Prototyping and Performance Evaluation of Household Cow Dung Gasifier Stove: Cooking and Environmental Performance in the Case of Ethiopia

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Abstract

Biomass energy is the most important primary energy sources in Ethiopia, above 90% of primary energy comes from biomass.Cow dung is one of the widely consumed biomass as a source of energy in rural areas of Ethiopia in traditional and inefficient cook stoves. To this end, this piece of research work is aimed at designing, manufacturing and experimentally testing its environmental and energy performance compared to the traditional three-stone stove. In this study water boiling test and control cooking test was used to investigate the performance of stoves. The proposed gasifier stove shows a better performance than three stones stove when water-boiling test conducted in terms of cooking duration, specific fuel consumption, and pollutant gases emission. The experimental results revealed that gasifier stove has shown an increase of thermal efficiency by 26.6% and reduced PM2.5 and CO emission by 58.9% and 88.6% respectively as compared to the traditional three-stone cook stove.Furthermore, the gasifier stove has shown 64% fuel saving efficiency as compared to the three stones stove and 54% cooking time saving to cook the same amount and kind of meal. In every aspect of the measuring parameters whether the energy efficiency performance or environmental performance the designed gasifier stove performs better than the traditional three-stone cook stoves. Therefore, with a small and simple modification, the gasifier stove could be disseminated to the rural community of the region in collaboration with the regional bureau.

1. Introduction

Biomass energy is the most important energy source for Ethiopia, on a world scale, about 14% of primary energy comes from biomass energy sources, but in Ethiopia,it is above 90% [1]. Ethiopian rural households are dependent on two main solid fuels (woody biomass and dung) for centuries [2]. Dung is a common source of energy in Ethiopia since it is abundantly available and cheap energy source, generated from everyday animal waste and it is cheaper than modern fuels. These fuels are typically burned in traditional stoves. As a result, these types of stoves produce higher air pollution, which results in an increased risk of acute respiratory infection and lung diseases, especially for women and young children [2]. Due to the overutilization of biomass the sustainability of Ethiopian biomass supply is not sustainable [3].

In Ethiopia, the utilization of solid biomass fuel is increasing from time to time with the population growth. In the present day, many of the population are facing a severe crisis in energy scarcity as local wood resources are depleted and more forests that are distantarecutdown,which leads to wasting of large percentage of their time for looking for fuelwood instead of performing productive work in agriculture. Fuelwood shortage has ledto a growing dependence on crop residues and animal dung as fuel[1].Now a days, different types of improved biomass cook stoves such aslakech, gonzie, mirt, and charcoal stoves are introduced and distributed for people living in rural and urban areas of Ethiopia by governmental and nongovernmental organizations,however the efficiency of the stovesstill need improvement[4].

The Lakechstove has an efficiency of 19–21%, only charcoal is used as fuel though charcoal is not a positive conversion of wood fuel,and it is popular among urban inhabitants.The stove is used mostly for coffee making and cooking wot (traditional curry)and they are made from clay and metal so that the heat loss can be minimized while the heat transfer is inhaced. Today, more than 2.5millionlakech stoves have been disseminated in a different region of Ethiopia[5]. The Gonzie stove has an efficiency of 23%. It has multi purposes, such as baking injera, cooking wot and boiling waterand it' fuel saving potential is 54% for baking injera and 44%for boiling and cooking compared with traditional three stones stove. Wood, dried leaves, and dung are used as fuel. The use ofGonzie stoves increases with the rapid growth of the population. Even thoughGonziestove is more efficient than both Lakech and traditional three stones stove, 78% of the energy is lost in the process of converting the biomass fuel into useful energy [6].

This entire disseminated cooking stove in Ethiopia needs to modernize and upgrade to reduce fuel consumption and indoor air pollution. Improving the efficiency of a stove thus requires attention due toa number of factors, such as increasing the heat transfer efficiency, engineers should design the stove in such a way that it transfers allenergy generated from the stove reactor to surface of the pot during cooking. Improving these cook stoves will not only save fuel but alsoreduces concentrations of smoke and indoor air pollutants, money and time for acquiring fuelwill also be saved (women's opportunity cost). It also significantly reduces workload for women, who are predominantly responsible for cooking and collecting fuelwood[7].Indirect benefits include reducing deforestation, reducig GHGemissions, improved stove adoptionand job creation in the community.

