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Comparative Study on Emissions from Traditional and Improved Biomass Cookstoves Used in India

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Abstract: Cooking is central to our lives. In developing countries, about 90% of rural households depend on the solid biomass fuels for cooking. Unprocessed solid biomass fuels are used by the poor urban and rural folk for cooking and heating. Approximately 67% of households in India (equivalent to 166 million households) remain wedded to solid fuels as their primary source of cooking fuel. The traditional cookstoves used for cooking are not energy efficient and the fuels are not burnt completely, thus resulting in release of complex mixture of health damaging indoor air pollutants like carbon monoxide and nitrogen oxide. This paper estimates and compares the extent to which the pollutants like carbon monoxide and nitrogen oxides are generated when biomass fuels is burnt in traditional cookstove (U-shaped) as compared to improved cookstove (Priyagini) which is commonly used in northern India. The thermal efficiency of the cookstoves and characteristics of biomass fuels were also established.

Key words: Crop residue; Dung cake; Emissions; Improved cookstove; Indoor air pollution; Traditional cookstove; Wood.

I. INTRODUCTION

The energy demand is increasing with increasing population and prosperity. The residential sector is the major energy-demanding sector in India, where highest percentage of thermal energy is consumed in cooking. Consequently, both the commercial (electricity, kerosene, and liquefied petroleum gas) and non-commercial (direct use of biomass) energy are used accordingly. The use of biomass fuels like wood, crop residue and dung cake is widespread in rural India. When used in simple cooking stoves, these fuels emit substantial amounts of toxic pollutants [1]. In households with limited ventilation, exposures experienced by household members, particularly women and young children who spend a large proportion of their time indoors, have been measured to be many times higher than World Health Organization guidelines and national standards.

According to the Census of India (2011), many households still rely on firewood fuel for cooking and approximately 20% rely on other forms of biomass fuels. In rural areas, approximately 80-90% of households are dependent on biomass for cooking. In contrast to cleaner fuels, kerosene and LPG were accounted for 19% and 48%, respectively [2]. Traditional fuels, as presently

used, have inherent disadvantage. In India, the most commonly used stove for cooking is the traditional stove called 'chulah'. While primarily designed for fuel wood, the same chulah has been adapted to burn crop residue and dung cakes. The main problems associated with these cooking devices are their inability to vent smoke out of a room, which causes significant levels of indoor air pollution [3, 4]. The use of traditional fuels may have serious consequences on human health. In spite of the inherent disadvantages associated with traditional fuels/stoves, majority of the rural population use them even in areas with access to the cleaner fuels. Most traditional stoves utilize only 2-10% energy generated by the fuel. One of the major reasons is the lack of control on air supply. Air to fuel ratio also cannot be maintained at constant level throughout the burning of fuel. When air enter at the bottom of the burning mass, the air to fuel ratio decreases and the air moves up through the fuel bed and may in some places fall below the level needed for proper combustion. This results in the formation of carbon monoxide. Emission of black smoke is a visual indication of incomplete combustion, it consist of sizes up to 5 microns. In addition to particulates, the flue gases consists of carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen and sulphur (NO_x and

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SO_x), hydrocarbon, aldehyde, ketones etc. [5]. In poorly ventilated households, concentration of the pollutants are ten to hundred times high and health related implications are reported to be high among women and children. As per reported burden of diseases estimate, indoor air pollution is the third most important risk factor, next to poor water and sanitation and malnutrition, of ill health and responsible for 17% of all deaths among children under five in India [6].

