, Carbon Monoxide Emission, ANOVA

1. Introduction

Energy use is closely linked with economic development, poverty reduction and the provision of vital services. Solid biomass energy (fuel wood, charcoal, agricultural residues, animal dung, etc.) plays a vital role in meeting local energy demand in many Sub-Saharan Africa (SSA) countries. Fuel wood is predominantly used by rural people, while charcoal is the preferred cooking fuel for most urban and peri-urban dwellers [1]. Basic Charcoal or lump charcoal is usually produced by a process known as slow pyrolysis, by heating wood or other biomass inside relatively air tight enclosure, like an earth covered pit in the ground (earth mound kiln). Reliance on wood-based biomass energy contributes sub-

stantially to continuing process of deforestation and soil erosion, and significantly to greenhouse gases (GHG) and black carbon emissions, fostering the global climate change [2] [3] [4] [5]. Besides being a major threat to the environment, burning wood-based biomass releases dangerous particulate matter (PM), carbon monoxide (CO), and other toxic pollutants due to incomplete combustion and leads to household air pollution (HAP) [6] [7] [8]. HAP is considered as a major contributor to several human health diseases such as acute low respiratory infection, chronic obstructive lung diseases, cataracts, etc. [8] [9]. In Senegal, exposure to HAP was responsible for at least 8,400 premature deaths and 24,000 disability-adjusted life years (DALYs), in 2010 [10] [11].

Wood fuel and charcoal meet approximately 52.3% of Senegal's domestic fuel requirements [12]. A national survey conducted recently with detailed questions on households cooking energy consumption and practices, revealed that the largest proportion of biomass fuel consumption consisted mainly of wood (61%) and charcoal (29%) [13]. More wood and consequently more forest are needed for producing charcoal in order to meet the demand, mainly from urban and semi-urban areas. This demand for solid wood outweighs natural regeneration and therefore puts Senegal's forest under tremendous pressure and has severe consequences for the ecosystem as a whole.

Therefore, improved cook stoves (ICS), (*i.e.* stoves with high efficiency, cleaner combustion and better safety) received significant attention as intermediate technologies to address adverse health and environmental impacts [14] [15].

Many authors suggested the use of insulation and radiation shields to decrease energy loss and optimizing heat transfer in order to improve charcoal stoves [16] [17] [18] [19]. However, by reducing the volume of the combustion chamber to a strict minimum and by controlling the space through which hot air can leave the combustion chamber, the traditional charcoal stove "Éclair-Taaru"¹ could be improved [20]. The channel gaps under and around the pot can be sized to optimize heat transfer efficiency [21]. Adding jets of preheated secondary air above the burning fuel is a technique suggested to decrease CO emission while using less fuel [22] [21]. Cook stove performance and emissions evaluation is influenced by a number of process factors including cook stove design, fuel type, pot, operational factors... and sometimes they are often ignored by researchers [23]. MacCarty *et al.* (2010) [24] reported that adding fan to a wood-burning stove reduce dramatically the average of CO and PM in the test kitchen and under the emissions hood. The study of Bentson *et al.* (2013) inferred the initial fuel load as an important and determining variable influencing the charcoal cook stove performance. An investigation on semi-gasifier biomass cook stoves concluded that emissions and efficiency varied substantially with stove design and fuel type [24].

However, to the best of our knowledge, no attempt has been made to study the interactive effect of process variables. Multivariate statistical techniques have

been used for analyzing situation in which a response of interest is influenced by several variables. In addition, these techniques are very useful tools to reduce the time and cost of studies and to obtain more information per experience [25]. The most commonly used statistical method is design of experiments (DOE), to predict the relationship between the responses and independent variables, especially if there is a need to optimize the responses of a process [26]. Now, there is a growing body of literature documenting the application of design of experiment (DOE) for process optimization [27]-[32]. Hence, this present paper aimed to evaluate the individual and interactive effect of some parameters such as stove type (stove with secondary inlet or without); fuel type, fuel initial load and venting that are likely to affect performance of charcoal cook stoves in terms of thermal efficiency and emissions. The outcome of this study will be useful to understand in depth-knowledge regarding the principal factors which are most influential on the response of cook stoves as well as their statistical significance.

2. Materials and Methods

2.1. “Éclair-Taaru” Stove

Cooking with charcoal in Sub-Saharan Africa is typically performed with a simple stove usually made out of scrap sheet metal by local artisans generally named “Malgache” with no airflow control. With this stove, the pot sits directly on the charcoal bed and can block the air passage in combustion chamber [20].

The improved cook stove (ICS) selected for this study is a new innovative design of charcoal ICS developed by GIZ firstly in Benin and Burkina Faso, called the “Éclair” referring to the fact that the device is fastest than other cook stove [33] and recently in Senegal, where it has been renamed “Éclair-Taaru”. “Taaru” in local language means beautiful referring to the fact that the device take care of users’ health, economy and environment.

To make difference between the stove with secondary air inlet and the stove without secondary air inlet, two stoves are considered in this study: “Éclair-Taaru”1 stove and “Éclair-Taaru”2 stove. That will limit the variability of certain factors.

