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Improving household energy systems in rural Ethiopia: A comparative study of traditional energy sources and biogas

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Introduction

Rural areas in developing countries mainly depend on traditional biomass as fuel. For Ethiopia the main sources are woody biomass (78%), dung (8%), crop residue (7%) and petroleum (5%) (Eshete ***et al.*** 2006). High demand for fuel wood and population growth in Ethiopia cause an acute scarcity of wood. Therefore, households are turning to dung and crop residue for energy (Bewket 2003). They thus lose their fertilizer benefits. During the low energy efficient combustion of biomass small particles and noxious gases are emitted which are one of the most threatening evitable risk factors in developing countries (Smith 2002). Improved stoves and alternative cooking methods are the most common methods to face those problems (Toonen 2009; Jagadish 2004). However, wood consumption even increases in villages with good market access while remaining constant in remote villages (Chen ***et al.*** 2006). Biogas technology offers an alternative renewable energy source with high potential in developing countries due to the ready availability of cow dung. This study was conducted in rural Ethiopia where small scale plants of 4 m^3 and 6 m^3 for single families are being promoted recently.

Material and Methods

Fresh and dried cow dung, biogas digestate out of biogas plants outlets and firewood from the households own wood supply were sampled as potential fuels and fertilizers. All samples were analysed for moisture content with the oven method. Further, calorific values of dung, slurry and wood were determined with the help of a calorimeter “PARR 6100”. Volatile matter of all samples was analysed according to DIN EN 15148 inside a muffle furnace at 900°C ± 10°C temperature for 7 min ± 5sec. For the ash content determination of dung, slurry and wood DIN EN 14775 was considered. Dung and slurry samples were analysed for their fertilizer values. C and N were determined by elementary analysis (dry combustion after Dumas), the other parameters, S, K, P, Ca, Mg, Na, Cu, Mn and Zn, were analysed by aqua regia dissolution using ICP-OES (inductively coupled plasma optical emission spectrometry). Standard water boiling tests (WBT) (VITA, 1985) were performed in rural households to simulate cooking processes with cow dung and firewood as fuel on traditional 3-stone stoves and with biogas on standard biogas stoves. For comparability in all tests 4 litre of water was brought to boil in a standard pot and cooked for 45 minutes with constant temperature. Water temperature was permanently measured with a digital thermo moisture meter. Water and fuel were weight before starting the test, after reaching the boiling point and at the end with a spring scale. Thus, fuel consumption and amount of evaporated water could be calculated which are components of the efficiency calculation. The efficiency calculation of the different stove-fuel combinations was done by:

$$\eta = \frac{m_W \cdot c_W \cdot (t_b - t_1) + m_{eva} \cdot L_{Wboil}}{m_{vuel} \cdot cv_{fuel}}$$

where m_w is mass of water, c_w is specific heat capacity of water, $(t_b - t_1)$ is change in temperature (from T_1 to boiling point), m_{eva} is mass of evaporated water, L_{wboil} is latent heat of boiling of water, m_{fuel} is mass of consumed fuel and cv_{fuel} is calorific value of fuel.

WBTs with the same setup were conducted in the laboratory under semi controlled conditions. Costs and benefits of investing in biogas at household level were also considered in this study. Decision criteria of cost benefit analysis technique including the internal rate of return (IRR) and the net present value (NPV) was used to assess the competitiveness of biogas plants compared to traditional energy sources. NPV and IRR are given as:

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t}$$

IRR is the discount rate '*i*' such that NPV becomes 0, where B_t is benefit in each year, C_t is cost in each year, *i* is Interest (discount) rate and *t* is number of years (life of biogas plant)

A discount rate of 4%is chosen for this study on the basis of the long run rate of return on capital (Jeuland 2010).

Results and Discussion

Regarding fuel properties dried biogas digestate could be used as substitute for dung cake as fuel since their characteristics are similar, if not mixed with clay or other non-inflammable materials as sometimes found in the households. However, firewood has higher calorific values comparable with the one of biogas found in Ethiopia with 18 MJ/kg. Yet, rainy years contribute to the decrease of fuel properties of dung cake and firewood because storage capacity is hardly available. In table 1, water contents are presented as water contents dry base and net calorific values give the amounts of energy in MJ released during the combustion of 1 kg of dry product.

Table 1. Fuel properties of different possible energy sources collected in Ethiopia

	Water Content [%]	Net Calorific Value [MJ/kg]	Volatile Matter [%]	Ash Content [%]
Dung	77	9-13	40-55	52-33
Digestate	91	13	52	36
Wood	11	18	84	1

Mineral contents of dung and digestate are in clear accordance regarding their N and Ca contents as to be seen in figure 1. By contrast, Potassium available in digestate has more than double the value than that of dung. In general, amounts of nutrients in digestate are higher than in dung which makes it a superior fertilizer. Ash remaining after combustion of firewood would be an adequate additional fertilizer especially for soils which are poor in Potassium, Calcium, Magnesium, Sodium and Manganese.