Carbon monoxide and Nitrogen Oxides are often considered to be the damaging air pollutants from health point of view [7,8]. Carbon monoxide is one of the primary products of incomplete combustion. Current estimates indicate that combustion of the fossil fuels and biomass fuels contributes about 44% of the total global CO budget [9]. CO is considered an indirect greenhouse gas due to its close coupling to atmospheric methane [10, 11]. Oxides of nitrogen is a broad term for the various nitrogen oxides (other than N₂O) produced during combustion when combustion temperatures reach a high enough level to burn some of the nitrogen in the air. NO_x is an ozone precursor and when dissolved in atmospheric moisture, it can result in acid rain. Oxides of nitrogen affect atmospheric chemistry in complex ways, including interactions with OH radicals and contributing to ozone chemistry. They are presently thought to be greenhouse-neutral overall [12, 13]. In the present work, an experimental investigation was undertaken to study the emission of Carbon monoxide and Nitrogen Oxide from the traditional and improved biomass cookstoves used in India. The cookstove generated CO and NO_x emissions were then compared with the health-based CO and NO_x standards and guidelines. The thermal efficiency of the biomass cookstoves was tested. The proximate analysis and ultimate analysis of the fuels was done and the calorific value of the three-biomass fuels was tested in the laboratory for studying the characteristics of the fuels.

II. METHODOLOGY

The two indoor air pollutants, that is, carbon monoxide and nitrogen oxide concentration was determined for three different biomass fuels in a U shaped traditional cookstove and improved cookstove 'Priyagini model', which is designed by CPRI, the Central Power Research Institute. The experimental study was carried out at the laboratory at Center for Energy Studies, Indian Institute of Technology, Delhi. Water Boiling Test (WBT), a standard international method, was performed systematically for

the six-fuels and cookstoves in a simulated kitchen. The emissions from solid biomass fuels are not constant and vary with time during the burning process. Therefore, integrated sampling is required to obtain the data that can cover the complete burn cycle from the first start of fuel combustion to the last fire extinction. This will represent the real burning situation of the fuels and cookstoves [14, 15, 16].

In WBT a pot containing known amount of water was placed on a cookstove during each experimental cycle. The initial and final water temperature and the amount of water evaporated were measured for each burn cycle. Hence, the energy received by the pot was determined. This procedure has an added advantage of enabling the simultaneous measurement of emissions and stove efficiencies, thus facilitating future calculations of the impact of changes in one or the other. The burn cycles ranged from 70 to 80 minute for all types of fuels and cookstoves. The details of the two experimental phases of Water Boiling Test are given below:

High Power Phase Test

1. Keep the timer ready and start it when the combustion of fuel is started.
2. Measure the water and pour it in the pot to fill two-third of the cooking pot with water at room temperature. Record the weight of the pot with water.
3. With the help of a wooden fixtures fixed the thermometer in the cooking pot at a height of 5cm above the bottom of the pot and at the center of pot. Now, measure the initial temperature of the water and make sure that this temperature is near to the ambient temperature.
4. After placing the pot on the cookstove start the fire in a reproducible manner and note down any other fuel material if used for starting the fire. Use the pre-weighed fuel for this also. Kerosene is generally used for starting the fire.
5. When the fuel starts combusting and the fire is caught, start the measurement. Record the time and temperature of this high power phase. Supply the fuels at a regular interval of time and keep the fire controlled.
6. When local boiling point is reached and confirmed by the digital thermometer. The following has to be recorded:
 - i. The time required to reach the boiling point and the temperature at which the water boils.
 - ii. After this boiling point is reached, boil the water for another 5 minutes.

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iii. This is the end of the high power phase test. Now, immediately start the low power phase test.

Low Power Phase Test (Simmering test)

The low power phase is useful in understanding the simmering of water and other liquids. This phase is followed after the high power phase and continued for another 45 minutes.

The procedures to be followed are as given below:

1. Set the timer again.
2. Place the thermometer again in the pot at the center and above 5cm from the bottom of the pot.
3. Supply the fuels at regular interval for 45 minutes and adjust the fire in such a way that the temperature of water does not fall 3°C below the water boiling temperature. The test fails if the temperature of water fall 6°C below the boiling point temperature.
4. After the end of the low power phase, the following has to be recorded:
 - i. The time required to complete this phase which is approximately 45 minutes and the final temperature of water which should be roughly recorded at 3°C below the earlier established boiling temperature.
 - ii. Measure the fuel left in the bundles of fuel prepared and the unburnt fuel left in the cookstoves to determine the exact amount of fuel used in the WBT.
 - iii. The weight of the pot with the left over water must be measured and recorded.
 - iv. The weight of the charcoal produced during the WBT has to be recorded at the end of the experiment. Collect all the charcoal, put it in a pan, and then record it weight.
 - v. WBT is completed with the completion of the two-power phase involved in the experiment. WBT has to be performed on each type of cookstoves and cooking fuels for three times to get an adequate result.

