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Emissions analysis from combustion of eco-fuel briquettes for domestic applications

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Abstract
In this study, flue gas emissions from combustion of eco-fuel briquettes in a ceramic lined stove were investigated. The eco-fuel briquettes were made of biomass such as spent coffee beans, mielie husks, saw dust, paper pulp and coal fines using a hand operated screw press. A combustion set-up consisting of digital weightometer, a ceramic lined stove and a complete chimney system was used. The emissions from the combustion process were measured using a Testo 350 gas analyser linked to the chimney system. The eco-fuel briquettes made from a mixture of biomass and coal fines burnt within the acceptable exposure limits as set out by the Occupational Safety and Health Agency (OSHA). The flue gas emissions from the combustion of eco-fuel briquettes were found to contain 74 parts per million (ppm) carbon monoxide (CO), 4.32 ppm hydrogen sulphide (H2S), 1.34ppm nitrogen oxides (NOx) and 3.67 ppm sulphur oxides (SOx). The measured gross calorific value was 18.9MJ/kg, with a burning rate of 2g/min. These properties make eco-fuel briquettes suitable for domestic applications. A survey conducted as part of this study also revealed a significant demand for eco-fuel briquettes in many informal settlements in Gauteng Province, South Africa, at a competitive selling price of R2.60/kg.

Keywords: biomass fuel, coffee grounds, clean air, eco-fuel, emissions, flue gas quality

1. Introduction

1.1 Eco-fuel briquettes

Due to the rising costs and historical lack of access to electricity, heat energy for cooking and heating in most townships of Gauteng Province in South Africa is obtained from the combustion of paraffin, fuel wood and coal. A recent survey conducted as part of this study has indicated that each household in these townships could use up to 200 kg of coal and 20 kg wood per month in addition to electricity for lighting and other applications in the winter season. Combustion of these fuels contributes significantly to air pollution resulting in potential risks to human health. 1 cubic meter of fuel wood emits 61-73 kg of carbon dioxide (CO_2) equivalents as well as other toxic and greenhouse gasses over its life cycle. Prolonged exposure to these, the toxic emissions such as carbon monoxide (CO), Sulphur Oxides (SOx) and Nitrogen oxide (NOx) may cause human health complications (Raymer, 2006).

Briquetting of biomass is a densification process which improves its handling characteristics, enhances its volumetric calorific value, reduces transportation cost and produces a uniform, clean, stable fuel or an input for further refining processes (Granada *et al.*, 2002). Fuel briquettes are bonded by the random alignment of fibers, generated when plant fibres and shredded waste paper are soaked in water. The process occurs at ambient temperature at a pressure of 1.5 to 3.0 MPa. To a large degree, the bonding force in the fuel briquette is mechanical, not chemical. Because of this, retaining fibre integrity and the right degree of plasticity in the mixture is crucial to the quality of the fuel briquette (Husain *et al.*, 2002).

Fuel briquettes made from corn stover, which is a major biomass stream in the United States of America, comprised roughly of 75% of total agri-

Figure 1: Production of briquettes using a manually operated screw press

cultural residues with an average bulk density of 42 kg/m^3. These briquettes are produced using a hydraulic piston and cylinder press at pressures of 5-15 Mega Pascal (MPa), (Mani *et al.*, 2006). Other fuel briquettes are made from palm shell and residue and are available in 40 mm, 50 mm and 60 mm diameters. They are also made using a hydraulic press at pressures of 5-13.5 MPa but have a higher density of 1200 kg/m^3 when compared with other briquettes, (Husain *et al.*, 2002).

The eco-fuel briquettes shown in Figure 1 were made from a mixture containing 32% spent coffee grounds, 23% coal fines, 11% saw dust, 18% mielie husks, 10% waste paper and 6% paper pulp contaminated water, using a very low pressure, of about 0.87MPa, hand operated screw press. All briquettes had an outer diameter of 100 mm, inner diameter of 35 mm and were 50 mm long. There was no need for a chemical binder; the material components underwent natural binding by interlocking themselves by means of partially decomposed plant fibres. They are not as compact as corn stover and Palm shell briquettes but yet have longer burning times and higher gross calorific values (Yaman *et al.*, 2001).