The “Éclair-Taaru” (**Figure 1**) works as a “quasi-gasifier” with natural air convection. The stove is made from metal sheets and local tinsmiths are trained to manufacture the stoves. The air inlet compartment consists of two concentric cylinders acting as primary/secondary air separator to separate flow passage of two combustion airs. Very few charcoal stoves have a secondary air controller. Primary air enters through a side door which can also be opened and close to regulate airflow. Inflow of primary air supplies the charcoal in the combustion chamber from underneath. Provision of primary/secondary air separator allows secondary air to enter at the bottom holes of the outer cylinder and to get heated and rise upward towards combustion chamber at of just above the top level of the burning fuel. Preheated secondary air between the metal walls is then mixed with existing volatile contents efficiently to ensure complete combustion.

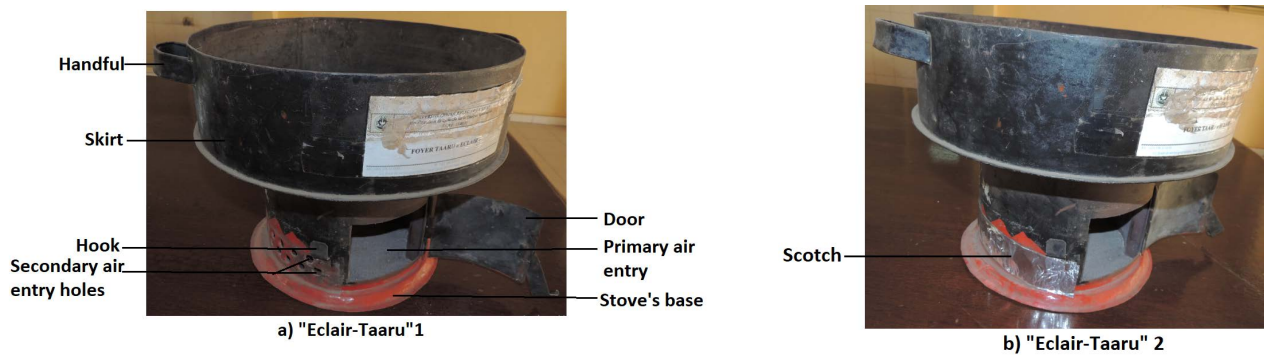


Figure 1. Pictorial view of the improved “Éclair-Taaru” charcoal cooking stove.

Primary and secondary airflow can be driven externally by a fan or blower. To avoid variations due to the change of cook stove, we have simply blocked the secondary air holes with the Scotch (or Duktape) that give us “Éclair-Taaru”2 stove (**Figure 1(b)**) without secondary air.

2.2. Fuels Used

The stoves were tested with two different fuel types: natural wood charcoal and typha lump charcoal. Wood charcoal is bought in Dakar local market and come from South and/or East Senegal by using many different wood trees. For the typha lump charcoal, it’s produced in Noth Senegal (Saint Louis) by family business. Wood charcoal in Senegal is produced by carbonizing wood in a low-oxygen atmosphere using traditional or improved Casamance kiln and can be purchased in the local market. The gathered charcoal consisted of a combination of thin and thick pieces randomly distributed. Typha lump charcoal obtained through agglomeration, from invasive *typha australis* are produced in a process including carbonization in kilns and agglomeration. The briquettes can have additive such as clay or molasses as binding agent. Typha lump charcoal used in this work have round forms. Indeed it has been proven by other researchers that variations in fuel dimensions have little influence and sometimes do not even influence the results on emissions and performance of cookstove. The effects of the size of wood fuel on efficiency and emission of the stoves was investigated. The fuel size had no significant influence on the efficiency of the stove. It was observed that burn rate increased as the size of fuel decreased. Burn rate can be regarded as comparable to firepower. It has been reported that with increasing firepower, generally stove efficiency tends to reduce, as more energy is lost to the surroundings rather than transferred to the pot [34]. The properties of the two fuel types are shown in **Table 1**.

2.3. Test Protocol

The Water Boiling Test (WBT) protocol “Version 4.2.2. (2013)” was used to determine cook stove power, energy efficiency and emissions (CO, CO₂ and PM). It is an internationally well known and well defined protocol that can be used to

Table 1. Fuels characteristics.

Fuels	Moisture mass fraction (%)	Volatil Mater (%)	Ash (%)	Fixed Carbon (%)	HCV (J/kg)
Wood Charcoal	5.05	39.94	7.05	53.01	$27,509.59 \times 10^3$
Typha lump charcoal	5.66	52.95	43.22	3.83	15479.13×10^3

test and compare any cook stove in the field and in the laboratory. This allows WBT results from any laboratory to be compared with those from other laboratories using other stoves. However, WBT is a simulation of actual cooking activities in communities. Intend at the design phase for relatively fast feedback on design modifications. The WBT consists of three phases:

- The first phase is the high power test or cold-start, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood or other fuel to boil a measured quantity of water in a standard pot.
- The second phase, the high-power test or hot-start, follows immediately after the first while stove is still hot. Again, the tester uses a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot.
- The third phase or low power test follows immediately from the second. Here, the tester determines the amount of fuel required to simmer a measured amount of water at just below boiling for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

The same initial charge is used for the boiling and simmering of the water throughout the test, no other fuel is added.

