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The Potential of Charcoal Making Stove to Enhance Energy Efficiency

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ABSTRACT: Wood and charcoal are the frontier energy sources in developing countries mainly for heating and cooking. However, the achievable efficiency of woodstove is limited due to the poor combustion characteristics of wood in its natural form; and production of charcoal on the other hand dissipates major portion of the primary energy on the kiln site as smoke. Hence, this paper assesses the likelihood of integrating charcoal making with cooking in a charcoal making stove to enhance energy efficiency by attaining better control over combustion and increasing energy availability for end use. The scenario was demonstrated by using a Top-Lit UpDraft natural draft (TLUD-ND) gasifier stove which employs flaming pyrolysis that generates and combusts wood-gas for cooking and then recovers charcoal as a byproduct. Through standard procedures of Water Boiling Test (WBT) and proximate analysis, the average values of cooking efficiency and energy recovery in charcoal were found to be 18.05±1.53% and 31.75±2.40% respectively. The results achieved were slightly higher than the algebraic sum of an independently operating woodstove and charcoal kiln, thus showing a potential of over 50 percent saving in fuel wood consumption. Furthermore, a loose (r^2 = 0.3098) relationship was observed between cooking efficiency and charcoal yield verifying the prospect of improving either parameter without negatively affecting the other to enhance the overall efficiency. Likewise, the technology of integrated cooking and charcoal making can also considerably contribute to global climate stability by reducing release of greenhouse gases and other pollutants from burning and carbonization of biomass.

KEYWORDS: Stove, pyrolysis, cooking efficiency, charcoal yield, combined efficiency.

1 INTRODUCTION

Utilization of fuelwood as energy source is an aged process that yet remains dominant at the households of developing countries in spite of its proven negative effects on the environment and livelihood [1]. Conversion of fuel wood to required energy form mainly trails either direct combustion in wood stoves or carbonization in earth mould kilns (efficiency = 10-20%) also causing indoor pollution via health threatening smoke [2]. The conventional charcoal making process in kilns that leaves about 70% of energy in the kiln site [3], when followed by 10-30% efficient charcoal stove [4] verify that an overall efficiency of charcoal utilization for cooking in traditional way is lower than 10%. Hence, this study hypothesizes enhancement of better efficiency of overall fuel wood conversion to end use in an apparatus that obeys the principle of flaming pyrolysis, namely, top-lit updraft natural draft (TLUD-ND) gasifier stove that embraces two basic attributes. Primarily, it disintegrates wood into combustible gas and charcoal which can be burned more efficiently in separate convenient medium. Secondly, it avails the energy in the smoke that would have been lost in the kiln site for cooking in the form of combustible gas. The operating principle of charcoal making stove thus incorporates separation of the volatiles and solid carbon (charcoal) by pyrolysis and then combust the volatiles to supply heat for cooking thereby recovering charcoal for further use in charcoal stove as illustrated in Fig. 1. This is possible by supplying limited primary air to the fuel to maintain pyrolysis and provide secondary air to combust the volatiles coming out of pyrolysis.

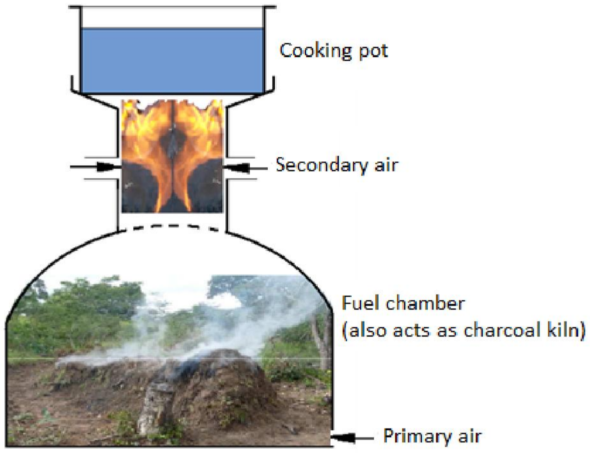

Fig. 1. A schematic of a charcoal making stove

Moreover, gasifier stoves are also reported to be appealing in ensuring fuel wood saving as it runs over wide variety of dry biomass and reduction of emissions improving the air quality of cooking environment [5]. However, this paper gives special attention to analysis of energy recovery in terms of both cooking efficiency and charcoal production.