Rural inhabitants of Ethiopia are dependent on traditional biomass fuels and uses primitive and inefficient technologies. Therefore, looking for technologies which can locally be manufactured at a reasonable price and which could reduce the fuel consumption rate as well as pollutant emission is not a point to argue.To this end, the aim of this research work is to design, manufacture and test an improved cow dung household gasifier cook stove.

2. Methods

In order to design the gasifier-cooking stove, knowing the physico-chemical characterictictsof the fuel is very essential. Accordingly,ultimate and proximate analyses of cow dung were performed to predict the behaviors of fuel. Proximate analysis is used to characterize biomass in order to measure its moisture content, volatile matter, and fixed carbon and ash contents. The ultimate analysis gives the actual chemical composition (C, H, N, S,and O) of biomass[8].

In addition, engineering design criteria such as insulation, gasification temperature or stove power output, safety, and gasifier reactor cross-sectional area, diameter, and its height were great important[1]. The gasifier stove was designed based on the fuel properties, specifically cow dung. The cow dung fuel was selected as a fuel source due to its availability, low cost, and easily piled in the home within a small area for further use in Ethiopia[1]. The gasifier reactor haddesigned and fabricated to meet the cooking energy requirement of fivefamily members[9].The stove was designed using important parameters that need to be considered to determine the appropriate size of the cow dunggasifier reactor, taking into consideration the thermal energy output or the output temperature required[2].In order to minimize heat losses, critical insulation thickness of material from ash was calculated during size and dimension analysis of gasifier section.The experiments were conducted on a fabricated gasifier stove and three-stonetraditional cook stove. The emission reduction and the thermal efficiency of the stove was evaluatedwith Water boiling test and control-cooking test,and Indoor Air Pollution Monitoring equipmentrespectively.

2.1. Raw Material Characterization

In order to design the gaifier stove the first step to be done is identifying the characterictics of the material to be used as a fuel, cow dung. The composition of the biomass fuel is expressed in terms of its basic elements except for themoisture (M) and inorganic constituents (ASH)[10]. Thus, hydrogen or oxygen in the ultimate analysis includes hydrogen and oxygen present in the organic components of the fuel. A typical ultimate analysis is **C + H + O + N + S + ASH + M = 100%**.Here, C, H, O, N, and S are the weight percentages of carbon, hydrogen, oxygen, nitrogen, and sulfur, respectively, in the fuel [11].

Proximate analysis wasconductedto characterize the biomass in order to measure its moisture, volatile matter, and fixed carbon and ash contents[12].Conventional solid fossil fuels are classified by a range of standard tests, which are determined by a number of considerations. The commercial ‘value’ of fuelwas determined by the Higher Heating Value, volatiles, ash content,and similar parameters [11].Proximate analysis of the raw feedstock was performed according to ASTM standards [13, 14, 15, 16]. It gives the amount of ash present in the biomass. If the ash content is less in the biomass it means the quality of the biomass is good and it helpsthe gasifier perform better [17]. A presence of moisturein the biomass reducesthe calorific value of product gas, needs more heat input to dry the biomass, gasifier performance and concentration of CO, $H_2$and CO_2[18].

2.2. Thermal performance evaluation

Thermal performance of cook stove wasevaluatedto estimate theinput power, specific fuel consumption, efficiency, and turndown ratio, andemission performance of cook stove was also performedto analyse the emission of pollutants[19, 20]. Characteristics of the fuel used, sizes and types of pots used, the type of cooking process hasa great effect on the operation of gasifier[18].The two most common methods to evaluatethe efficiency of the gasifier stove are Water Boiling Test (WBT) and Controlled Cooking Test (CCT) methods [21].Those tests consist of both high power and low power test that immediately follows each other [22].The other power test is the lowest power test that provides the amount of fuel required simmering a measured amount of water at just below boiling point for 30 minutes [22, 23].