A. Measurement of CO and NO_x

A typical sampling configuration from upstream to downstream included a sampling probe, a filter holder, a pump and an instrument for CO and NO_x measurement, Testo 350 'XL'. The stoves were placed under a hood built for the study, and the probe was placed inside the hood exhaust pipe. The indoor CO and NO_x was measured with a battery operated Testo 350 'XL' regularly at an interval of one minute during the complete WBT burn cycle. Even after extinguishing the fire the concentration was further monitored until its concentration

reduced to the background value. Three successful tests with complete burn cycles were piloted for each fuel and cookstoves.

B. Thermal Efficiency of the Biomass Cookstoves

Thermal efficiency is defined as the ratio of energy entering the pot to the energy contained of the fuel consumed. The energy entering the pot produces two measurable effects - raising the temperature of water to the boiling point and then evaporating the water. The former was measured by a thermometer and the latter by weighing the water before and after the combustion process. Initial mass of the fuel, added fuel and char remaining at the end of burning cycle were similarly determined by weighing it. The heating value, size, moisture content and feeding rate of fuels affect the efficiency of fuel burning stoves. Further stove components, its materials and size of cooking pot also affect the heat utilization efficiency. The energy content of the fuel consumed was calculated by the following equation [17].

$$\eta (\%) = \frac{[W_i \times S \times \Delta T + (W_i - W_f) \times L]}{F \times t \times CV} \times 100 \quad (1)$$

Where,

η = efficiency (%)

W_i = initial weight of water (kg)

W_f = final weight of water (kg)

S = specific heat of water (kJ/degree-kg)

ΔT = Temperature difference = $T_2 - T_1$ (°C)

T_2 = temperature final (°C)

T_1 = temperature initial (°C)

L = latent heat of vaporization for water (2260 kJ/kg)

F = burn rate (kg/h)

t = duration (hour)

CV = calorific value of fuel (kJ/kg)

C. Characteristics of the Biomass Fuels

The three fuels used for the study were acacia, mustard and cow dung cake. Acacia is a tree which is small in size and commonly found grown on the sides of road and barren land. Since it is easily found in all parts of India, it is one of the typically used biomass fuel in India. The crop residue is used by 10% of the households in India. Crop residues are obtained in the form of stalk, straw, husk and fibrous material after the main crop has been extracted in the field. These are the left over part of the energy crops grown in an agricultural land. Based on the type of

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crop grown in an area, the crop residue will vary from one field land to another. Most ordinarily used crop residues in India are rice straw, wheat straw, arahar stalk, mustard stalk, cotton stalk, jute stalk, tobacco stalk, and various pulse stalks. Dungcakes are mainly made from dungs of cow, buffalo, cattle and camels. The dungcake is prepared by mixing small amount of crop residue with the dung after which it is sun-dried. Dungcakes are normally used in the villages and semi-urban areas in the country. Haryana and Utter Pradesh have the greatest use of dungcake as a fuel. Overall 8% of people in India use dungcakes for cooking [18, 19].

1) Proximate Analysis of the Fuels

For characterization of solid fuels, the proximate analysis of fuel was carried out. Proximate analysis indicates the percentage by weight of the fixed carbon, volatile matter, ash, and moisture content in fuel. The amount of fixed carbon and volatile combustible matter directly contribute to the heating value of fuel. Fixed carbon acts as a main heat generator during burning. On heating of biomass fuels, volatile matter (flammable gas and smoke) is liberated. This burns as visible flame on supply of sufficient air, time, temperature and turbulence. High volatile matter content indicates easy ignition of fuel. Complete combustion of volatile matter leads to dark smoke, heat loss, pollution hazard and soot deposition on boiler surfaces. Ash is the incombustible solid mineral matter in the fuel. It mainly contains silica (SiO_2), Alumina (Al_2O_3), Iron (FeO , Fe_2O_3), CaO and MgO etc. The proximate analysis of fuel was carried out using ASTM methodology.

