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Biogas Production vs. Dung Combustion as Household Energy in Rural Ethiopia

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Abstract: The objective of the study was to investigate the potential of dung as primary and secondary energy source, i.e. direct combustion of dung and combustion of its secondary products biogas or dried digestate, under consideration of its quality as fertilizer. The results of the analysis show the similarity of dung and digestate regarding combustion characteristics. Fertilizer values proved better for digestate. However, calorific value of dung proved much lower than those of biogas. Thus, biogas represents a good alternative energy source with double benefit. Besides its better combustion characteristics compared to dried dung, it also delivers a superior fertilizer.

Keywords: biogas, digestate, dung, energy source, fertilizer

1. INTRODUCTION

Rural areas in developing countries mostly depend on traditional fuels like fire wood and cow dung for cooking and heating. In Ethiopia, biomass supplies up to 94% of total national energy consumption and up to 99% of rural energy consumption. Overall, the main sources of energy include woody biomass (78%), dung (8%), crop residue (7%) and petroleum (5%) (Eshete ***et al.*** 2006). The high demand for fuel wood leads to large scale deforestation and therefore to damages like erosion, desertification, decreased soil fertility and increased danger of flooding. As the population growth in Ethiopia causes an acute scarcity of fuel wood, households are turning to dung and crop residue for energy (Bewket 2003). They thus lose their fertilizer benefits. Cooking is the main energy requiring process for rural households in Ethiopia. As combustion of wood and dung generally is incomplete, toxic gases and small particles are emitted besides the fact that they have low energy efficiency. According to WHO, health risks caused by indoor air pollution are one of the most threatening evitable risk factors in developing countries (Smith 2002). Various efforts were made to reduce indoor smoke and the fuel wood consumption with the help of improved stoves and alternative cooking methods (Toonen 2009; Jagadish 2004). However, according to Chen ***et al.*** (2006) wood consumption even increased in villages with good market access while remaining constant in remote villages. Due to wood shortage and the opportunity costs of dung as fertilizer, alternative energy sources have to be found, which are energy-effective and cost-efficient at the same time. Biogas technology offers a renewable energy source with high potential in developing countries because of the ready availability of cow dung, which have received much attention and promotion recently. This study was conducted in rural Ethiopia where biogas technology is being promoted. Especially small scale plants of 4 m³ and 6 m³ for the energy supply of single families play a large role. The aim of the study is to compare the application of cow dung as primary and secondary energy source. Thereby biogas represents the promising secondary energy source due to its relatively clean and efficient combustion and the possibility to use its side product, namely digestate, as fertilizer. Results were also compared to data gained from cow dung and digestate collected at German farms, to identify their similarity and therefore their ability for application in further research in this field. In comparing energy sources and their energetic values, the study provides the technical coefficients for an economic assessment of the above mentioned biogas plants in the context of rural households and farming systems in Ethiopia.

2. MATERIALS AND METHODS

Fuel and fertilizer sampling and analysis

Potential fuel and fertilizer samples, namely cow dung, biogas digestate and fuel wood, were collected in three *woredas* (districts) in Ethiopia and taken for analysis. Those *woredas*, namely Dale, Arsi Negele and Meskan are situated around 300 km, 230 km and 130 km respectively south west of the capital Addis Ababa. Fresh cow dung from kraals where cattle are kept overnight and dung cake, dried for cooking purposes were sampled, as well as biogas digestate out of biogas plants outlets and fire wood from the households own wood supply. Dung and slurry were put in containers and plastic bags rinsed with formalin to protect them from decomposition and closed air tight. Wood was also preserved in air tight plastic bags. Further dung samples from various cattle breeds were taken in Southwest Germany and handled the same way as the Ethiopian samples.

Moisture content

Dung and slurry samples were analysed for moisture content with the oven method. Therefore, the samples were weighed and put in a Memmert Oven until mass constancy was reached. With the final weight of the dry material its moisture content was calculated using the following formula:

$$MC_{w.b.} = \frac{W}{W + DM} \cdot 100 \qquad (1)$$

where $MC_{w.b.}$ is moisture content wet base, W is water content and DM is dry matter.