Thermal efficiency and emissions data were collected only for high-power cold start and low-power. The hot start was omitted to save testing time. In the high power cold start the test begins with the cook stove, pot and water at ambient temperature and uses a pre-weighed amount of charcoal to boil 5 liters of water in a standard pot. The low-power simmering phase continues immediately from the cold start and used to simmer water 3°C below boiling temperature for 45 min. For stove with a door to control air supply, the door was kept open for high-power cold start test and closed during low power test.

2.4. Experimental Design and Statistical Analysis

The experimental design for the study consisted of four factors (or independents variables): cook stove type (traditional stove, improve cook stove), fuel type (lump charcoal, briquettes), fuel initial load (maximum load, minimal load) and ventilation (with ventilation, without ventilation); each with two levels denoted by (“low (-1)” and “high (+1)”). Independent variable and their levels are presented in **Table 2**. Analysis of variance (ANOVA) with Fisher’s statistical test (F-test) was applied to ascertain statistical significant difference in average values of factors and their interaction at a confidence level of 95% [35]. Further, Newman-Keuls test was conducted in order to identify factors means that are significantly different from each other.

Table 2. Independent variables and their levels used in the experimental design.

Response	Variables	Symbol coded	Range and levels	
			+1	+1
Y_{eff} . Thermal Efficiency	Stove type	X_1	“Éclair-Taaru”1	“Éclair-Taaru”1
	Fuel type	X_2	Wood Charcoal	Wood Charcoal
Y_{em} -CO Emission	Fuel initial load	X_3	0.73 kg or 1.00 kg	0.73 kg or 1.00 kg
	Fan	X_4	With Ventilation	With Ventilation

A general linear interaction model Equation (1) which accounts for the main effect of factor with their interaction effects was considered in this study [36] [37].

Usually, two values (called levels) of the X 's are used in the experiment for each factor. The response functions measured were emission Y_{em} and efficiency Y_{eff} . The responses were related to coded value (X_i) by linear interaction model shown in Equation (1).

$$Y = \beta_o + \sum_{i=1}^4 \beta_i X_i + \sum_{i=1}^4 \sum_{j=1}^4 \beta_{ij} X_i X_j + \sum_{i=1}^4 \sum_{j=1}^4 \sum_{k=1}^4 \beta_{ijk} X_i X_j X_k + \beta_{ijkl} X_i X_j X_k X_l + \varepsilon_{m(ijkl)} \tag{1}$$

with: $i \neq j; i \neq k; j \neq k$

where

Y : is the predicted response of the process (% yield of thermal efficiency (Y_{eff}) or CO emissions (Y_{em}))

β_o = the overall mean response

β_i = the main effect for factor ($i = 1, 2, 3, 4$)

β_{ij} = the two-way interaction between the i th and the j th factors,

β_{ijk} = the three-way interaction between the i th, j th, and k th factors

β_{ijkl} = the four-way interaction between the i th, j th, k th, and l th factors.

$\varepsilon_{m(ijkl)}$: is the experimental error which is due to different variations of the environment or uncontrollable variables.

Table 3 presents the mechanism interaction effects

Columns of same color have the same combinations and produce the same result in the final answer.

$x_1^0 x_2^0 x_3^0 x_4^0 = (1)$: indicates that the 4 factors are at their low level

$x_1^1 x_2^1 = x_1 x_2$: indicates that the 2 factors are at their highest level as well as for

$x_1 x_3, x_2 x_3, x_2 x_4, \dots$

$x_1^1 x_2^1 x_3^1 x_4^1 = x_1 x_2 x_3 x_4$: indicates that the 4 factors are at their highest level.

Table 4 presents the general content of an ANOVA table.

$$df = \text{number of levels} - 1 = (2 - 1) = 1$$

$$df_{error} = (\text{total number of tests} - \text{number of tests without repetition}) - 1 = (24 - 8) - 1 = 15 \tag{2}$$

$$df_{tot} = \text{number of tests} - 1 = (24 - 1) \tag{3}$$

Table 3. Mechanism of interactions.

Runs	Combination	The mechanism interactions effects														
		X_1	X_2	X_3	X_4	X_1X_2	X_1X_3	X_1X_4	X_2X_3	X_2X_4	X_3X_4	X_3X_4	$X_1X_2X_4$	$X_1X_3X_4$	$X_2X_3X_4$	$X_1X_2X_3X_4$
1	(1)	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
2	x_2x_4	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
3	x_1x_3	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
4	x_1x_2	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
5	x_2x_3	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
6	$x_1x_2x_3x_4$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	x_3x_4	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
8	x_2x_4	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
9	x_2x_4	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
10	$x_1x_2x_3x_4$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	x_3x_4	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
12	x_1x_4	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
13	(1)	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
14	x_2x_3	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
15	x_1x_3	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
16	x_2x_3	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
17	(1)	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
18	x_1x_4	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
19	x_1x_3	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
20	x_1x_2	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
21	$x_1x_2x_3x_4$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
22	x_3x_4	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
23	x_1x_4	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
24	x_1x_2	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1

Table 4. Analysis of the variance.