The moisture content of the fuel was determined by taking 1 gram of fuel in a crucible and drying it at $(105 \pm 5)^\circ\text{C}$ for 2 hour. The loss in weight represents the moisture content of the fuel. The volatile matter was determined by placing a weighted quantity of powdered fuel in the crucible, covering with a lid, in a furnace at a temperature of 950°C for 7 minute. The loss in weight represents the volatile matter. The ash content was determined by placing a weighed quantity of powdered fuel in an open crucible in a furnace at a temperature of 575°C for 4 hour. The fixed carbon was determined by subtracting the sum of moisture, volatile matter and ash content from 100.

2) Ultimate Analysis of the Fuels

The ultimate analysis indicates the common organic elemental chemical constituents such as Carbon, Hydrogen, Nitrogen, Oxygen and Sulphur in the fuel. It is useful in determining the

quantity of air required for combustion, the volume and composition of the combustion gases, water vapor content in the flue gas, sulphur content of flue gas and calorific value of fuel that depends upon carbon and hydrogen content of fuel. This information is useful for the calculation of flame temperature and the flue duct designing.

The ultimate analysis of the fuel was determined by an ASTM D3176 Analyzer. The samples were tested in the analyzer for the carbon, hydrogen, nitrogen and oxygen content in the fuel.

3) Calorific value of the Fuels

The calorific value of the fuel was determined by the bomb calorimeter using NREL methodology and detailed procedure described by Hubbard et al. Benzoic acid was used to standardize the bomb calorimeter. 1 gram of sample was taken in a crucible and made into a pellet and the initial weight was noted. It was placed in the bomb, which was pressurized to 18 atmosphere of oxygen.

The calorimeter was placed in an isothermal jacket with an air gap separation of 10 mm between all surfaces. The bomb was placed in a vessel containing a measured quantity of water. The ignition circuit was connected and the water temperature was noted. After ignition, the temperature rise was taken every minute until a constant temperature was recorded. The pressure was released and the length of unburned fuse wire was measured.

The following formula was used to calculate the calorific value of the fuel.

$$\text{CV (KJ/Kg)} = [(T_c \times W) - (m_1 + m_2)] / \text{weight of sample} \quad (2)$$

Where,

T_c = temperature rise ($^\circ\text{C}$)

W = apparent heat capacity by benzoic acid (J)

m_1 = calorific value of thread (J)

m_2 = calorific value of Nichrome ignition wire (J)

III. RESULTS

The emissions from the six-biomass cookstoves were assessed and then the emissions from the traditional and improved cookstoves were compared. The thermal efficiency of the cookstove was also calculated during the WBT. The efficiency of the traditional

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cookstove was low as compared to the improved cookstove that resulted in the wastage of fuel accompanied by huge emission. The characteristics of the three fuels, i.e. wood, crop residue and cow dung cake were analysed and is presented in Table 1.

A. CO and NO_x Emissions

Figure 1 show the average values of CO and NO_x emitted from the traditional and improved biomass cookstoves tested in the study. As per National standards set by Central Pollution Control Board (CPCB) the safer limit for CO and NO_x are 2 ppm and 0.2 mg/m³ for 1 hour respectively [20]. These national standards were exceeded by CO and NO_x exposures caused by biomass cookstoves. The emissions were maximum from the dung cake followed by the crop residue and wood. However, the emissions were reduced by 1.5 to 2.5 times by the use of the improved cookstoves in place of the traditional cookstoves.