Moisture contents of dung cake and wood used for cooking purposes in Ethiopia were determined with the help of the "Sartorius Moisture Analyzer" Model MA150. Small amounts of the product are dried during permanent recording of its weight. If weight constancy occurs for a certain period, the final moisture content is determined according to equation (1). For better comparability the moisture content was converted to moisture content dry base which states the amount of water in kg being available in one kg of now dry matter (equation 2).

$$MC_{d.b.} = \frac{MC_{w.b.}}{100 - MC_{w.b.}} \qquad (2)$$

where $MC_{d.b.}$ is moisture content dry base.

Calorific values

The calorific values of dung, slurry and wood were determined with the help of a calorimeter "PARR 6100". An amount of 1 g dried and powdered sample was placed inside the bomb and put under 30 bar of pressure. By igniting the bomb which was put inside a water bath of 20°C, the sample burned completely. The increase of temperature inside the water bath in combination with the initial sample weight and moisture is used for the calculation of the calorific value.

Volatile matter

Volatile matter was analysed according to DIN EN 15148. The dried and powdered sample was weight to around 1g and placed inside a muffle furnace heated with a temperature of 900°C ± 10°C for 7 min ± 5sec. Initial and final weight of the samples was measured with a precision balance rounded to four digits after the decimal point. The proportion of volatile matter V_d of the sample was calculated with the formula:

$$V_d = \frac{100\left(m_4 - m_1\right)}{\left(m_3 - m_1\right)} \cdot 100 \qquad (3)$$

where m_1 is mass of empty crucible, m_3 is mass of crucible with sample after drying and m_4 is mass of crucible and ash.

Ash content

For the ash content determination of dung, slurry and wood DIN EN 14775 was considered. Approximately 1g of dried and powdered sample was put for 24 hours inside a muffle furnace with a temperature of 550°C ± 10°C. Initial and final weight of the samples was measured with a precision balance rounded to four digits after the decimal point. The following formula was used for the calculation of the ash content A_{db} of each sample:

$$A_{db} = \frac{m_4 - m_1}{m_3 - m_1} \cdot 100 \qquad (4)$$

Fertilizer values

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).

Stove tests

WBT in Ethiopia

Water boiling tests (WBT), which were first developed by Volunteers in Technical Assistance (VITA, 1985) and then revised by the University of California Berkeley/Shell Foundation, were done in rural households in the research area to simulate a cooking process with cow dung, firewood (especially eucalyptus) and biogas as fuel. For cooking with dung and firewood, the traditional 3-stone stove was used in two rural households, whilst the standard biogas stove was used for cooking with biogas in 3 different households. All tests were conducted in the same way for their comparability. An aluminium standard pot with a volume of 6.3 l, and a material thickness of 1 mm was used for all of the tests. An amount of 4.2 litre of water, available on site, which corresponds to ¾ of the pots' capacity as denoted in prevalent literature, was brought to boil and afterwards cooked 45 minutes with constant temperature. The fire was set as traditionally done with locally collected and processed fuel and on the usual place of the house to simulate the original cooking conditions. To light the fire for the WBT on the 3-stone stoves using wood and dung as fuel, a small amount of glowing charcoal was put in between the fuel and ventilated. Water was chosen as specimen due to its all-around availability and its easy and repeatable preparation. The standard water boiling test is divided into 3 phases: The high power phase with cold and with hot start, where the water is brought to boil with cold or already used, hot equipment, and the simmer phase, where the water boils at constant temperature for a defined time range. The high power phase with hot start was left away, since cooking in rural areas of Ethiopia is mainly performed with cold cooking equipment. The water temperature was permanently measured in the centre of the pot, 1 cm above the bottom with a digital thermo moisture meter GMH 3330 from Greisinger electronics. During the WBT on the 3-stone stoves the pot was either situated on 3 normal stones or 3 clay pots which served as stones. The approximate distance between the fire base and the pot bottom amounts to 10 cm whereby the distance at the biogas stove measures 1.7 cm. Before starting the test, after reaching the boiling point and at the end, the pot with water was weighed with a spring scale with an accuracy of 2 positions after decimal point. Thus, the amount of evaporated water could be calculated which is component of the efficiency calculation. Further, air temperature, air humidity and wind conditions were noted, as well as the time needed for boiling. To determine the fuel consumption during the two cooking phases the fuel was weighed before and after use, as well as the char remaining after combustion. Typical fuel sizes were 40 x 4 x 2 cm³ for wood and 3 x 2 x 1 cm³ for dung cake. For the WBT with biogas, a flow meter was attached between the biogas plant and the stove, as seen in figure 1, to determine the consumption of gas.