Source of variation	Degrees of freedom (DF)	Sum of Squares (SS)	Means of Squares (MS)	F-value	F-critical
Treatment (A or B or ...)					
Error					
Total					

$$SS_A = \frac{(\sum A_{-1})^2 + (\sum A_{+1})^2}{\text{number of } A_{-1}(12)} - \frac{(\sum_{tot})^2}{24} \tag{4}$$

$$SS_{AB} = \frac{(\sum A_{-1}B_{-1})^2 + (\sum A_{-1}B_{+1})^2 + (\sum A_{+1}B_{-1})^2 + (\sum A_{+1}B_{+1})^2}{\text{total number of } A_iB_j(6)} \tag{5}$$

$$- \frac{(\sum_{tot})^2}{24} - SS_A - SS_B$$

$$SS_{tot} = \frac{\sum (tot)^2}{1} - \frac{(\sum tot)^2}{24} \quad (6)$$

$$SS_{error} = SS_{tot} - \sum_{i=1}^n SS_i \quad (7)$$

$$MS_A = \frac{SS_A}{df_A} \quad (8)$$

$$\text{Ratio or } F_{Value(A)} = \frac{MS_A}{MS_{error}} \quad (9)$$

F-critical is obtained by looking at the fisher table (at the 5% level) between the value given by the DF line of the numerator and DF column of the denominator.

where:

df is degrees of freedom

SS is Sum of Squares

MS is Means of Squares

3. Results and Discussion

3.1. Results

The 2-levels half fractional factorial design was employed to assess the effects of the independent variables on the response functions Y . Therefore a total of $2^{4-1} \times 3 = 24$ runs of randomize experiments was conducted. The experimental plan which contains the run of test, the factors model, the fuel load used for each test and the responses Y_{eff} and Y_{em} corresponding respectively to thermal efficiency and CO emissions are in **Table 5**.

3.2. Discussion: Interpretation of Results by ANOVA Analysis

Analysis of variance with Fischer's statistical test (F-test) was applied to establish the influence of the independent parameters on the studied responses.

The interpretation of results is based on compared the F-value and F-critical. It is found that in **Table 6** the fuel type (X_2) has the highest influence on thermal efficiency, followed by the fuel load (X_3) and the interaction stove type-fuel type (X_1X_2) or the alias fuel load-fan (X_3X_4), respectively.

Alias are interactions which have the same effect on the response simultaneously with the source. To know which of fuel type (Typha lump charcoal or wood charcoal) and fuel load (minimal or maximal load) or which of interaction (X_1X_2) or (X_3X_4) provide better effect on thermal efficiency, we calculate the mean of thermal efficiency for each one. The average of each of the levels of the main factors X_2 (fuel type) and X_3 (initial fuel load) is in **Table 7**.

In **Table 7**, extraction of the average of each level, we show a significant difference between the levels. The level with the highest mean is the optimum level "PANDEY *et al.* (2014)" Therefore, from the above analysis, it is observed that charcoal and minimum load (fill in under the combustion chamber holes) are parameters which mainly affect the thermal efficiency.

Table 5. Experimental plan with responses.

Runs	coded values				Fuel weight (kg)	Y_{eff} (%)	Y_{em} (kg/s)		Boiling time (s)
	X_1	X_2	X_3	X_4			CO boiling	CO simmer	
1	-1	-1	-1	-1	0.73	27.5	74.5×10^{-6}	38.8×10^{-6}	2280
2	-1	1	-1	1	0.50	29.5	21.2×10^{-6}	9.67×10^{-6}	1080
3	1	-1	1	-1	1.00	21.1	40.7×10^{-6}	28.8×10^{-6}	3000
4	1	1	-1	-1	0.50	31.0	11.2×10^{-6}	3.00×10^{-6}	1740
5	-1	1	1	-1	0.73	22.4	5.67×10^{-6}	0.83×10^{-6}	2220
6	1	1	1	1	0.73	26.7	22.7×10^{-6}	3.33×10^{-6}	1260
7	-1	-1	1	1	1.00	21.9	34.5×10^{-6}	16.8×10^{-6}	1560
8	-1	1	-1	1	0.50	27.3	0.83×10^{-6}	9.83×10^{-6}	1020
9	-1	1	-1	1	0.50	29.2	19.0×10^{-6}	8.33×10^{-6}	1140
10	1	1	1	1	0.73	27.3	14.0×10^{-6}	3.67×10^{-6}	900
11	-1	-1	1	1	1.00	22.7	13.2×10^{-6}	6.17×10^{-6}	1800
12	1	-1	-1	1	0.73	24.4	14.5×10^{-6}	7.50×10^{-6}	1680
13	-1	-1	-1	-1	0.73	26.1	44.5×10^{-6}	44.5×10^{-6}	2400
14	-1	1	1	-1	0.73	20.9	34.2×10^{-6}	6.67×10^{-6}	1980
15	1	-1	1	-1	1.00	25.9	27.3×10^{-6}	14.5×10^{-6}	2580
16	-1	1	1	-1	0.73	26.0	46.8×10^{-6}	8.83×10^{-6}	1800
17	-1	-1	-1	-1	0.73	23.6	106.2×10^{-6}	74.5×10^{-6}	2940
18	1	-1	-1	1	0.73	23.6	16.8×10^{-6}	10.7×10^{-6}	1440
19	1	-1	1	-1	1.00	24.6	23.2×10^{-6}	12.7×10^{-6}	2880
20	1	1	-1	-1	0.50	29.5	8.33×10^{-6}	6.50×10^{-6}	1860
21	1	1	1	1	0.73	29.0	11.0×10^{-6}	0.83×10^{-6}	840
22	-1	-1	1	1	1.00	24.4	73.3×10^{-6}	22.7×10^{-6}	1020
23	1	-1	-1	1	0.73	25.9	22.3×10^{-6}	18.0×10^{-6}	1860
24	1	1	-1	-1	0.50	29.8	20.5×10^{-6}	13.7×10^{-6}	2040