2 EXPERIMENT DESIGN AND METHODOLOGY

Total of twelve experiments have been conducted on the stove to analyze its performance under possible combination of three selected parameters (fuel size, presence and absence of chimney, and full load and part load conditions), based on which the experiments were named (see Table 1).

Eucalyptus wood prepared in cubes with sizes: A=25x25x25mm^3, B=20x20x20mm^3 and C=15x15x15mm^3 in harmony with the recommended limit of 5 x 10 x 20 mm, plus or minus half of each dimension established for similar stoves [4],[6] were used as feedstock. Additional experiments conducted on eucalyptus feedstock have revealed moisture content of 8.9% on dry basis and proximate analysis of dry fuel: fixed carbon (FC) =23.2%, volatile matter (VM) =75.1% and Ash=1.7%, with corresponding lower heating value (LHV) of 16.9MJ/kg.

Table 1. Nomenclature of stove tests

Fuel size	**Without chimney**		**With chimney**	
	Part load	**Full load**	**Part load**	**Full load**
A	STA1	STA2	STA3	STA4
B	STB1	STB2	STB3	STB4
C	STC1	STC2	STC3	STC4

Performance of the stove was then determined using the standard Water Boiling Test (WBT) procedure for all the twelve experiments [7]. The quantity of fuel used, remaining charcoal at the end, water used for WBT, and water remained in pot at the end of each experiment as shown in Table 2 were measured using digital weighing balance having 0.1gram precision level. The changing temperature of water was also measured using a thermocouple placed in cooking pot 5cm above its bottom surface. Higher heating value (HHV) of the yielding charcoal was then determined based on proximate analysis made according to ASTM D 1762-84 procedure [8].

3 RESULT AND ANALYSIS/DISCUSSION

3.1 DATA MEASURED FROM WBT

Measurements were taken during the WBT to determine values of several parameters that are required to compute performance of the charcoal making stove. Table 2 presents gravimetric and temperature measurements recorded both in the input and result side of each experiment. The parameters to be gauged were decided so as to enable tracing the energy flow.

Table 2. Data recorded from WBT on charcoal making stove

Test No	M_{iw} [gm]	M_f [gm]	M_{ch} [gm]	M_{ew} [gm]	T_i [^{0}C]	ΔT [^{0}C]	T_{avg} [^{0}C]
STA1	2503.78	302.87	43.62	58.7	29	39	48.5
STA2	2500.06	443.84	59.96	125.4	30	43	51.5
STA3	2500.02	374.08	63.57	59.07	28	50	53
STA4	2500.00	443.48	73.43	135.42	30	58	59
STB1	2499.97	376.31	69.06	107.88	29	56	57
STB2	2500.03	411.89	71.18	147.53	28	61	58.5
STB3	2500.46	354.20	64.38	54.71	27	48	51
STB4	2500.94	399.44	65.44	171.73	29	58	58
STC1	2503.76	344.00	58.68	131.64	28	48	52
STC2	2500.03	400.48	68.83	132.34	30	58	59
STC3	2500.00	360.26	61.11	84.17	28	56	56
STC4	2500.05	432.52	69.32	149.92	28	64	60

Where: M_f = Weight of fuelwood used, M_{iw} = Initial weight of water used, M_{ew} = Weight of water evaporated, M_{ch} = weight of charcoal remained, T_i = Initial temperature of water, ΔT = Change in temperature of water, and Average temperature of the boiling water, $T_{avg} = T_i + \Delta T/2$,

Establishment of the stove's overall performance requires determination of the deciding factors like charcoal yield along its energy content and thermal efficiency. As such, energy flow during cooking in a charcoal making stove and the subsequent charcoal stove is discussed in the following sections.

3.2 ENERGY RECOVERY IN CHARCOAL

The charcoal yield and its proximate analysis were evaluated for ease of comparison with earth mould kiln both on quantity and quality basis. The energy recovered in charcoal was then determined by multiplying the yield in kilograms and heating value (computed based on proximate analysis (see Table 3) in Mega joules per kilogram. The obtained charcoal was richer in fixed carbon content than charcoal from kilns, which is reported to have 20-40% volatile matter [2]. Nonetheless, the produced charcoal can be used in a nearby stove to reduce the possible losses during handling due to its friable behavior that arise from volatile matter content less than 30% [9].