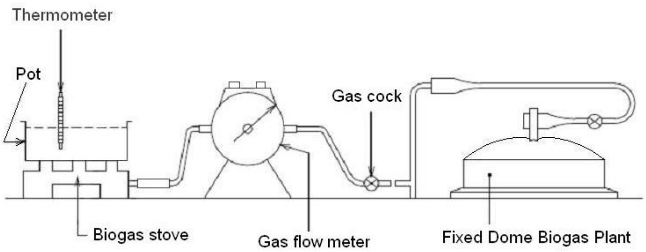

Fig. 1. Experimental setup of the water boiling test (WBT) with biogas as fuel

The efficiency calculation, i.e. the ability of the stove to convert the energy from fuel into the energy gained by the medium such as water (CES/IOE, 2001) of the different stove-fuel combinations was done applying equation (5):

$$\eta = \frac{m_W \cdot c_W \cdot (t_b - t_1) + m_{eva} \cdot L_{Wboil}}{m_{vuel} \cdot cv_{fuel}} \quad (5)$$

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.

This calculation was done for the High Power Phase, which is the heating process of water from the initial water temperature to boiling, and the Low Power Phase, which describes the simmering of the water over a defined time frame, in this case over 45 min. The calorific values of wood and dung applied in this formula were determined in the University of Hohenheim, out of samples taken in the research area in Ethiopia, as described above. However, the calorific value of biogas was taken from current literature about biogas production in developing countries. The efficiency calculation can be done in different ways under consideration of different parameters. Therefore, the efficiencies of the same stove-fuel combination can be different depending on the test method. The method used in this project calculates the heat gained by the water exposed for heating under consideration of the water evaporated during the process and the amount of fuel used therefore. Although for the WBT with biogas as fuel, a more precise calculation exists which includes the gas temperatures and the different pressures inside the gas hose and of the ambient air, the previously mentioned calculation was used to have a better comparability with the efficiency of the WBT performed with solid fuels. The same calculation was applied under consideration of the vessel properties (mass of vessel and its specific heat capacity). Since the results were the same as without those properties, they were neglected in further calculations, to simplify matters.

WBT in Hohenheim

Whilst the WBTs performed on site in Ethiopia were tests under uncontrolled conditions, WBTs were also conducted in the laboratory at the University of Hohenheim in Germany under semi controlled conditions. The test setup matches with the one assembled in Ethiopia. The Cambodian biogas stove is shown in figure 2. It has been used for efficiency and emission analysis.

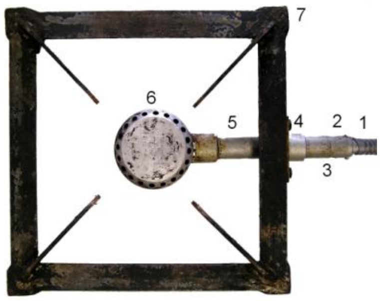

Fig. 2. Cambodian type stove

Where 1 is hose connection, 2 is venturi valve, 3 is primary air opening, 4 is air regulator, 5 is mixing tube, 6 is burner with burner head, 7 is stove frame.