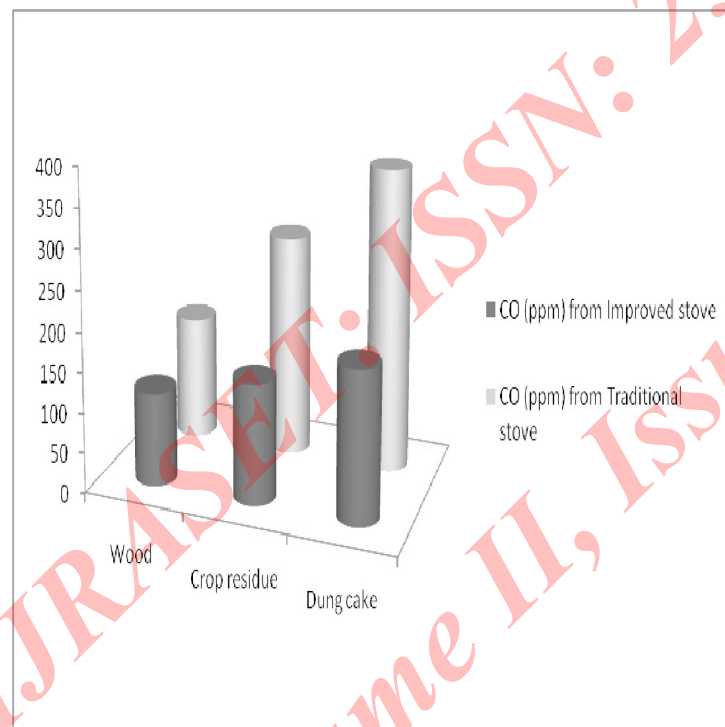


Figure 1.1. CO emission from traditional cookstoves (U-shaped) and improved cookstoves (Priyagini) during Water Boiling Test

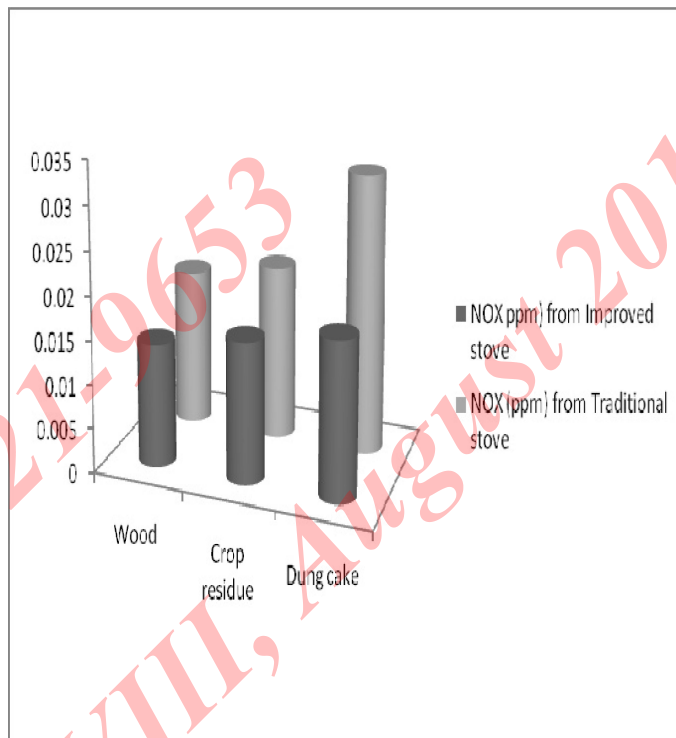


Figure 1.2. NO_x emission from traditional cookstoves (U-shaped) and improved cookstoves (Priyagini) during Water Boiling Test

B. Thermal Efficiency of the Biomass Cookstoves

The thermal efficiency of the traditional cookstove was low which resulted in the wastage of fuel accompanied by the huge emission. In improved cookstove, the design of traditional cookstove was improved by providing a chimney and a grate for proper combustion and this resulted in improved heat utilization and lesser emission. The vital factor for efficient combustion is the quantity of air supplied. It was not just enough that the required oxygen was present in the system, it was also necessary that there was very intimate contact of oxygen and the combustibles. The thermal efficiency of the six biomass cookstoves is presented in figure 2. The efficiency of the tested traditional stoves varies from 9% to 17% and that of the improved stoves varies from 10% to 23%.