Table 3. Proximate analysis and higher heating value (HHV) of the yielding charcoal

Test No	Proximate analysis of produced charcoal			*HHV[MJ/kg]
	%FC	%VM	%ASH	
STA1	89.36	9.61	1.01	33.10
STA2	89.01	9.36	1.63	32.92
STA3	88.34	10.02	1.64	32.79
STA4	86.38	11.32	2.30	32.29
STB1	81.39	17.48	1.13	31.50
STB2	83.72	14.72	1.56	31.89
STB3	85.24	12.86	1.89	32.13
STB4	84.21	13.43	2.35	31.85
STC1	86.96	11.54	1.50	32.54
STC2	87.56	9.72	2.72	32.46
STC3	84.85	12.99	2.16	32.01
STC4	87.26	10.33	2.41	32.45

*HHV = 0.3536(%FC) + 0.1559 (%VM) – 0.0078(%ASH), [10]

Fig. 2 below shows the charcoal yield and energy recovered in charcoal for which average value were found to be 18.05±1.53% and 31.75±2.40% respectively. The observed variation illustrates the effect of feedstock size on the yield although the heating value was more or less the same, thus pointing out the importance of using appropriate feedstock size for a give stove.

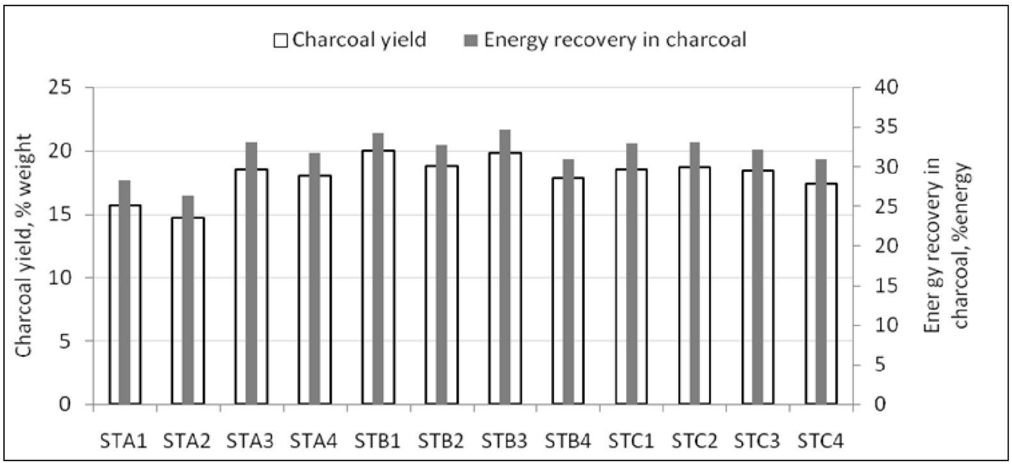

Fig. 2. Charcoal yield and corresponding energy recovery by charcoal making stove

Since the charcoal was produced in a cooking stove, its production efficiency in this context was calculated by considering the summation of heat transferred to water during WBT and the energy recovered in charcoal as useful energy. Hence is calculated using Eq. 1 to enable comparison between considered cooking stove and the conventional earth mould kiln as charcoal makers.

$$\eta_{ch.p} = \frac{[L \times M_{wev} + M_{wi} \times C_{pw}\ (\Delta T)\,] + [M_{ch} \times HHV_{ch}\,]}{M_f \times LHV_f} \qquad (1)$$

Accordingly, charcoal production efficiency of 36.41 - 47.54% has been achieved with mean value of 44.37±3.36%. Corresponding values of charcoal production efficiency for each stove test are also graphically presented in Fig. 3.