The difference between controlled and uncontrolled test lies in the possibility to control the multiple parameters which influence the cooking process. This starts with the type, size and humidity of fuel used, the pot form, size and material and how a person conducts the test. Further the temperature, humidity and movement of the ambient air influences the test as well as the accuracy of the measurement devices. For the WBTs on the biogas stoves, more parameters are included, like gas temperature, quality and pressure, the amount of air mixed to the gas and the degree to which the gas valve has been opened. For the WBTs in Hohenheim, biogas with a methane content of 50% - 60% was taken from the institute owned biogas plant built for African conditions and feed only with a dung-water mix, similar to the procedure in Ethiopia. The amount of biogas being available for combustion was tried to approximate to the amount, measured during the WBTs in Ethiopia. This averages to 1.4 kg biogas per hour used for the High Power Phase and 0.8 kg/h for the Low Power Phase. The exact amount could not be reached, since a special storage system for the collected biogas, inside of the inner tubes of truck tires, was used. In doing so, the pressure necessary to obtain the demanded amount of gas could not be achieved.

3. RESULTS AND DISCUSSION

Sample taking and analysis

Sample characteristics

The characteristics of different fuels collected in the Ethiopian study area are listed in Table 1 together with German dung attributes. 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. Ethiopian dung and slurry show similar characteristics concerning calorific value, volatile matter and ash content. Water content of slurry is higher than from dung because the biogas plants are feed with dung and water in a 1:1 relation. The sampled dung cakes, dried dung ready for burning, have a rest water content of 10%. Their calorific value is with 9 MJ/kg surprisingly lower than the one from dung. This is probably due to the fact, that the dung cake was collected in another area as the dung and additionally contained a higher amount of external components with lower calorific values like grass and soil. Therefore also the ash content is at a higher percentage compared to dung and slurry. Considering the different types of wood reveals their similar calorific values, as well as the volatile matters. The water contents range from 9% - 12% from dried eucalyptus and mixed wood to 34% from coffee plants during open air storage and 45% from mixed wood at collection.

Table 1. Characteristics of different fuels collected in the research area in Ethiopia

	Water Content [%]	Net Calorific Value [MJ/kg]	Volatile Matter [%]	Ash Content [%]
Ethiopia				
Dung	77	13	55	33
Slurry	91	13	52	36
Dung Cake	10	9	40	52
Wood	11	18	84	1
Germany				
Dung	83	17	70	18

Since the period of research was more rainy than usual, wood could not be stored dry outside and often people were forced to cook with wet fuel. This led to lower cooking efficiencies as well as higher smoke formation with higher emissions, imposing danger in particular for women and children. Some people also dried their fuels above the fire during non-cooking periods. However, the fire therefore burned the whole day which causes additional emissions as well. Biogas with a calorific value of around 18 MJ/kg would be a good alternative also regarding the moisture problem, since it does not have to be dried and the smoke formation is very low.

Fertilizer values

Figure 3 shows the content of carbon and nitrogen as percentage in the dry matter of dung sampled in Ethiopia compared to Germany. In both cases, the amount of C is clearly higher. Ethiopian dung has a carbon content of around 30 - 35% compared to German one with 40 – 42%. Likewise nitrogen is found to be at 1 - 2% in Ethiopian and 2 - 3% in German dung.

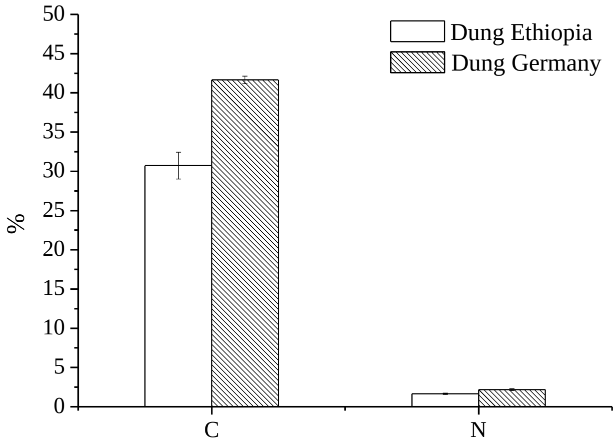

Fig. 3. Content of carbon and nitrogen in cow dung, collected in Ethiopia and Germany

Other nutrients found in dung are presented in figure 4. Except for Manganese, all nutrients and heavy metals are available in a higher amount in German cow dung. Calcium with 15 g/kg and Potassium with 12.5 g/kg of Ethiopian dung present the nutrients with the highest values analysed. Phosphor and Magnesium average to 5.2 and 4.8 g/kg in Ethiopian dung and to 6.9 and 5.9 g/kg in German dung.