2.3. Environmental Performance test

Estimation of indoor pollutant emissions fromboth improved cow dung gasifier cook stove and traditional three-stone cook stove was conducted under controlled settings following water boiling test procedures[24].Indoor air pollution measuring device was used to knowwhat really happens when the stoves are used indoor. This device tells us almost the exactlevels of smoke in thehouse. An average value of the emission is taken and compared to the world health organization (WHO) air quality guidelines. The mainpollutantsthat measured with this device are the concentration of carbon monoxide (CO) and concentration of particulate matter ($PM_{2.5}$). The indoor air pollution equipmentbox contains two sensors and a fan, control circuitry, a rechargeable battery, and a memory stick (SD card). The fan draws air through the box so that pollutants can be accurately measured. The measured data is processed using a Visual Basic Macro-Free version software, which is designed by aprovechoresearch center specifically for this purposein Microsoft Excel. This spreadsheet can accept up to 10,000 data points. This software analyzes the logged data and converts into physical concentrations, and provides output in graphical form. Average concentrations, as well as highest concentration are provided automatically in a format that can easily be copied into a master spreadsheet for comparison with other tests.The test had performed three times for both the three stones stove and improved gasifier stoves so that an idea of the typical Indoor Air Pollution (IAP) reduction seen by the stoves can be found.

3. Result And Discussion

3.1. Characteristics of cow dung through ultimate and proximate analysis

3.1.1. Proximate Analysis

Proximate analysis of cow dung cake gives information for the sizing of the gasifier stove, determining the amountofair to be supplied and sizing ash removal mechanism of the gasifier stove [25].The moisture content of cow dung is high, which drains much of the deliverable energy from a gasification plant, sincepart of the energyis used to evaporate the moisture which is not recovered.

This important input design parameter must be known for the assessment of the cost of energy for drying the cow dung as well[8]. Therefore, it is one of the criteria for the selection of energy conversion technology.Biological-based conversion technologies such as fermentation or anaerobic digestion require biomass with high moisture content. However, thermal conversion technology such as direct combustion,pyrolysis, and gasification requires biomass fuels with low moisture content[18].

The moisture content of dung fuel has a negative effecton the heating value of producer gas. In gasification processes, it is vital to reduce the moisture content of dung fuel. High moisture contents will reduce thermal efficiency since the heat is used for drying purpose[8].To determine the moisture content of cow-dung, we dried the weighed amount of sample in an open crucible-plate which is kept at 105℃ for 24 hr. in the oven.The loss in weight represents the amount of moisture content and sample left in the crucible-plate are total solids (TS) in the sample. The average moisture content of the cow dung is estimated to be 9.88% [Figure 3.1].

The volatile matter of the sample is determined by taking2gram of a dried sample of cow dung and keptin a closed crucible. The sample was heatedto 900℃ in a furnace in the absence of air. The weight loss of matterwas treated as the volatile matter of cow dung. The mass residual in the crucible, minus the mass of ash is called fixed carbon. The ash contentwas determined by burning 2 gram of cow dungat 575 °Cfor 24 hours in presence of air [19].

Figure 3.1 shows the proximate composition of cow dung fuel in this study compared to the proximate composition of corn cob and rice husk[18,26].Those two selected fuels were compared with cow dung cake by proximate analysis to predictthe percentage of biomass fuel burned in the gaseous and solid states, and the amount of non-combustible ash formed.

The highest or caloric valuewas estimated to be 16.13 MJ/kg (cow dung cake) and 15.38 MJ/kg (rice husk) respectively[Figure 3.1],which is one of the most important properties of biomass fuels for design calculations inthermal conversion systems for biomass fuel.The higher calorific value depends onthe percentage of moisture and fixed carbon of biomass fuel[27].In general, high moisture content indicatesthat more energy could be required to evaporate the water in the biomass.Since cow dung has higher fixed carbon, the heating value is also higher as compared to corncob and rice husk.

The highest and lowest volatile matters were 71.38% forcorncob and 60.11% for cow dung cake[Figure 3.1].It could be easier to ignite corn cob than cow dung and rice huskdue toitshaghervolatile matter content, which is 62.37% and a fuel which hashigh volatile matter guarantees trouble-free ignition[26]. It is observed that rice huskhas the highest ash content among the three fuels, having almost doublethe ash content of corncob.The higher the ash content of the biomass thelowerheating value[24].