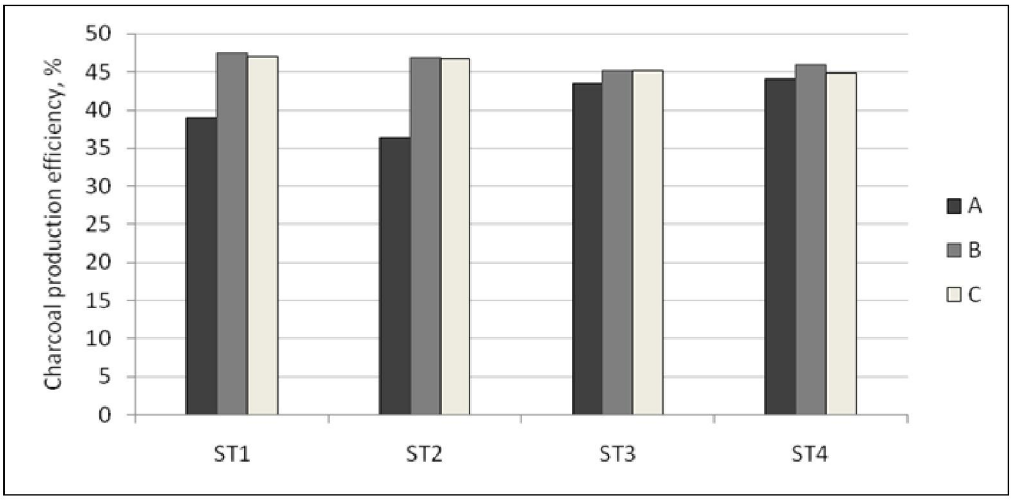

Fig. 3. Charcoal production efficiency of the TLUD-ND gasifier stove

When similar calculation is made for charcoal production in traditional kilns, the figure becomes smaller since there is no heat recovered from the released gases for cooking in the site. Hence, a typical traditional kiln fed with feedstock having LHV of 16.86MJ/kg and resulting in charcoal yield of 20% or less [2] with HHV of 28MJ/kg realizes charcoal production efficiency of 33.21% or less. This is considerably lower compared to the result from charcoal making gasifier stove analyzed in this study. Hence, production of charcoal in a stove avails more energy for end use than the independent conventional firewood burning and charcoal production practice do.

3.3 COOKING EFFICIENCY OF THE CHARCOAL MAKING STOVE

Cooking efficiency shows how well the stove performed in terms of transferring fuel energy into water in the cooking pot. Since the stove produces charcoal as end product, cooking efficiency is computed by exclusive of the energy recovered in charcoal from the energy input as shown in Eq. 2. Thus, cooking efficiency is the ratio of useful energy that has been transferred to water in the pot to the energy extracted from the fuel during WBT.

$$\text{Cooking efficiency },\eta_c = \frac{(L \times M_{wev}) + (M_{wi} \times C_{pw} \times \Delta T)}{(M_f \times LHV_f) - (M_{ch} \times HHV_{ch})} \qquad (2)$$

Where:

LHV_f = Lower heating value of fuel

HHV_{ch} = Higher heating value of charcoal

L = latent heat of vaporization at average temperature rise (read from steam table)

C_{pw} = specific heat capacity of water at constant pressure (=0.004186MJ/kg.K)

η_c = Cooking efficiency

As it is shown in Fig. 4, the average cooking efficiencies over the four runs with each fuel size were *15.63%, 19.82%* and *20.17%* for size A, B, and C respectively. The level of efficiency variation with respect to fuel size was tested using Analysis of Variance (ANOVA).

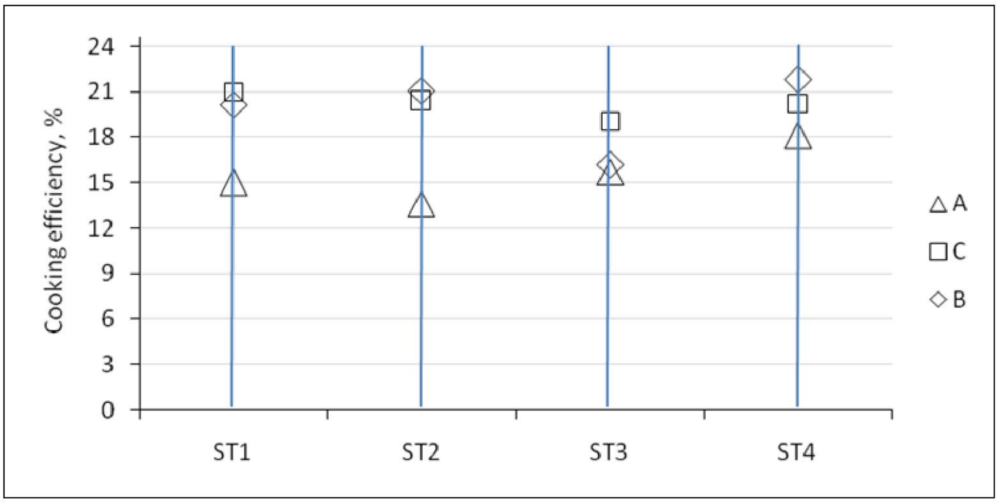

Fig. 4. Cooking efficiency of the charcoal making stove under all test conditions