1.2 Flue gas emissions

Flue gas emissions from biomass combustion refer to the gas product resulting from burning of biomass solid fuel. Household solid fuels are mostly burnt with ambient air as opposed to combustion with pure oxygen. Since ambient air contains about 79 volume percent gaseous nitrogen, which is essentially non-combustible, the largest part of the flue gas from most fossil fuel combustion is inert nitrogen, (Demirbas and Sahin, 1998). The next largest part of the flue gas is carbon dioxide which can be as much as 10 to 15 volume percent. This is closely followed in volume by water vapour created by the combustion of the hydrogen in the fuel with atmospheric oxygen.

A typical flue gas from the combustion of fossil fuels will also contain some very small amounts of nitrogen oxides (NO_x), hydrogen sulphide (H_2S), sulphur oxides (SO_x) and particulate matter (Debdoubri *et al.,* 2005). The nitrogen oxides are derived from a very small fraction of the nitrogen in the ambient air as well as from any nitrogen-containing compounds in the fossil fuel. The sulphur dioxide is derived from any sulphur-containing compounds in the fuels.

1.3 Toxicity of combustion emissions

The potential health hazard to humans from exposure to combustion emissions depends on the inherent toxicity of the gases and the frequency and duration of exposure. Keeping exposure to below the permissible limits can be achieved by taking precautions. The permissible limits of concentration for the long-term exposure of humans to toxic gases are set by the threshold limit value (TLV). This is defined as the upper permissible concentration limit of the gases believed to be safe for humans even with an exposure of 8 hours per day, 5 days per week over a period of many years (Wright & Welbourn, 2002).

Recommended TLV values are published in the hazardous substance database bank by the Occupational Safety and Health Agency (OSHA). The OSHA database is assumed to be appropriate to be used as a benchmark for toxic gas exposure limits in the South African context. With the uncertainties involved in the designation of occupational exposure standards and the variability of the occupational environment, it would be unreasonable to interpret occupational limits as rigidly as one might interpret an engineering standard or specification (Peters and Timmerhaus, 1991).

2. Materials and methods

The experimental apparatus comprised of a digital weightometer, POCA ceramic lined stove and extraction system complete with a chimney. The gas extraction manifold was linked to a 980 mm stainless steel pipe of 90 mm diameter and 2 mm thickness as shown in Figure.2. A multi-purpose gas probe was installed 50 mm above the manifold for continuous gas sampling and analysis. Emissions from the eco-fuel briquettes combustion chamber were sampled directly from the chimney tunnel through the multi-purpose probe on a real time basis and measured through the Testo 350 analyzer electrochemical cells. Eco-fuel briquettes of known mass were combusted in a POCA stove and a 4 litre stainless steel pot was filled with cold water and put on the stove. The stove and pot were transferred to a weightometer in order to monitor the fuel consumption rate and heat transfer efficiencies. Data was collected over a 210 minute period for analysis. The velocity of natural incoming air was measured using an anemometer and this together with the cross sectional area of the incoming path was used to establish the air flow rate.

The combustion behaviour of the briquettes could be predicted and modified by varying the manufacturing conditions, mainly the diameter factor and the raw material. The unburnt ash content of the fuel briquettes can be estimated using the empirical model suggested by Tabares *et al.* (2000). The model defines the ash content as a function of fixed carbon being the principal factor of the weight characteristics during combustion. The relationship function is defined by Tabares *et.al* (2000) as follows:

$$W = fc(2.46 - 0.36fc + 3.9 \times 10^{-4}d + 0.13d_i + 0.05e^{4.59-0.037t} - 0.26\mathrm{m} - 1.2 \times 10^{-4}C_v)$$

Where,

W is the remaining weight of ash in (w/w %).

fc is fixed carbon in (w/w %)

m is the final moisture content in the briquette in (w/w %)

d_i is the briquettes diameter in (cm)

d is briquette density in (kg/m3)

t is burning time in (minutes)

Cv is the calorific value of the briquettes in (kJ/kg)