3.1.2. Elemental analysis of cow dung

Elemental analysis of the dung cake samples was performed using an elemental analyzer “EA 1112 Flash CHNS-O- analyzer” at Addis Ababa University (AAU) Chemistry department. Conditions for the ultimate analysis were Carrier gas(Helium gas) flow rate of 120 ml/min, reference flow rate 100 ml/min, oxygen flow rate 250 ml l/min, furnace temperature of 900 °C and an oven temperature of 75 °C.A sample was placed in the analyzer, and the analyzer returned results for carbon, hydrogen and nitrogen content. Oxygen was calculated by subtracting the sum of carbon, hydrogen, nitrogen and ash from 100 percent. The sample was analyzed repeatedly to avoid the bias of taking a single value and therefore the average value of different replicated experiment was taken as a representative.Analyzing the chemical composition of the dung cake is essential to estimate the primary and secondary airrequirements.

Biomass fuel properties would be estimatedby elemental analysis of biomass fuel. It is useful in estimating the quantity of air required to carry on the combustion and gasification reactions. Normally, fuels with more carbon content are expected togivemore energy per unit mass for the duration of the combustion reaction[10]. Low-quality fuel is expected to have high H/C and O/C ratios because Carbon-Carbon bonds have high energy content thanCarbon-Hydrogen and Carbon-Oxygen bonds[28].The lowest O/C ratio and H/C ratio were observed in cow dung duringthis study as compared to rice husk and corncob [Figure 3.2].It is witnessedthat the highest oxygen content of the biomass the lowest energy content and the higher the carbon content of the biomass the higher heating value. Therefore, to increase the energy content of biomass fuel, the percentage content of oxygenhas to be reduced as a result the moisture content will also be reduced.

3.2. Performance Evaluation of stoves

3.2.1. Water boiling test

The water boiling test (WBT) protocol developed by the Shell Foundation was employed in assessing theperformance of the stove [29]. It is a standard method for evaluating the performances of cooking stoves.WBT contains three phases: a high-power (cold start) phase, a high power (hot start) phase, and a low power (simmer) phase[15]. Each of the phase's tests was performed three times after allowing the stove to cool down before starting the next round and then the average value is taken to obtain the burning rate, the time required to boil 5-liters of water, the thermal efficiency and firepower of stoves.

According to the WBT, the traditional three-stone stove (TSS) and gasifies stove (GS) recorded least time taken to boil water during high power (hot start) is 29.33 and 19.7 minutes respectively. In addition, the TSS and GS recorded highest average time taken to boil water during high power (cold start)were 31.7 and 22.3 minutes respectively.Thisshows that gasifier stove can savetime toboil 5 liters water. Their higher time record during cold start is due to the initial energy required to warm up the gasifier reactor, which also consumes some amount of energy from the fuel[Figure 3.3].

Testes on burning rate were carried out with gasifier and three stones stove to compare the cow- dung fuel consumption [Figure 3.4].The three stones stove (TSS)consumes higher fuel on cold start test while gasifier stove consumes less fuel. The factors that affect fuel-burning rate are air and fuel mixture ratio, reactor type and size of fuel[30]. The results of the burning rate at cold start, hot start and simmering are (79, 28), (81, 34) and (41, 28) for TSS and GS respectively.

The amount of water evaporated (kg) during water boiling test by the two stoves at cold start, hot start and simmering are plotted [Figure 3.5]. The tests show that the three stones stove-burning ratewas 79 g/min fuel dung to evaporate 429 g of water from 5-liters of waterin34.67 minutes. However, the gasifier cook stove-burning rate was 18 g/min fuel dung to evaporate 531 g of water from 5-liters water in23.67 minutes during high power (cold start) phase test. The three stones stove-burning ratewas 81 g/min fuel dung to evaporate 531 g of water in33.67 minutes, while the gasifier cook stove-burning rate was 21 g fuel dung to evaporate 650 g of water for 19.67 minutes from 5-liters of waterduring the high power (hot start) phase test. The gasifier type stove-burning rate was 28 g/min fuel dung in30 minutes to vaporize 2704 g water while the three stone stove-burning rateswere41 g/min fuel dung in 30 minutes to vaporize 983 g water during low power phase (simmering test). In general, when we use gasifier stove to boil 5-liters of water it consumes600-gram fuel while the three stones stove consumed 2200-gram of cow dung cake. Therefore, the gasifier stovesaves 1600-gram cow dung as compared to thethree stones stove.