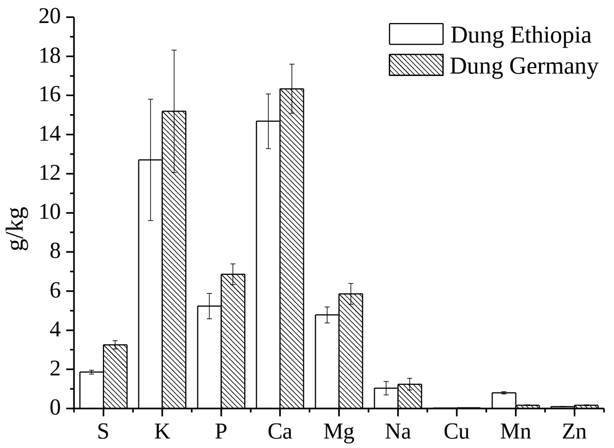

Fig. 4. Nutrient contents in cow dung, collected in Ethiopia and Germany

Nutrients in biogas digestate, as to be seen in figure 5, behave similar to the ones found in cow dung. Again, Manganese presents the only exception with higher amounts in the Ethiopian substrate. Potassium represents with 32.4 g/kg the main compound of Ethiopian digestate. It hast to be mentioned, that data from German biogas digestate originates from plants fed with crops and vegetable residues besides animal dung. Therefor data cannot be compared directly to Ethiopian digestate, which develops from cow dung and water only but its ability to serve as replacement for Ethiopian digestate in further experiments can be determined.

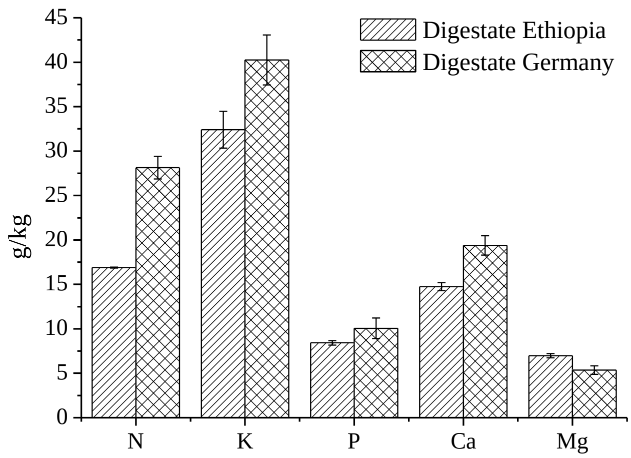

Fig. 5. Nutrient contents in biogas digestate, collected in Ethiopia and Germany

By comparing the nutrient contents of dung and slurry their utility as fertilizer can be shown. Noticeable is the clear accordance of dung and digestate sampled in Ethiopia regarding their N and Ca contents as to be seen in figure 6. 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.