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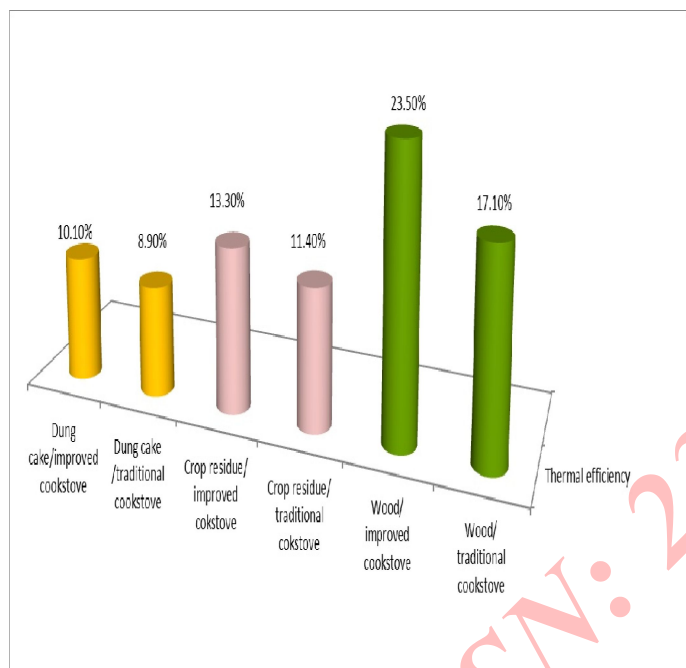


Figure 2. Thermal efficiency of various fuels and biomass cookstoves

Table 1. Proximate Analysis, Ultimate Analysis and Calorific Value of the fuels

FUELS	Wood (Acacia)	Crop Residue (Mustard)	Cow dung cake
Proximate Analysis			
Moisture (%)	5.30	16.50	7.82
Ash (%)	9.14	3.90	31.46
Volatile matter (%)	71.59	64.32	47.91
Fixed carbon (%)	20.00	15.28	13.30
Ultimate Analysis			
Carbon (%)	49.91	42.80	32.97
Hydrogen (%)	4.65	4.60	4.50
Nitrogen (%)	0.26	0.22	0.32
Oxygen (%)	45.18	52.38	62.21
Gross Calorific Value (MJ/ kg)	16.21	14.20	9.79

C. Characteristics of the Biomass Fuels: - Proximate Analysis, Ultimate Analysis and Calorific Value of Fuels

For characterization of solid fuels the proximate analysis and ultimate analysis of the three fuels was done. The result is given in the table 1. The gross calorific value (higher heating value) of the fuels was determined by the bomb calorimeter. Among the three fuels, wood shows the highest carbon content and calorific value. It may be noted that dung cakes have exceptionally high ash content as compared to wood and crop residue. However, the crop residue has higher moisture content than the wood and dung cakes.

This higher calorific value of acacia shows that it is comparatively the potential biomass for the production of bioenergy. The percentage of ash in cowdung cake, mustard and acacia were found to be 31.46%, 3.90%, 9.14% respectively. By the experimental studies, it was detected that the cow dung cake shows high percentage of ash compared to the mustard. VM of acacia was higher. It was typically around 72%. High VM content of acacia makes it more readily devolatilized than cow dung cake, liberating less fixed carbon, hence making them more useful for pyrolysis and gasification.

D. Exposure Reduction from Improved Cookstoves

Our estimates indicate that switching from the traditional cookstoves to improved cookstoves would lower the CO and NO_x emission drastically [21]. Even switching from one type of biomass fuel to another would result in a significant reduction of emissions. For example, switching from dung cake

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to fuel wood would lower the CO emission by about 2.5 times. The best option for CO and NO_x reduction is to encourage the use of improved cookstoves having chimneys. By doing so, only a fraction of CO and other pollutants emitted from fuel combustion will be directly released into the kitchen. For example, CO concentration measured in the simulated kitchen with an improved cookstove was 50% less than that of the emitted by traditional cookstove. Similarly, there was NO_x reduction of about 1.3 to 2 times when the traditional cookstoves was replaced by an improved cookstoves. Even though the emission to the atmosphere was not changed, the use of improved biomass cookstoves substantially reduces the pollutant concentrations in the kitchen and consequently reduces the exposures and health risks [22, 23, 24].