Thermal efficiencies of two stoves are presented [Figure 3.6].Thermal efficiencies of gasifier stove and three stones stoves at cold start, hot start and simmering are (33.61%, 7.7%), (35.3%, 8.3%) and (49.2%, 59%) respectively. The efficiency of the stove depends on the insulating material, design principle and fuel types. The production of the synthesis gas increases the thermal energy efficiency by decreasing the fuel consumption for cooking purpose[31].These results indicate thatthe gasifier stove has a higher thermal efficiency than the three-stone stove due to its lower burning rate since both parameters are inversely proportional to each other. The lower thermal efficiency of the threestones stove is due to its improper insulation to reduce heat losses by conduction and poor in radiation and convection heat transfer to the pot.

Average firepower (W) for water boiling by the GS and TSS stoves at cold start, hot start simmering were recorded as(5733.2, 16154), (6902, 16534) and (5652, 8319) respectively [Figure 3.7]. This indicates that three stones stove consumes more fuel than gasifier stoves.

These average temperature corrected specific energy consumption comparison between gasifier stove (GS) and three-stones stove measures by kilo joules shows that GS was consumed lowerenergy than TSS at cold start, hot start and simmering phase [Figure 3.8]. The reason is three stones stove is not properly designed based on engineering principle, so a higher average temperature corrected specific energy consumption to boil the same amount of water with in those stoves indicates more energy lost to the environment.

3.2.2. Control cooking test

In this study, control-cooking test (CCT) was designed to analyze theperformance of the stoves while preparing potato meal for average household members of five.The two points in CCT we analyzed are the specific fuel consumption and the cooking duration.In these tests, meals were cooked by using the three stones and improved gasifier stoves three times each.

Based on the analysis of the test result, the gasifier stove has achieved 64% fuel saving efficiency as compared to the baseline three stones (traditional) stove[Figure 3.9].While gasifier stove consumed 431 grams of fuel per kg of a cooked meal, the three stones stove has consumed 1206gram per kg of a cooked meal.

In terms of cooking duration, the gasifier stove saved time by 54% over the three stones stove. The gasifier stove took 17 minutes for cooking the same amount of meal while the three stones cook stove took 37 minutes.

3.2.3. Environmental performance evaluation

The environmental performance evaluation is performed to estimate the technical potential of CO and particulate matter (PM 2.5) emission reduction through substitution of traditional three stonescookstove with gasifier stove.TheIndoor Air Pollution (IAP) monitoring device hasbeenused to collect data during water boiling test. Average concentrations during the test were used to compare the emissions from each stove. However, emissions collections using indoor air pollution meter processing excel provides a much more detailed measured data.

In this run(test one), the average concentrationof PM2.5 for gasifier stove and three stones stove were827 μg/m^{3}and 12,217 μg/m^3 respectively. Moreover,the average concentrationof CO for gasifier stove and three stones stove are 6.9 ppm and 15.6 ppm respectively [Figure 3.11]. The reduction in concentration between gasifier stove and three stones stove is93.23% for PM2.5and 55.76% for CO concentration.

In this run(test two), the average concentrationof PM2.5 for gasifier stove and three stones stove were836 μg/m^{3}and 3622 μg/m^3 respectively. The average concentration ofCO for gasifier stove and three stones stove were0.4 ppm and 8.6 ppm respectively [Figure 3.12]. The reduction in concentration between gasifier stove and three stones stove is77% for PM2.5 and 95.34% for CO concentration.