The test by ANOVA revealed existence of significant difference among the efficiencies recorded with the three different sized fuels. Furthermore, the Tukey-Kramer procedure used to identify where the difference lies has also indicated that the stove tests conducted with fuel size "A" have resulted in lower cooking efficiency than the runs with "B" and "C" sized fuel at significance level of 5% ($\alpha = 0.05$). The observed low cooking efficiency for "A" sized fuel was attributed to combined effect of uneven fuel distribution and low bulk density which let combustion in place of pyrolysis by allowing free air flow and localized starting.

3.4 Combined Efficiency

The need of determining combined efficiency is to enable comparison of fuel saving capacity of the charcoal making stove with the conventional charcoal production and utilization route that is diagrammatically shown in Fig. 5.

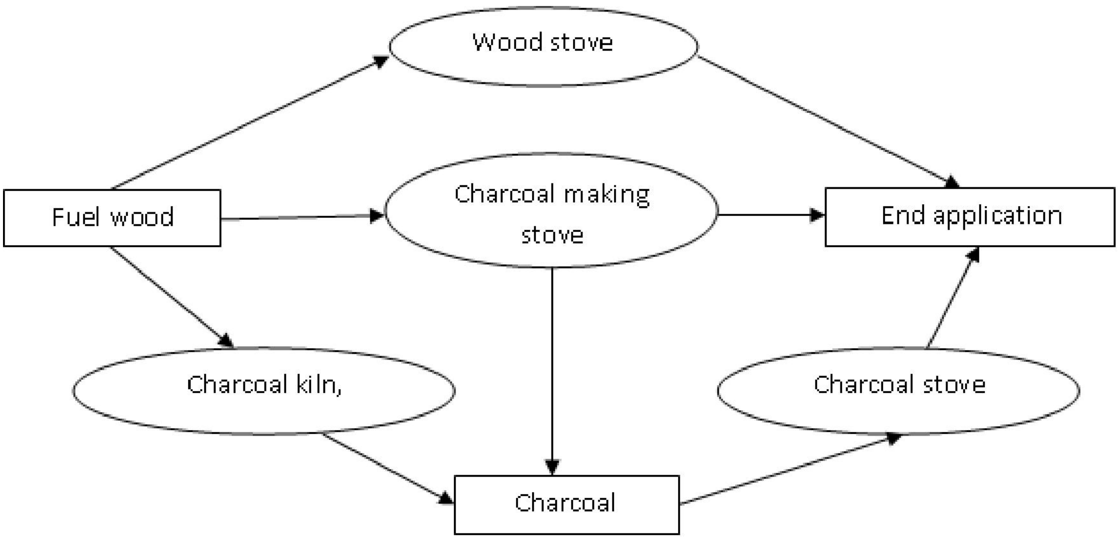

Fig. 5. Energy flow diagram of cooking with fuel wood

Combined efficiency thus describes the cumulative outcome of cooking efficiencies in charcoal making stove and the subsequent charcoal stove that run on charcoal produced in the gasifier stove. This study assumed a charcoal stove with efficiency of 30% for combustion of charcoal produced in the charcoal making stove. As such, it is the fraction in percent of fuel energy that can be put into the final application under a given combination of charcoal making stove and charcoal stoves (see Eq. 3).

$$\eta_{comb} = \frac{[L \times M_{wev} + M_{wi} \times C_{pw}\ (\Delta T)\ ] + M_{ch} \times LHV_{ch} \times \eta_{chs}}{M_f \times LHV_f} \quad (3)$$

Equation (3) can be rewritten in simplified form as Eq. 4 below

$$\eta_{comb} = \frac{\eta_c \times (LHV_f - y_{ch} \times HHV_{ch}) + y_{ch} \times LHV_{ch} \times \eta_{chs}}{LHV_f} \quad (4)$$

Where:

y_{ch} = charcoal yield,

η_{chs} = Assumed efficiency of charcoal stove, and

LHV_{ch} = Higher heating value of charcoal (Note:-Charcoal contains almost no hydrogen at temperatures above 700^0C [11], hence the net heating value is equal to HHV)

The combined efficiency of the stove falls in the range between 18.33 and 24.55% with mean value of 22.05±2.01% (see Fig. 6 for the values from each experiment). Thus, when the scenario of similar charcoal yield from charcoal making stove and earth mould kiln is considered, the energy used for cooking in the stove can be regarded as bonus.