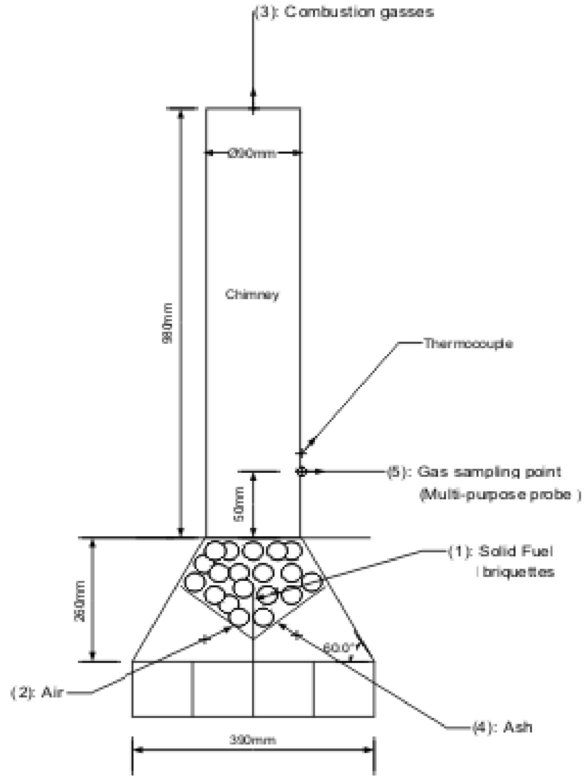

Figure 2: Schematic diagram of the combustion system used

3. Results and discussions

A survey was conducted at various informal settlements in Gauteng Province, South Africa, revealed that there is a need for alternative renewable energy source in addition to the existing ones. Table 1 summarizes the prices paid by households towards energy sources. Responses from this survey clearly indicate that, although people in the townships have access to electricity and other various energy sources, there is still a need for additional alternative energy sources such as fuel briquettes. The need for alternative sources is mainly driven by the current overall cost of energy. It has also been determined from the survey that an average home would spend around R430.00 to meet the household energy demands per month. Most people are trying to save energy so as to offset higher food prices. Paraffin and liquid petroleum gas are not widely used due to their costs and fire hazards. The briquettes could be a potential additional source of energy, not as a substitute for current sources of energy. The raw materials from which eco-fuel briquettes are produced are seasonal and may not be

Table 1: Domestic alternative fuel prices as per survey conducted in March 2009

Type	*Electricity*	*Coal*	*Wood*	*Paraffin*	*LPG*	*Eco-fuel briquettes*
Rate	R0.89/kWh	R2.6/kg	R2.80/kg	R13.50/kg	R15/kg	R2.26/kg
Energycontent	3.6MJ/kWh	25.92MJ/kg	16MJ/kg	42MJ/kg	49.3MJ/kg	18.9MJ/kg
Fuel cost	R 0.25/MJ	R 0.10/MJ	R 0.175/MJ	R0.32/MJ	R 0.304/MJ	R 0.119/MJ

consistent to meet continuous demand. Furthermore, they produce the least heat energy per kilogram compared to existing gaseous, liquid and solid fossil fuels. They are also slightly more expensive than low grade coal which is widely used as a fuel.

3.1 Properties of eco-fuel briquettes

Ultimate and proximate analyses of dry eco-fuel briquettes were conducted using the ICP-Optima model 2100DV. Eco-fuel briquettes contain 26.30% fixed carbon, 39.34% volatile matter, 10.9% moisture and 10.46% ash as per proximate analysis. The ultimate analysis show 36.65% carbon, 4.60% hydrogen, 36.3% oxygen, 0.75% nitrogen and 0.34% sulphur in the briquettes. Bomb calorimeter tests have shown the briquettes yielding a gross calorific value of 18.9MJ/kg. The dry bulk density was measured as 721 kg/m^3. It was noticed that the Tebares *et al.* (2000) correlation defined by Eq. 1 does not give an accurate ash content estimation for eco-fuel briquettes. This could be as a result of the geometry of the eco-fuel briquettes being a hollowed cylindrical shape as opposed to the solid cylindrical briquettes used to derive the Tabares *et al.* empirical correlation.

Table 2 outlines the comparisons of properties between coal and eco-fuel briquettes. This comparison indicates that coal is still a better fuel in terms of its higher calorific value (25.92MJ/kg), carbon content (61.2%) and lower ash content of 12% compared to the eco-fuel briquettes which have calorific value, carbon content and ash content of 18.9MJ/kg, 22.5% and 28.4% respectively. However, the eco-fuel briquettes are made of organic waste material with a lower sulphur content of 0.002% compared to 3.9% in coal.