In this run(test three), the average concentrationof PM2.5 for gasifier stove and three stones stoveswere2,004 μg/m^{3}and 3266 μg/m^3 respectively. Moreover,the average concentrationof CO for gasifier stove and three stones stove were1.1 ppm and 11.5 ppm respectively [Figure 3.13]. The reduction in concentration between gasifier stove and three stones stove is38.6% for PM2.5 and 90.43% for CO concentration. The relative reduction in the concentration of pollutants for cook stove shows that cow dung gasifier stove performs betterin emission reduction than three stone stove. In the three stones stoves smoke, air and flame are not well mixed; the smoke can go in one direction and flame can go in other directions. The smoke can easily break out combustion, so CO and PM2.5 emissions are often high. The average CO and PM2.5concentration in the test room weredramatically reduced when a gasifier stove is used. However, the worst PM emission concentrationis recorded during thetest conducted on the three stones stoves.It is evident that cooking on three stones stove results in a considerableirritation in the short term and respiratory impact in the long run[32].

The U.S. Environmental Protection Agency (EPA) ambient air quality standards for carbon mono oxide concentration is 9 ppmfor eight hours of exposure[23]. Figure 3.14 shows that CO concentration of household having gasifier stove is lower than the environmental protection agency standard of 9 ppm.Dung fuel produces higher amounts of poisonous CO emissions compared to wood and agricultural residues[11]. When we compare the highest concentration of CO on test one (3 ppm), test two (2.5 ppm) and test three (4 ppm) of gasifier stoves have significance difference from the highest concentration of CO on test one (15.6 ppm), test two (14 ppm) and test three (53 ppm) of three stones stove stoves. Therefore, the release of CO is one of the most hazardous products from biomass combustion stoves but micro-gasification prior to combustion can reduce harmful emissions production, and also promotes the production of biochar[11]. The objective of reducing indoor air pollution is protecting the health of a household. Cleaner burning stoves have many other benefits beyond improving health including timesavings, cleaner kitchens, reduced effort to gather fuel and more sustainable use of a limitedenergy resource.

4. Conclusions And Recommendations

Ethiopian rural people who are dependent on traditional fuels use primitive and inefficient technologies. To reducefuel consumptions and emissions, designing and using improved stoves are important, which will intern helps to ensure sustainable energyin Ethiopia. In this piece of researchwork the performance of the improved gasifier cook stove was evaluated using water boiling test and control cooking test methods as compared to the three stone stoves. The results of the cold start high power, hot start high power and lower power phase tests showed that the gasifier type stove performed better in terms of cooking duration and specific fuel consumption. It has a lower burning rate, therefore burns fuel more efficiently and economically than the three stones stove, which has a higher burning rate. The thermal efficiency of this stove is 34.49%, while that of the three stones stove is 7.9%. In the control-cooking test, the gasifier stove has achieved 64% fuel saving as compared to baseline three stones (traditional) stove. In terms of cooking duration, the gasifier stove saved time by 54% over three stones stove.

The study also evaluates the environmental performance of the designed gasifier cook stoves. Accordingly, the worst PM and CO emission content were recorded for the three stones stove. In contrary, the gasifier cook stove showed the best environmental performance considering CO and PM 2.5 concentration reduction as compared to the three stones cook stove.

Declarations

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Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

Conflict of interest

The authors declare that they have no competing interests

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Authors' contributions

The manuscript is part of Adamu’s masters thesis and the other two authors are supervisors of the student during the course of masters study.