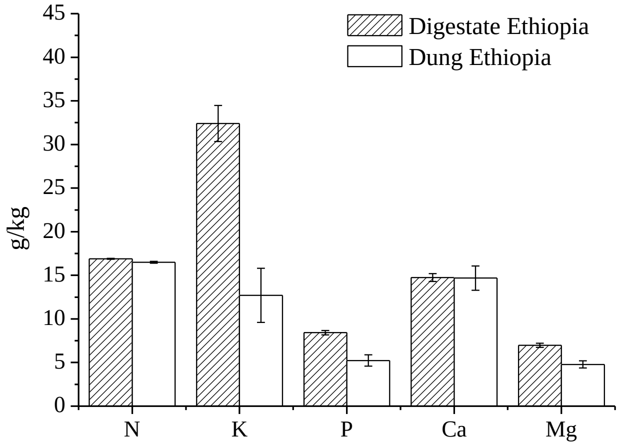

Fig. 6. Mineral contents of cow dung and biogas digestate collected in Ethiopia

The tests conducted on dung samples indicate that an average of 38 kg of dung is necessary to reach the same amount of phosphor as available in 1 kg of Diammonium Phosphate (DAP), the widely used type of fertilizer in Ethiopia. Respectively, 11 kg of dung are equivalent to 1 kg of DAP regarding N content. Using biogas digestate as fertilizer, the same amount of 11 kg as dung has to be applied to reach the N content of 1 kg DAP. Considering phosphor as main nutrient, only 24 kg digestate are necessary, since its content is higher than the one found in dung. 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. Normally dung contains around double the amount of nitrogen divided into 50% of NH3 – N (ammonia N) and NO3 – N (nitrous N) each. Due to the fermentation process plant available nitrogen increases as to be seen in a higher proportion of ammonia N in slurry compared to dung. Since the samples had to be dried before analysis because of transport purposes, mass loss occured in combination with nitrogen loss.Due to the better fertilizer values from digestate compared to dung it can be assumed that digestate presents a higher quality substitute for dung as fertilizer. Usually dung finds its application as N fertilizer with additional function as Phosphor provider. By using it appropriate, soil fertility can be enhanced, having a positive effect on crop yield. Hence there is a positive feedback between crop-livestock systems and energy.

Stove tests

WBT in Ethiopia and Hohenheim

The WBT on a 3-stone stove with dried dung cake as the only fuel, as seen in Figure 7, did not prove successful. Although the fire was ventilated constantly by fanning air with the help of a plate, the water did not cook and its temperature stagnated at around 80°C. Hence, the simmer phase was followed up at this point and the test interrupted thereafter. A second experiment did not yield better results. The traditional way of cooking with dung cake in the research area is by mixing the cakes with branches and leaves in a ratio of approximately 1 unit of dung to 2 units of braches and leaves. For further research it is recommended to perform the WBT with a defined mixture of those components, similar to the one used by local households.

Fig. 7. WBT with dung cake as fuel

Cooking on wood fire, as mostly performed in rural Ethiopia, proved to be more successful. Time until boiling of the water was averaged at 20 minutes with a fuel consumption of 2.38 kg/h. The amount of wood used for simmering the water over a period of 45 minutes was considerably lower with 0.98 kg/h. In total, the efficiency of the 3-stone stoves, including high power and simmer phase, amounts to 14.53%. Other sources show similar results. Ballard-Treemer ***et al.*** (1996) for example measured an efficiency of 14% on open fires with a boiling time of 22 min whilst the Summary Evaluation Report of Fuel-Efficient Stoves in Darfur IDP Camps (2008) gives a slightly higher efficiency of 16,3% and a boiling time of 20 min. The variation of the efficiencies is due to different factors like environment, fuel, distance fire to vessel and vessel and demonstrates the normal situation under uncontrolled conditions. The Summary Evaluation Report of Fuel-Efficient Stoves in Darfur IDP Camps (2008) for example also compares improved wood burning stoves with the traditional 3-stone stove. On average, the improved stoves achieve thermal efficiencies around 50% better than the open fire. Thereby differences between the open fire and improved stoves for time to boil were not significant. However, the improved stoves generate higher thermal efficiency ratings than the three-stone fire, particularly when it comes to simmering. Alternatively to improved stoves the possibility of other, “cleaner fuels” like biogas emitting lower amounts of flue gases, exists. In literature 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 WBTs in Ethiopia with uncontrolled conditions delivered an efficiency of roughly 33% and around 41% were reached with the semi-controlled test in Hohenheim. This shows a good accordance to literature. Table 2 compares fuel consumption and efficiency of the different WBTs conducted. It shows that the efficiency of the biogas stove compared to cooking with wood on 3-stone stoves is 54.5% better during field tests and 67.5% during laboratory tests. The heating time of 4 L water from 20-100°C is around 5 minutes shorter with biogas. Heating 1 L of water requires four times the amount of fuel using firewood and more than four times the energy of biogas. During the following simmer phase of 45 min, the laboratory test used around 45% less and the 3-stone stove test 20% more fuel than the biogas field test.