3.2 Eco-fuel briquettes combustion

Variation of flame temperature with the concentration of oxygen in the combustion gases is shown in Figure 3. The oxygen concentration drops below 8.31% at the maximum combustion rate at a flame temperature of 197^0C. As the flue gas temperature drops, the oxygen concentration in the flue gasses increases, meaning that less oxygen is consumed when the combustion process slows down. The final oxygen concentration of 20.57% is attained when the flue gas temperature is equal to the ambient temperature, providing evidence that the combustion process stopped and oxygen was no longer consumed. The air to fuel ratio of 1.44:1 was obtained which shows that 60% of air was consumed for every 40% of fuel combusted.

Table 2: Comparison of coal and fuel briquettes properties

Combustion gas properties	*Eco-fuel briquette*	*Coal*
Gross calorific values	18.9	25.9
Specific gravity	0.71	0.86
Carbon w/w%	22.5	61.2
Hydrogen w/w%	0.71	4.3
Oxygen w/w%	43.8	7.4
Sulphur w/w%	0.0020	3.9
Nitrogen w/w%	0.0010	1.2
Ash w/w%	28.4	12.0
Water w/w%	10.9	10.0
Carbon dioxide: volume%	19.7	15.0
Oxygen: volume %	13.4	3.7
% Excess air	12.8	20.0
Nm^3/GJ:8MJ/1.14m^3	142.5	293.6

3.3 Eco-fuel briquettes emissions

Table 3 shows a comparison between the actual gas emissions from fuel briquettes and maximum human exposure limit over 8 hours. The table clearly indicates that the gas emission produced by the fuel briquettes conforms to the Occupational Safety and Health Agency (OSHA) occupational exposure standards as indicated in Table 4. High carbon dioxide concentration indicates compete combustion resulting in carbon monoxide been oxidized to less toxic carbon dioxide which is more of a greenhouse gas as opposed to other toxic emissions presents in Table 3. Proper ventilation for dilution of high carbon dioxide concentration in the emission is essen-

Table 3: Emissions for the selected toxic emissions vs. the maximum exposure limit over 8 hours

CO_2(ppm)	*CO(ppm)*	*H_2S (ppm)*	*SO_2 (ppm)*	*NO (ppm)*	*NO_2 (ppm)*	
21332	73.78	4.32	3.67	1.34	2.73	Briquettes emissions
5000	50 -200	20	5	25	5	OSHA limit

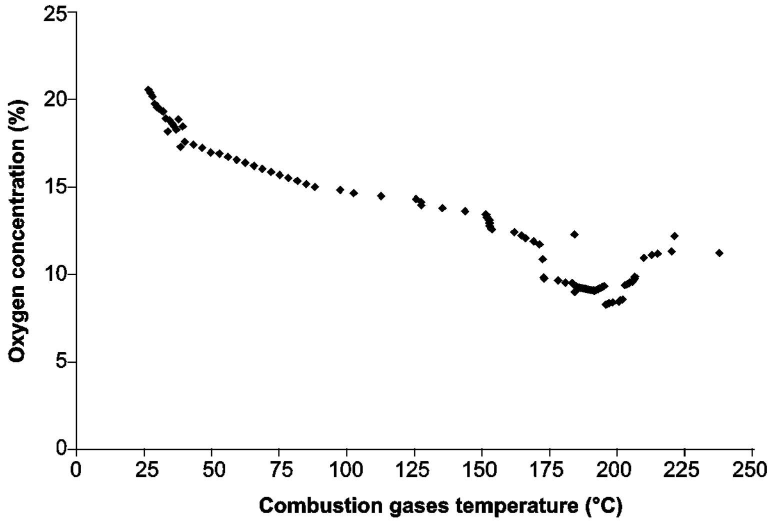

Figure 3: Flue gas temperatures with oxygen concentrations

tial, not only for prolonged exposure but also to ensure that enough oxygen in the air is provided for efficient combustion.

Although the other gases are in low concentrations as shown in Figure 4, the maximum safe exposure time to the combustion gasses produced by the fuel briquettes is 11.25 minutes due to the high carbon dioxide concentration. In principle, the fuel briquette is deemed a clean fuel compared to other fossil fuels. The carbon dioxide produced is 2 892 times the carbon monoxide, which indicates complete combustion. Furthermore, carbon dioxide is less toxic than carbon monoxide; therefore, combustion of fuel briquettes is even more suitable for well ventilated indoor applications.