Table 6. ANOVA thermal efficiency.

SOURCE	Degree of Freedom (DF)	Alias	Sum of Squares (SS)	Mean of Squares (MS)	F-value	F-critical
X_1 (Stove type)	1	$X_2X_3X_4$	0.00124	0.00124	4.06	4.54
X_2 (Fuel type)	1	$X_1X_3X_4$	0.00572	0.00572	18.72	4.54
X_3 (fuel load)	1	$X_1X_2X_4$	0.00498	0.00498	16.30	4.54
X_4 (fan)	1	$X_1X_2X_3$	0.00005	0.00005	0.15	4.54
X_1X_2	1	X_3X_4	0.00148	0.00148	4.83	4.54
X_1X_3	1	X_2X_4	0.00098	0.00098	3.20	4.54
X_1X_4	1	X_2X_3	0.00075	0.00075	2.45	4.54
$X_1X_2X_3X_4$	1	(1)	0.00000	0.00000	0.00	4.54
ERROR	15		0.00458	0.00028		
TOTAL	23		0.01977			

Table 7. Optimal levels of thermal efficiency.

FACTOR CODE	MAIN FACTORS	MEAN (%)
X_2 (fuel)	Typha lump charcoal	24.3
	Wood Charcoal	27.4
X_3 (load)	Minimum load	27.3
	Maximum load	24.4

For interactions (X_1X_2 or X_3X_4) which have significant effect on thermal efficiency, extraction of their average is not enough to concluded on which interaction have really significant effect.

The ANOVA study only can't distinguish differences due to interaction factors in the responses. To know which interaction at which levels has significance effect, we do the Newman-Keuls test and results are in **Table 8**.

Newman-Keuls test in **Table 8** shows that three interactions (“Éclair-Taaru”1-charcoal, minimum initial load-without fan and minimum initial load-with fan) generate a very near mean and have the highest significant effect on thermal efficiency. On the other hand, interaction “Éclair-Taaru”1-charcoal is the optimal level whit 28.9% of thermal efficiency. The interaction minimum initial load-with fan has lower effect among significant interaction factors. So fan does not make any difference to the thermal efficiency. When the results are very close, the Newman-keuls test says that interactions have same effect on the response: either their effect is significant or not.

To maximize the thermal efficiency in this study, we should use “Éclair-Taaru”1 stove, with minimal initial load of wood charcoal fuel and with or without fan. For this first analysis, secondary air stove (“Éclair-Taaru”1) is better than stove without secondary air (“Éclair-Taaru”2).

Therefore the efficiency of charcoal cookstove depends on the nature of the charcoal (lump charcoal or wood charcoal), the initial load of charcoal and the presence of secondary air.

Table 9 shows that X_1 (Stove type) and X_2 (Fuel type) are factors which have significant effect on CO emissions during cold start. The most important effect is produced by fuel type. To know which fuel between wood charcoal and *typha* lump charcoal and which stove (“Éclair-Taaru”1 or “Éclair-Taaru”2) provide the best effect, we calculate the mean of each level. **Table 10** presents the results.

As what is desired here is to minimize CO emissions, extraction mean of analysis of variance showed a significant difference between the levels and the optimal levels of significant factors are “Éclair-Taaru”1 and wood charcoal. The “Éclair-Taaru”2 cookstove produce much CO and lump charcoal too. The difference between stoves is the secondary air. So this secondary air contributes to reduce CO emissions during the boiling phase. The significant factors are factors which minimize CO emissions in the boiling phase.

Table 8. Optimal levels of thermal efficiency (interactions effect).

Factors combination	INTERACTIONS	Mean (%)
X_1X_2 (Stove – fuel)	“Éclair-Taaru”2-Typha lump charcoal	24.4
	“Éclair-Taaru”2-Wood charcoal	25.9
	“Éclair-Taaru”1-Typha lump charcoal	24.2
	“Éclair-Taaru”1-Wood Charcoal	28.9
X_3X_4 (load – fan)	Minimum initial load-Without fan	27.9
	Minimum initial load-With fan	26.6
	Maximum initial load-Without fan	23.5
	Maximum initial load-With fan	25.3

Table 9. CO emissions during boiling phase ANOVA.