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

	Germany Biogas	Ethiopia Biogas	Wood fuel
fuel consumption (kg/h)	0.83	1.24	2.38
η (%)	41.24	32.53	13.16
power (kW)	4.10	6.09	16.23
heating time 20-100°C (min)	16.47	14.56	20.33
fuel consumption (kg/K_{4L})	0.00	0.00	0.01
fuel consumption 20-100°C (kg)	0.23	0.30	1.19
fuel consumption (kg/L_{Water})	0.04	0.06	0.29
energy consumption (kJ/L_{Water})	694.71	1033.91	4917.31

By comparing different flow rates based on low, adequate and maximum flame adjustments it could be seen that the bigger the flame, i.e. the higher the gas flow rate, the shorter was the time required to heat up the water (table 3). Although it took about 35 min to heat up 4 L of water from 20 up to 100°C with a low flame compared to only 15 min with the maximum flame, the gas consumption only differed by nearly 0.03 kg. Comparing time ratio (2.3 to 1) and consumption ratio (1 to 1.2) between low and maximum flame shows that only 20% higher consumption leads to less than half the cooking time. The described consumption reflects the stove efficiency, which is higher at low flow rate and therewith leads to overall smaller gas consumption for the same energy input required to raise the temperature of water by a certain value.

Table 3. Efficiency, gas consumption and heating time of the biogas stove at different flame adjustments

	low flame	medium flame	maximum flame
fuel consumption (kg/h)	0.29	0.46	0.78
η (%)	49.09	46.85	41.74
power (kW)	1.45	2.27	3.84
heating time 20-100°C	34.84	23.53	15.29
fuel consumption (kg/K_{4L})	0.0021	0.0023	0.0025
fuel consumption 20-100°C (kg)	0.1710	0.1808	0.1993
fuel consumption (kg/L_{Water})	0.0331	0.0384	0.0424
energy consumption (kJ/L_{water})	586.29	679.99	749.60

The average specific heat capacity of water between 20 and 100°C is 4.186 kJ/ (kg K). Heating 1 L of water from 20-100°C requires an energy input of 293.02 kJ. Taking the caloric value of the used biogas (18 MJ/m³) as basis for the calculation of the theoretically required amount of biogas, i.e. provided an efficiency of 100%, leads to 0.0199 kg. The actually measured consumption values, between 0.0331 kg and 0.0424 kg as shown in table 3 are clearly higher due to the actual stove efficiencies between 49.09% at low flame and 41.74% at maximum flame.

4. CONCLUSION

Biogas technology allows dung use as indirect energy source featuring a higher calorific value and cleaner combustion than during direct dung combustion. Besides, cow dung as sole fuel proved incapable for cooking of meals, which explains the common practice in rural Ethiopia of using a mix of dung, firewood and branches for cooking. Field tests also proved dry wood as minor energy source compared to biogas despite same calorific values. Energy necessary to heat 1 L of water with biogas is at least four times lower than during wood combustion. Shorter heating times combined with lower fuel consumption could be observed as well. Lowering the flame during cooking with biogas reduces the cooking time considerably but fuel consumption only marginally. Therefore, the importance of time saving has to be weighed up against fuel saving. Comparison of fertilizer values show that slurry has very similar characteristics as dung which makes it an optimal substitute for dung application in the fields as nutrient provider for crops with even higher plant available nitrogen.

Thus promotion of slurry use as fertiliser remains an integral part of biogas programmes in developing countries. In summary it can be said that biogas as alternative energy source represents a multi beneficial product by providing energy and contributing to food security at the same time by supplying digestate as organic fertilizer for crop production.

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