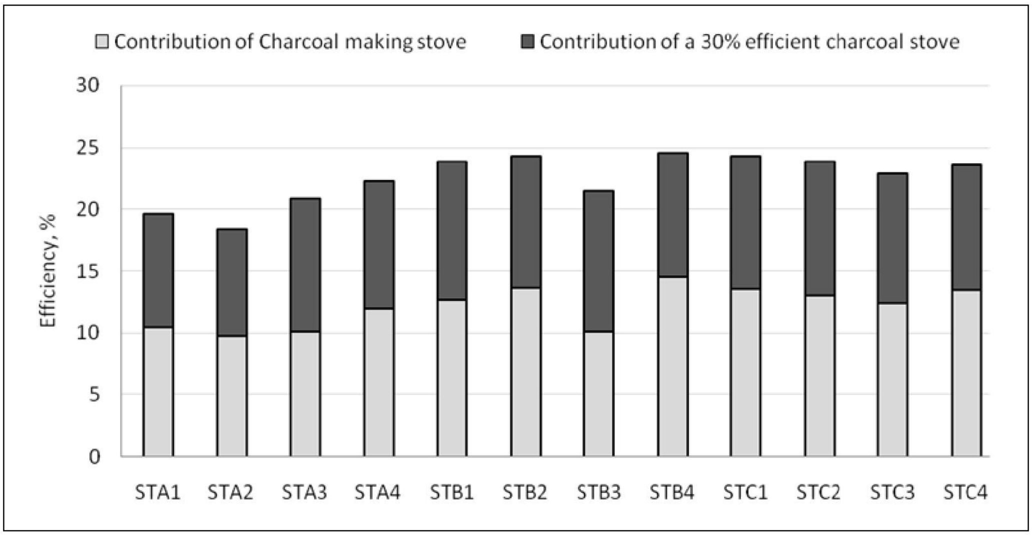

Fig. 6. Combined efficiency of charcoal making stove and 30% efficient charcoal stove

For ease of comparison, the combined efficiency of conventional charcoal production in kilns followed by burning in charcoal stove was calculated using Eq. 5 shown below. The formula was deduced from Eq. 4 by eliminating the component of energy that has been transferred to water in the pot while making charcoal.

$$\eta_{comb} = \frac{y_{ch} \times LHV_{ch} \times \eta_{chs}}{LHV_f} \quad (5)$$

Where: η_{chs}chs= Efficiency of charcoal stove

Accordingly, when a typical charcoal from earth mould kiln having yield of 15-25% and LHV of about 28 MJ/kg [4] is burned in a 30% efficient charcoal stove, it results in an overall efficiency of only 7.5-12.52%. Thus, the studied charcoal making stove when used in place of charcoal kiln doubles efficiency of conventional charcoal utilization practice thereby reducing fuel consumption to half. In other words, an individual that produces charcoal making TLUD-ND gasifier stove gains bonus of that energy used for cooking in the stove compared to the one that uses charcoal from kiln. These values also give clue about possibility of making carbon credits through charcoal sequestration (depositing charcoal in to soil) whenever found of higher importance.

Moreover, the contribution of charcoal making stove and the assumed 30% efficient charcoal stove to the total useful energy, the former contributing 53.68±3.33% in average, is also shown in Fig. 6. Based on the fact that only about 32% of energy is recovered in charcoal (see Fig. 2), the above figure justifies occurrence of larger loss in the charcoal making stove. This result therefore dictates that effective strategy to enhance combined efficiency is focusing on improvement of cooking efficiency of the charcoal making stove. The effect of improving cooking efficiency on charcoal yield is analyzed in the following section.

3.5 RELATIONSHIP BETWEEN COOKING EFFICIENCY AND CHARCOAL YIELD

Since combined efficiency is function of both cooking efficiency and charcoal yield, its further improvement depends on augmenting either one or both if possible. Hence, relationship between the two parameters is investigated to see the likelihood of negative effect on charcoal yield that may occur from improvement on cooking efficiency or vice versa. Thus, study of their correlation intends to decide the focus point for further improvement of overall performance by optimizing the two.