IV. DISCUSSIONS

The results showed in figure 1 and figure 2 support a typical household energy ladder concept. Cleanliness, energy efficiency, and capital cost increase along the energy ladder in the following order starting from the lowest: dung cakes, crop residue, wood, kerosene, gas and electricity as shown in figure 3. When using the estimated CO and NO_x concentrations as shown in figure 1 as an indicator of the fuel cleanliness, our results was in general agreement with the energy ladder concept [25]. Regardless of which stove was used, the CO and NO_x concentration measured in the kitchen air was the highest during burning of the dung cake, followed by the crop residue, and wood. The calorific value of the wood was highest followed by the crop residue and dung cake. The trend across the tested biomass fuels is consistent and agrees with the energy ladder concept.

Many household surveys on expenditure and energy expenditure show that most families have an ideal fuel preference 'ladder' running from biomass fuels through kerosene, LPG to electricity. The dominant cooking fuel most preferred by the richer households is LPG and electricity in India. The main reason for their preference is that they are clean to use, highly controlled in terms of power output to match different household needs and storing and fetching costs are almost negligible. Nevertheless, in the present situation it seems that complete switching to cleaner fuels like LPG, biogas and electricity is difficult to achieve in near future keeping in view the economic, technical, social and traditional constraints. The demand of biomass fuels may not disappear as fast as may be predicted on a pure fuel transition approach.

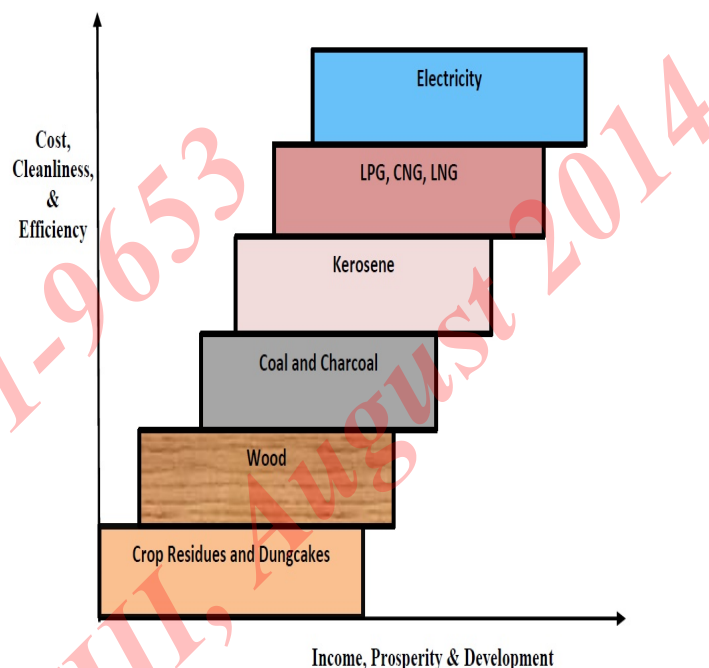


Figure 3. The Energy Ladder: Linkage between Household Energy (cost, cleanliness and efficiency) and income, prosperity and development

V. CONCLUSION

The use of solid fuels for cooking and heating is the largest source of indoor air pollution. From the study done we can conclude that the dung cakes used in the traditional cookstove is the dirtiest fuel in terms of CO and NO_x emissions while improved cookstove with wood gives the least emissions. Biomass fuels should be used in the improved cookstoves for increasing the energy efficiency. The thermal efficiency of the improved cookstove was 12% to 28% more than that of the traditional cookstove. Thus, the use of the improved biomass cookstoves will conserve the biofuels. The monitoring of the air pollutants from the operation of the cookstoves in a variety of design and the development of the less pollutant-releasing cookstoves is a necessity for improvement of indoor air quality.

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