Table 5 summarizes the flue gas compositions for natural gas, fuel oil and coal. From this summary, it is evident that combustion of eco-fuel briquettes emits less toxic gasses compared to other fossil fuels. A theoretical air requirement for combustion of the fuel briquettes was estimated as 2.57m^3 of air for every kg of fuel combusted. The experimental dry air consumed during combustion was measured as 752.65g at absolute pressure of 82.96 kPa. The average volumetric flow rate of the flue gas was measured as 0.4m^3/h over a period of 210 minutes and absolute pressure of 82.96 kPa, which is equivalent to 3.20m^3 of flue gas production per kilogram of eco-fuel combusted.

4. Conclusions

Combustion of fuel briquettes in a laboratory-scale POCA ceramic stove was investigated to evaluate its combustion characteristics and gas emission quality. The results show that high combustion efficiencies could be achieved by choosing appropriate operating conditions. The efficiencies were between 91-95% for carbon utilization efficiency and over 99.5% for CO combustion efficiency at an estimated air-to-fuel ratio of 1.44:1. The average burning rate of 2g/min was obtained from the test work, meaning that 1 kg of eco-fuel briquettes can burn

Table 4: Occupational Safety and Health Agency (OSHA) occupational exposure standard, obtained from the hazardous substance data bank

Gas component	Occupational exposure standard
Carbon monoxide (CO)	CASRN: 630-08-0 OSHA Standards: [29 CFR 1910.1000 (7/1/98)]. Permissible Exposure Limit: 8-hr Time Weighted Average: 50 ppm (55 mg/cu m). Vacated 1989 OSHA PEL WA 35 ppm (40 mg/cu m); Ceiling limit 200 ppm (229 mg/cu m) is still enforced in some states.
Nitrogen oxide (NOx)	CASRN: 10102-43-9 OSHA Standards: [29 CFR 1910.1000 (7/1/98)]. Permissible Exposure Limit: 8-hr Time Weighted Average: 25 ppm (30 mg/cu m).
Hydrogen sulphide (H_2S)	CASRN: 7783-06-4 OSHA Standards: [29 CFR 1910.1000 (7/1/98)] Permissible Exposure Limit: Acceptable Ceiling Concentration: 20 ppm. Permissible Exposure Limit: Acceptable maximum peak above the acceptable ceiling concentration for an 8-hour shift. Concentration: 50 ppm. Maximum Duration: 10 minutes once, only if no other meas. exp. occurs.
Sulphur oxides (SO_x)	CASRN: 7446-09-5 OSHA Standards: 1910.1000 (7/1/98)] Permissible Exposure Limit: 8-hr Time Weighted Average: 5 ppm (13 mg/cu m). [29 CFR]

Table 5: Comparison of flue gas quality of various fuels

Chemical species	*OSHA-max limit (ppm)*	*Natural gas*	*Fuel oil*	*Coal*	*Eco-Fuel Briquettes*
Nitrogen (N_2)	-	78-80%	78-80%	78-80%	60.3%
Carbon dioxide (CO_2)	5,000	10-12%	12-14%	10.6%	21.3%
Oxygen (O_2)	-	2-3%	2-6%	7%	12.8%
Carbon monoxide (CO)	50-200	70-110ppm		5,579ppm	74ppm
Nitrogen dioxide (NO_2)	5			1%	2.73ppm
Nitric oxide (NO)	25			1%	1.34ppm
Ammonia (NH_3)	50				
Sulphur dioxide (SO_2)	5			>2,000ppm	3.67ppm
Hydrocarbon (C_xH_y)	-				
Hydrogen sulphide (H_2S)	20				4.32ppm
Ash	-	0	0	12%	28.4%