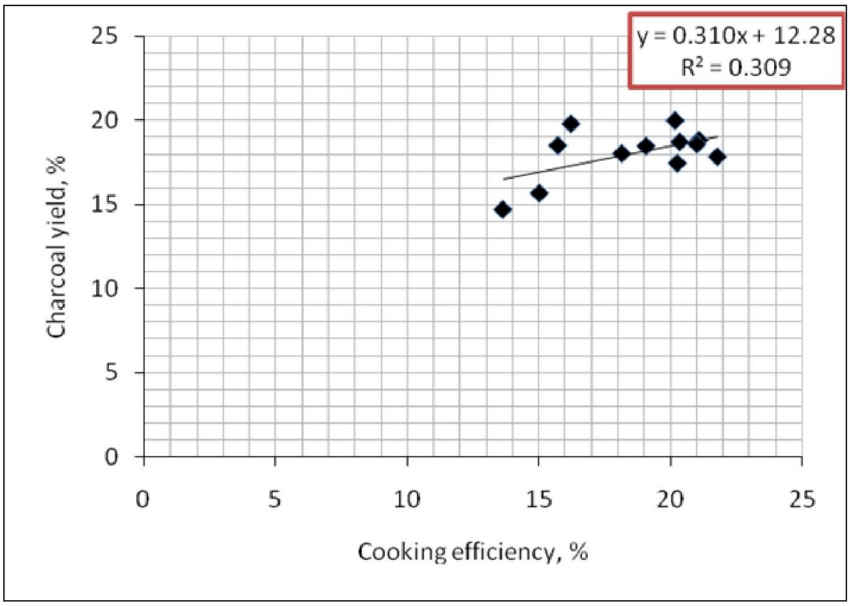

Fig. 7. Charcoal yield against cooking efficiency graph for the charcoal making stove

The strength of correlation was expressed in terms of Karl Pearson's Coefficient of Correlation (r) calculated as follows:

$$r = \frac{\sum xy}{\sqrt{(\sum x^2)(\sum y^2)}} \qquad (6)$$

Where: $x=(\eta_c)_i-\eta_{c,Avg.}$ and $y=(y_{ch})_i-y_{ch,Avg.}$, for i=1,2,3,....12

Substituting values from Fig. 7,

$$r = \frac{25.55}{\sqrt{82.27x25.62}} = 0.5566$$

$$r^2 = 0.3098 = 30.98\%$$

The obtained value of r is interpreted as loose as it falls out of the fair correlation range, 0.7 to 1 or -0.7 to -1 [12], and the relation is not significant at α=5%. However, the existence of positive correlation implies that 30.98% percent of total variation in one variable is accounted for the variation on the other variable in a similar direction. Hence, the calculated value of correlation coefficient illustrates that improvement on thermal efficiency is accompanied by improvement on charcoal yield although it is slight; and it has no declining effect at all. For instance, improving combustion efficiency of the volatiles in the stove is unlikely to have any effect on the charcoal yield since this is post pyrolysis activity. On the other hand, eventual restoration of charcoal helps to increase efficiency as combustion of charcoal in the stove leads to large amount of heat loss due to the distance gap between the pot and charcoal.

4 Conclusion

In contrast to conventional cooking with charcoal, it has been shown that charcoal making stove is capable of reducing fuel wood consumption by about fifty percent when loaded with appropriately sized fuel. Besides, since a charcoal making stove primarily breaks the biomass feedstock into volatiles and carbon rich charcoal, both burn nearly free of visible smoke in respective stoves resulting in cleaner cooking environment. Moreover, enhancement of efficiency reduces load on fuel collectors, minimizes deforestation rate, and trims down related pollutants and greenhouse gases.

In addition, the relationship between thermal efficiency and charcoal yield was found to be loose and positive (r=0.56) indicating that recovering charcoal from the stove (or avoiding burning of charcoal in the stove) contributes to improvement of the overall stove performance. Hence, efficiency of charcoal making stove can be further improved without affecting charcoal yield.

Accordingly, it is strongly recommended to avoid production of charcoal in remote forest area by encouraging further researches that customize charcoal making stoves to existing cooking habits and improve its efficiency.

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