SOURCE	Degree of Freedom (DF)	Alias	Sum of Squares (SS)	Mean of Squares (MS)	F-value	F-critical
X_1 (Stove type)	1	$X_2X_3X_4$	8.7	8.7	6.96	4.54
X_2 (Fuel type)	1	$X_1X_3X_4$	11.4	11.4	9.07	4.54
X_3 (fuel load)	1	$X_1X_2X_4$	0.0	0.0	0.02	4.54
X_4 (fan)	1	$X_1X_2X_3$	4.8	4.8	3.85	4.54
X_1X_2	1	X_3X_4	3.9	3.9	3.11	4.54
X_1X_3	1	X_2X_4	1.6	1.6	1.29	4.54
X_1X_4	1	X_2X_3	2.1	2.1	1.71	4.54
$X_1X_2X_3X_4$	1	(1)	0.0	0.0	0.00	4.54
ERROR	15		18.9	1.3		
TOTAL	23		51.5			

Table 10. Optimum levels of CsO at the boiling.

FACTOR CODE	MAIN FACTORS	MEAN ($\text{kg}\cdot\text{s}^{-1}$)
(Stove type)	“Éclair-Taaru”1	19.3×10^{-6}
	“Éclair-Taaru”2	39.5×10^{-6}
(Fuel type)	Wood charcoal	18.0×10^{-6}
	Typha lump charcoal	41.0×10^{-6}

The other factors or interactions factors have not significant effect on CO emissions during the boiling phase. Those factors which are not significant on CO emissions can be used at the level desired by the experimenter or the cooker.

In **Table 11**, except the interaction X_1X_4 or X_2X_3 all factors and interaction have significance effect on CO emissions during the simmer. But the most

Table 11. CO emissions during simmer phases ANOVA.

SOURCE	DF	Alias	SS	MS	F-value	F-critical
X_1 (Stove type)	1	$X_2X_3X_4$	2.31	2.31	8.13	4.54
X_2 (Fuel type)	1	$X_1X_3X_4$	7.31	7.31	25.67	4.54
X_3 (fuel load)	1	$X_1X_2X_4$	2.14	2.14	7.50	4.54
X_4 (fan)	1	$X_1X_2X_3$	2.76	2.76	9.69	4.54
X_1X_2	1	X_3X_4	1.44	1.44	5.04	4.54
X_1X_3	1	X_2X_4	2.46	2.46	8.64	4.54
X_1X_4	1	X_2X_3	0.64	0.64	2.26	4.54
$X_1X_2X_3X_4$	1	(1)	0.00	0.00	0.00	4.54
ERROR	15		4.27	0.28		
TOTAL	23		23.34			

important effect is provided by the fuel type. To know which fuel between wood charcoal and *typha* lump charcoal provide the best effect; for this purpose, the test of Newman-keuls is necessary.

In **Table 12** average levels of different factors which have significant influence on CO emission help us select the optimal factors to minimize emissions.

Table 12 groups together the mean of main factors and Newman-keuls test results (interactions effects). It is found that among the main of significant factors: “Éclair-Taaru”1 stove, wood charcoal, with maximum initial load and presence of fan are optimal level because they minimize CO emissions during simmering phase.

So wood charcoal, maximum initial load and presence of fan (ventilation) have good effect on CO emissions during the simmer phase when they are used on the “Éclair-Taaru”1 stove however this is not the same on the “Éclair-Taaru” 2 (without secondary air inlets). Typha lump charcoal with minimum initial load, and without fan have bad effect on CO emissions during the simmer when they are used on “Éclair-Taaru”2. The secondary air has positive effect on CO emissions and type of fuel has the higher effect. The control of type of stove and type of fuel are very important during the test or during the cooking.

Fuel type (X_2) and fan (X_4) present the higher effect on water boiling time.

The boiling time ANOVA in **Table 13** shows that both factors (fuel type and fan) have a significant effect on the boiling time of the water. The fan has a very significant effect (92.40) while the fuel type has a slightly significant effect (35.95). Remember that the production and quantity of heat depends on these two factors (oxygen and fuel). These two factors entering into the combustion reaction produce heat used to boil the water. On the other hand, we do not know at what level the type of fuel and the fan allow us to reach boiling in record time. It is thanks to **Table 14** that we have decided on this fact.

Table 12. Optimal levels of CO at simmer.