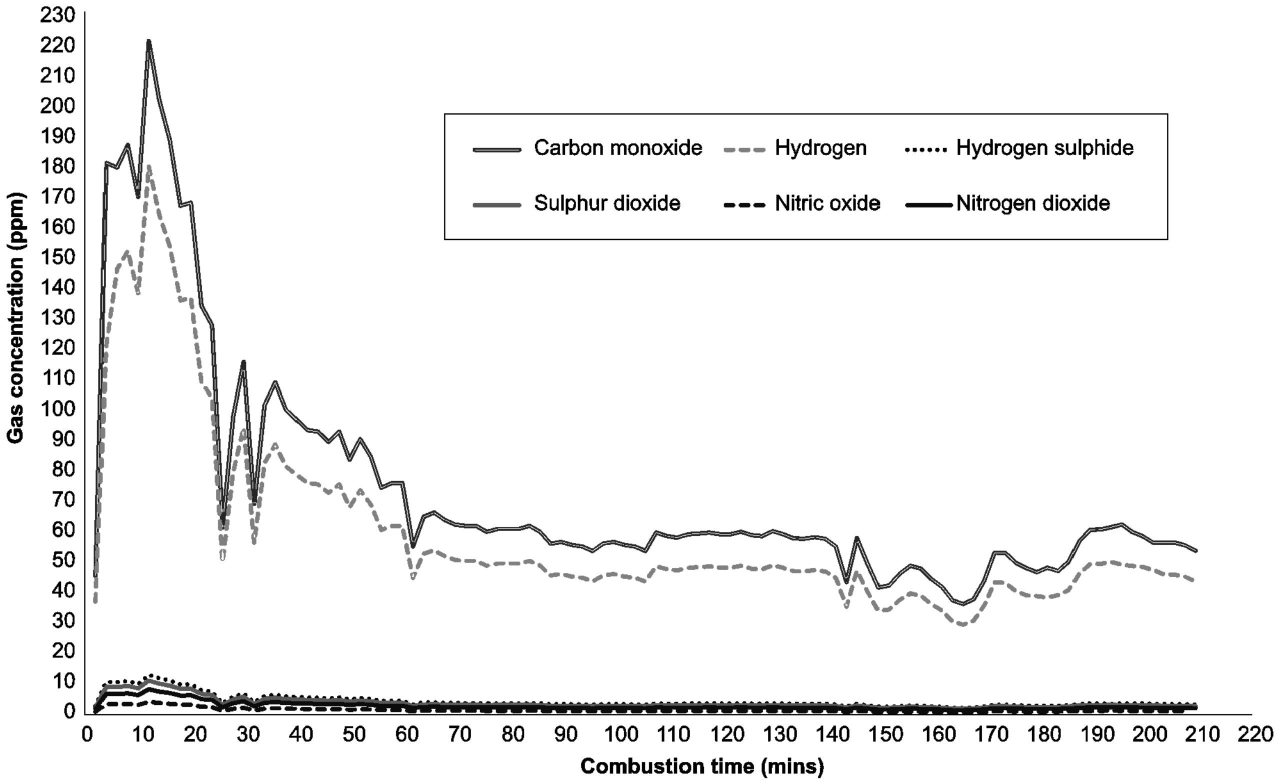

Figure 4: Variations of low concentration emissions in the flue gas

for 7 hours which makes it ideal for domestic applications. The standard enthalpy of formation of the briquettes was estimated as -1619.3kJ/mol.

The flue gas produced from this reaction consisted of 2.13 vol% CO_2, 74 ppm CO, 4.32 ppm H_2S ,1.34 ppm NO, 3.67 ppm SO_2, 5.5 vol% water vapour (H_2O), 59.8 ppm hydrogen(H_2), 60.3 vol% nitrogen (N_2) and 12.8 vol% oxygen (O_2). The gas was mostly dominated by inert atmospheric nitrogen, oxygen, carbon dioxide and water vapour. The test results have shown that combustion of Eco- fuel briquettes emits less toxic emissions compared to fossil fuels based on controlled condition combustion and atmospheric combustion.

5. Recommendations

The effects of operating parameters on fuel briquettes combustion, such as gas velocity and excess air, and preheated air temperature and velocity may need to be investigated in details in order to model the combustion efficiency of the briquettes under given conditions. The empirical correlation suggested by Tabares *et.al* (2000) for estimating the ash content of the eco-fuel briquettes may need to be studied for various briquettes geometry.

Although eco-fuel briquettes burn cleanly within the acceptable OSHA emission exposure limits, consumers need to be educated of the health hazards associated with the exposure of combustion gasses over prolonged periods, and without sufficient ventilation, in addition, combustion of eco-fuel briquettes using uncertified stoves may cause excessive emissions due air-fuel ratio imbalances.

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