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Figures

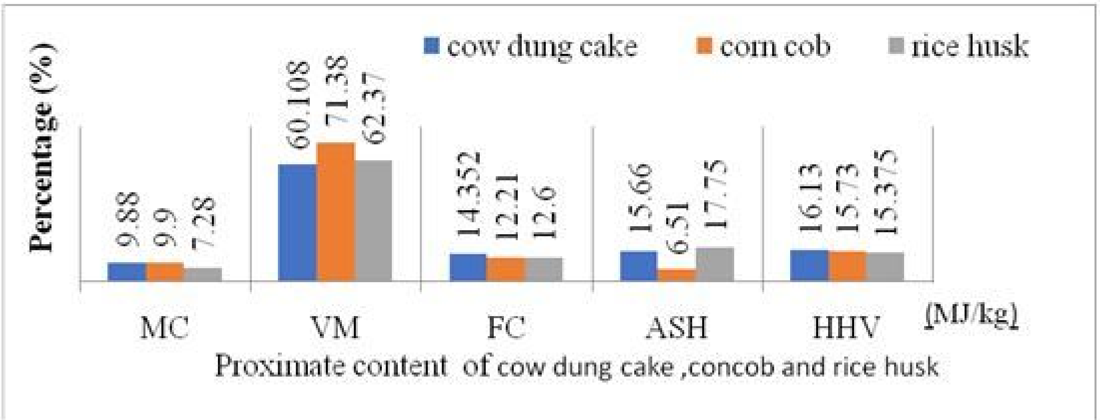


Figure 1

Proximateanalysis of cow dung cake, corncob and rice husk

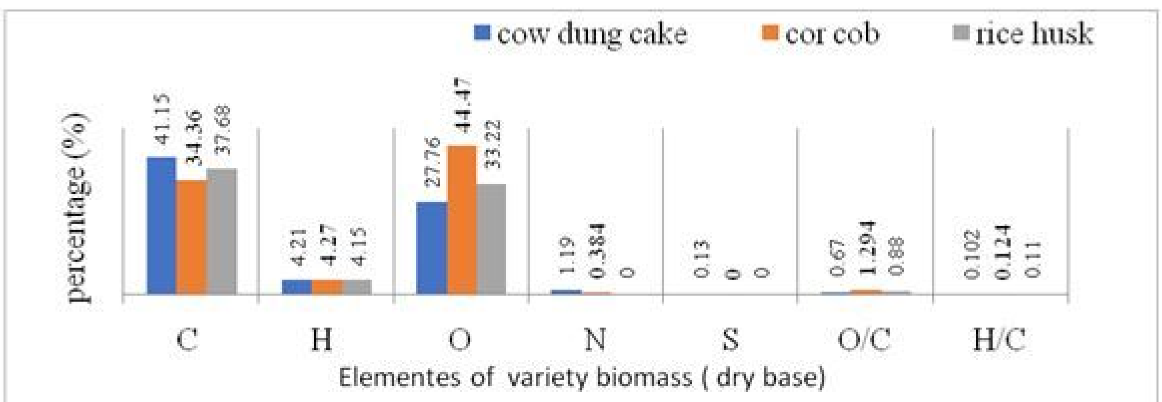


Figure 2

Elemental analysis of cow dung cake and two selected biomass [13,26].