FACTOR CODE	MAIN FACTORS	MEAN (kg·s ⁻¹)
X_1 (Stove type)	“Éclair-Taaru” 1	10.33×10^{-6}
	“Éclair-Taaru” 2	20.67×10^{-6}
X_2 (Fuel type)	Wood charcoal	6.33×10^{-6}
	Typha lump charcoal	24.67×10^{-6}
X_3 (load)	Maximum initial load	10.50×10^{-6}
	Minimum initial load	20.50×10^{-6}
X_4 (Fan)	With fan	9.83×10^{-6}
	Without fan	21.17×10^{-6}
INTERACTIONS		MEAN (kg·s ⁻¹)
X_2X_3 (Fuel type—load)	Typha lump charcoal—Min load	32.33×10^{-6}
	Typha lump charcoal—Max load	17.00×10^{-6}
	Wood charcoal—Min load	8.50×10^{-6}
	Wood charcoal—Max load	4.00×10^{-6}
X_1X_4 (Stove type—fan)	“Éclair-Taaru”2—without fan	29.00×10^{-6}
	“Éclair-Taaru”2—With fan	12.17×10^{-6}
	“Éclair-Taaru”1—Without fan	13.17×10^{-6}
	“Éclair-Taaru”1—With fan	7.33×10^{-6}

Table 13. Time to boil water ANOVA.

SOURCE	DF	Alias	SS	MS	F-value	F-critical
X_1 (Stove type)	1	$X_2X_3X_4$	8.17	8.17	0.44	4.54
X_2 (Fuel type)	1	$X_1X_3X_4$	661.50	661.50	35.95	4.54
X_3 (fuel load)	1	$X_1X_2X_4$	1.50	1.50	0.08	4.54
X_4 (fan)	1	$X_1X_2X_3$	1700.17	1700.17	92.40	4.54
X_1X_2	1	X_3X_4	48.17	48.17	2.62	4.54
X_1X_3	1	X_2X_4	20.17	20.17	1.10	4.54
X_1X_3	1	X_2X_3	0.17	0.17	0.01	4.54
$X_1X_2X_3X_4$	1	(1)	0.00	0.00	0.00	4.54
ERROR	15		276.00	18.40		
TOTAL	23		2715.83			

Table 14. Optimum levels of boiling time.

FACTOR CODE	MAIN FACTORS	MEAN (s)
(Fan)	With fan	1300.20
	Without fan	2310.00
(Fuel type)	Wood charcoal	1489.80
	Typha lump charcoal	2119.80

The calculation of the mean of each level of the different factors that have a significant effect on the boiling time of the water helps us to know the optimum level and to choose the best factors to cook with this stove and to make the best profit. **Table 14** shows that with fan and wood charcoal the boiling time is low (1300.2 s with fan and 1489.8 s with charcoal) compared to 2310 s when no fan is used and 2119.8 s with typha lump charcoal. This allows us to say that the ventilation contributes to accelerate the boiling water by increasing the quantity of heat transmitted to the pot.

Table 15 summarizes the optimum factors levels that have a significant effect on thermal efficiency, CO emissions and boiling time in the 24 tests of our experimental design. The fact is that it is easy to say that the “Éclair-taaru”¹ stove, the charcoal fuel and the ventilation are the optimum levels factors that give us the best results in thermal efficiency, low CO emissions and low boiling time. On the other hand for the initial fuel load, the results are equal for both levels, which can make the choice difficult. But since it is sought to minimize the costs of use, it is chosen to load the stove with a minimum charge. In this study, PM_{2.5} emissions are not taken into account because they are low when the fuel is carbonized (case of wood charcoal and lump charcoal) and it is not interesting to study the effect of our parameters on the latter. According some researchers, “the coal has little impact on fine particle pollution, giving it a harmless image; while the main problem of coal is the massive emission of CO₂ the PM_{2.5} emissions of charcoals were lower than PM_{2.5} from current biomass cookstoves. However, the CO emission was very high at which 2 times or even more than 20 times higher than some normal cooking stoves” [38] [39].

These results are confirmed in our study giving up to $39.5 \times 10^{-6} \text{ kg}\cdot\text{s}^{-1}$ of CO emission with normal cookstove and $19.3 \times 10^{-6} \text{ kg}\cdot\text{s}^{-1}$ of CO emission with secondary air cookstove (**Table 10**). Similarly, we have at **Table 12** between 20 and 29 $\text{kg}\cdot\text{s}^{-1}$ of CO emission with the normal cookstove and between 7 and 13 $\text{kg}\cdot\text{s}^{-1}$ of CO emission with secondary air cookstove.

To confirm the reliability of the methodology and the results of optimum factors, validity tests are performed using the optimal combination of these four factors. The results of the validity test are given in the **Table 16**.

The three tests of validity give us conclusive results because they are between the extreme values of the 24 tests did in this experience. So it is possible to situate their mean in relation to IWA performance tiers [40]. So on 4 tiers defined by IWA, our results are in the middle (for thermal efficiency and CO at the boiling) and on a good level for CO at the simmer. For boiling time, we are under the optimal levels of **Table 14** (1300.2 s) and allows us to confirm that these factors are the best possible for this cookstove.

This study clearly shows that wood charcoal is the best fuel for charcoal cookstoves. But with the DOE and ANOVA, we understand that, when it is used at different levels of charge, it give different responses on thermal efficiency and CO emissions. The secondary air cookstove “Éclair-Taaru”¹ used with ventilation exhibit very low emissions and good efficiency with minimum load of wood

Table 15. Recapitulation of optimal parameters which gives us best results.