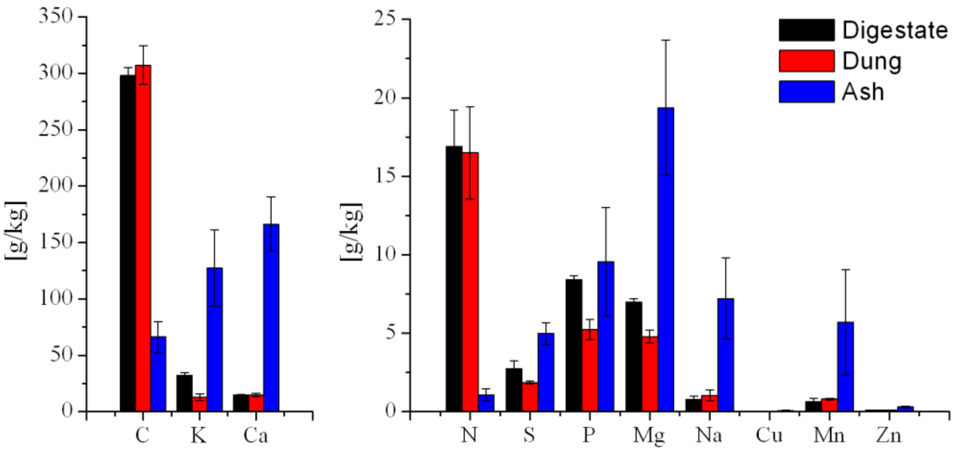

Fig. 1. Mineral contents of dried biogas digestate, dung and ash collected in Ethiopia

Usually dung finds its application as N fertilizer with additional function as Phosphor provider. An average of 11 kg of dung or digestate is necessary to reach the same amount of N as available in 1 kg of Diammonium Phosphate (DAP), the widely used type of fertilizer in Ethiopia. Respectively, 38 kg of dung are equivalent to 1 kg of DAP regarding P content whilst only 24 kg digestate are necessary to substitute the same amount of DAP-P. Comparing fertilizer values of cow dung and biogas digestate with the amount of N in Urea, 13 kg of both substrates are equivalent to 1 kg of Urea. By using it appropriate, biogas digestate can enhance soil fertility and improve crop yield.
WBTs on 3-stone stoves with dried dung cake as the only fuel did not prove successful. The tests had to be stopped. Traditionally 1 unit of dung and 2 units of woody biomass are used for cooking which makes the process more efficient. For cooking with firewood around four times the amount of fuel and 1/3 more time was necessary to heat the same amount of water from 20°C to 100°C than with biogas. This leads to an efficiency of 13% for the 3-stone stove operated with firewood and 33% for the biogas stove. Ballard-Treemer ***et al.*** (1996) and the Summary Evaluation Report of Fuel-Efficient Stoves in Darfur IDP Camps (2008) present similar efficiencies and boiling times on open fires. The efficiency of biogas stoves was found to be around 49%, 44% and 32% percent for perfectly controlled, semi-controlled and uncontrolled conditions respectively (CES/IOE. 2001). The efficiencies of the biogas stove could be improved by adjusting the flame size but thereby the cooking time increased and the overall fuel consumption approximated one value for all flame sizes, as to be seen in table 2.

Table 2. Performance of the biogas stoves tested in Germany and Ethiopia and the 3-stone stoves tested with wood in Ethiopia

	Germany low flame	Germany max. flame	Ethiopia Biogas	Ethiopia Wood fuel
fuel consumption (kg/h)	0.29	0.78	1.24	2.38
η (%)	49	42	33	13
power (kW)	1.45	3.84	6.09	16.23
heating time 20-100°C	35	15	15	20
fuel consumption 20-100°C (g)	171	199	296	1187
energy consumption (kJ/L_{water})	586	750	1034	4917

Results presented in table 3 indicate that biogas is economically feasible for households in Ethiopia yielding positive NPV for all household scenarios. Adopting biogas technology is most beneficial for households entirely purchasing their firewood whilst households collecting firewood stand to benefit least. Under all scenarios, over 65% of costs and benefits are accounted for by dung and slurry use as fertiliser respectively.

Table 3. Results of cost benefit analysis for biogas as substitute for different household scenarios

Description of costs and benefits	Scenarios (prices in ETB*)					
	Purchasing firewood		Collecting firewood		Collecting dung	
	4 m^3	6 m^3	4 m^3	6 m^3	4 m^3	6 m^3
NPV	20 407	29 561	4 957	6 386	7 957	9 386
IRR	28.29	34.78	10.52	11.90	14.57	15.13

* 1€~18ETB, 1Us$~13ETB (April 2010)

with NPV: Net Present Value and IRR: Internal Rate of Return

Conclusions and Outlook

Households can benefit from biogas technology through the use of digestate as fertilizer, savings in energy expenditure and time for collecting fuel. Thereby the double advantage of having a free superior fertilizer compared to cow dung and a renewable energy source which is more efficient than traditional fuels by using less fuel to heat the same amount of water is the crucial factor. Only by also considering the effect of the digestate as fertilizer, the economical advantage is given for different household scenarios whereby biogas technology proved most beneficial for households purchasing their firewood to date. Thus, biogas technology has high potential for areas in developing countries where the necessary conditions are given, but the plants should be seen as whole system and their products are to be used properly.

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