Responses	Optimal parameters and their levels			
Thermal efficiency	“Éclair-taaru”1	Wood Charcoal	Min load (0.50 kg)	With or Without fan
CO emissions to boil	“Éclair-taaru”1	Wood Charcoal	Min load (0.50 kg) Max load (0.73 kg)	With fan
CO emissions to simmer	“Éclair-taaru”1	Wood Charcoal	Max load (0.73 kg)	With fan
Time to boil water	“Éclair-taaru”1 “Éclair-taaru”2	Wood Charcoal	Max load (0.73 kg) Min load (0.50 kg)	With fan

Table 16. Validity tests.

N° test	Thermal efficiency (%)	CO at boiling (kg·s ⁻¹)	CO at simmer (kg·s ⁻¹)	Boiling time (s)
V ₁	26.60	7.17 × 10 ⁻⁶	6.50 × 10 ⁻⁶	1020
V ₂	26.50	12.50 × 10 ⁻⁶	8.83 × 10 ⁻⁶	1140
V ₃	28.00	13.30 × 10 ⁻⁶	8.50 × 10 ⁻⁶	1020
Mean	27.03	11.00 × 10 ⁻⁶	8.00 × 10 ⁻⁶	1060.2
Tier	2	2	3	

charcoal but with maximum load of wood charcoal, it exhibit high emissions with low efficiency of stove.

It is safe to say that despite the nature of charcoal and ventilation, secondary air is responsible for reducing CO emissions during testing and moderately improving thermal efficiency.

It is important to note that in many classic studies, results discussion are limited only on the main effect of studied parameters and does not take into account what interactions can bring. This type of study is found in “test results of cook stove performance” of MacCarty *et al.*, 2010 [41] or in “comparative study of effect of different parameters on performance and emission of biomass cook stoves” of Kumar *et al.* 2013 they consider only the effect of individual factors on improved study cook stove. On the other hand, the studies focus on the external parameters (the dimensions of the combustion chamber, the quality of the material, ...) to improve or to have a good quality of stove [23]. With the DOE, we were able to exploit the internal parameters of the cookstove, which allowed them to be optimized in order to make the most profit without having to modify the stove in question or a dimension of the parts of the stove. In our case, thanks to the DOE, we went further taking into account the effects of the interactions on the thermal efficiency and the CO emissions. These results allow us to observe that even if an isolated factor does not have a significant effect on one response, it can have one when it interacts with other factors.

4. Conclusions

The effects of different parameters on performance and CO emissions of two

charcoal cookstoves have been investigated. Parameters such as fuel type, fuel load, secondary air inlet and ventilation were examined using a traditional cookstove (“Éclair-Taaru”2) and improved cookstove (“Éclair-Taaru”1). The “Design of Experiment” methodology has been used to determine the effect of parameters level and the effect of interactions parameters on responses.

The ANOVA and the Newman-keuls test allow us to understand how to profit from a cookstove (by determine the optimal level of parameters to used). The improved cookstove is better than the traditional cookstove because it saves charcoal (minimum load, maximum efficiency), it is clean at this level of load (it emits less CO₂) but it must be used under ventilation.

However, during the experiences, the peak of CO ($106 \times 10^{-6} \text{ kg}\cdot\text{s}^{-1}$ at the boiling phase and $74.5 \times 10^{-6} \text{ kg}\cdot\text{s}^{-1}$ at the simmer phase) is obtained with the combination “Éclair-Taaru”2, typha lump charcoal, maximum load and without ventilation. The lowest CO ($0.833 \times 10^{-6} \text{ kg}\cdot\text{s}^{-1}$) is obtained with the combination “Éclair-Taaru”2, wood charcoal, minimum load without ventilation or the combination “Éclair-Taaru”1, wood lump charcoal, minimum load with ventilation during simmer phase. For thermal efficiency, the best combination does not always for CO emissions. Since human health is what that matters, we will choose the factors that will lower emissions of CO for the entire period of cooking, even if it reduces the thermal efficiency of the stove.

This study clearly shows that wood charcoal is the best fuel for charcoal cookstoves at minimum charge of combustion chamber. But with the DOE and ANOVA, we understand that, when it is used on different cookstoves, it give different responses on thermal efficiency and emissions. The “Éclair-Taaru”1 cookstove used with ventilation exhibits very low emissions and good efficiency with minimum load, but with maximum load of wood charcoal, it exhibits high emissions with low efficiency of stove.

The ventilation brings much oxygen which accelerates combustion reaction, converting CO to CO₂. Finally, wood charcoal is definitely fuel that best meets objectives of thermal efficiency and CO emissions if we look at the results. Therefore factors to be used together to satisfy our need for heat or for cooking while maintaining good health is “Éclair-Taaru”1 stove (container secondary air inlet), with minimum initial load of wood charcoal and with proper ventilation.

This Design of Experiments method can be extended to the study of CO₂ emissions and breathable particles (PM_{2.5}) to know if PM_{2.5} is negligible at any level.

Conflicts of Interest

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

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