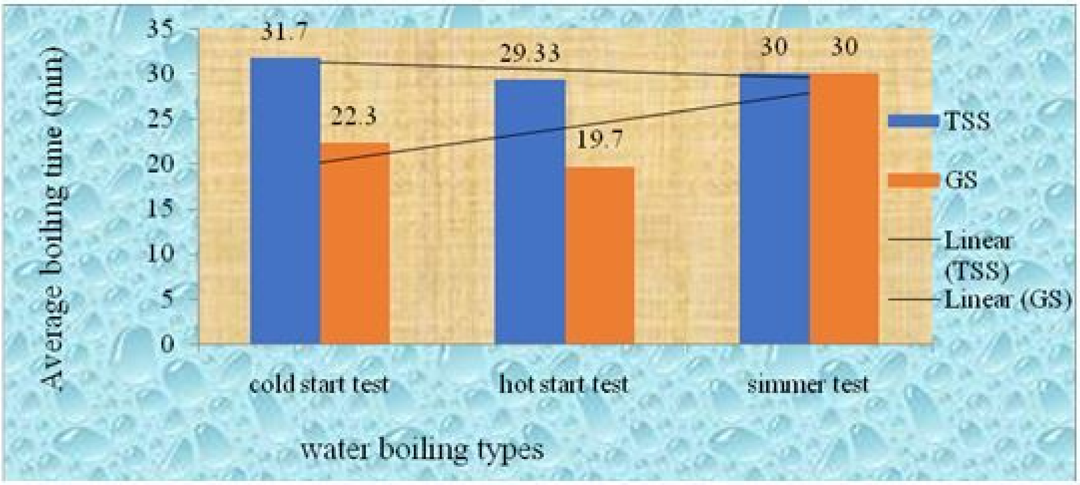


Figure 3

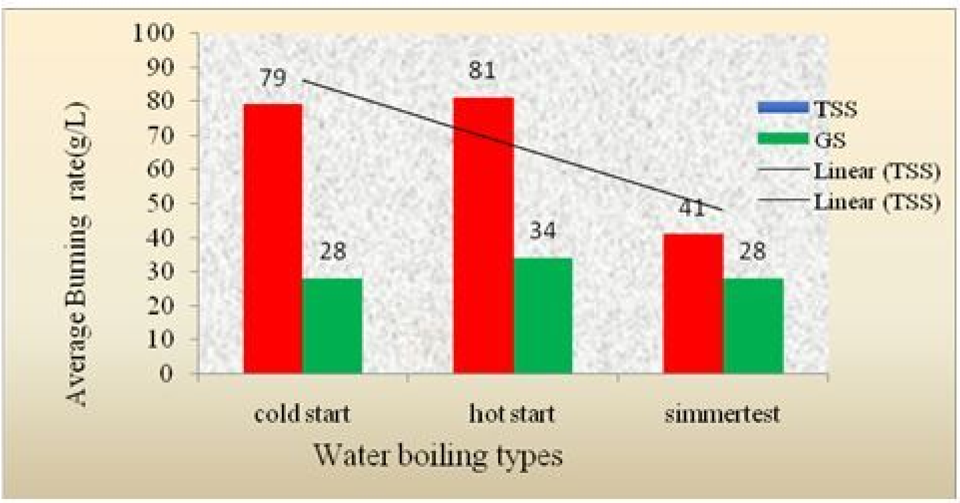


Figure 4

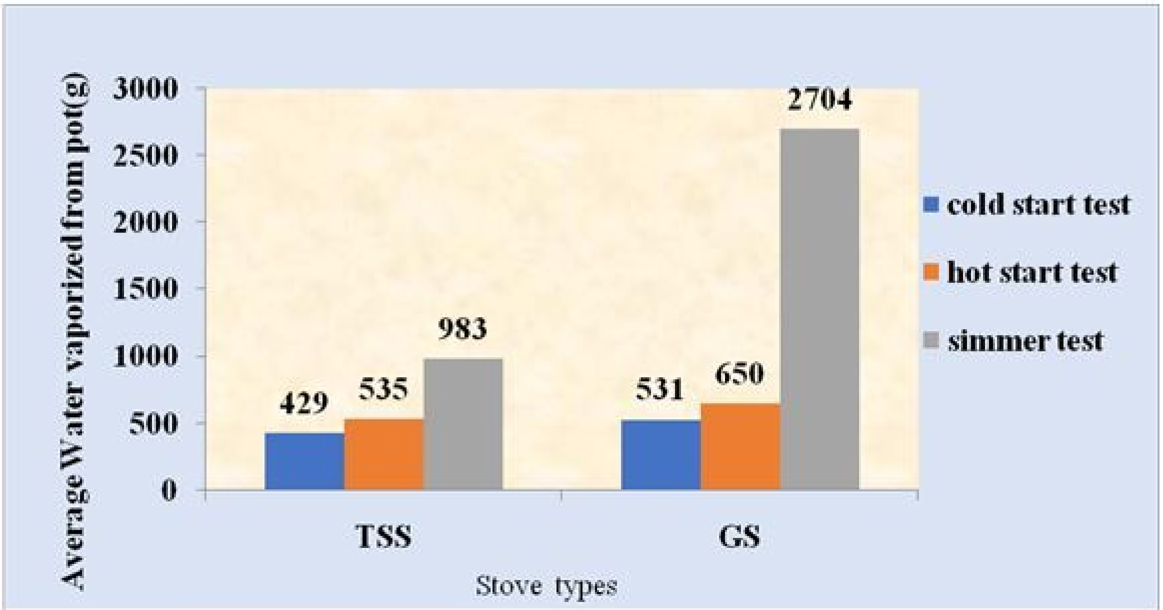


Figure 5

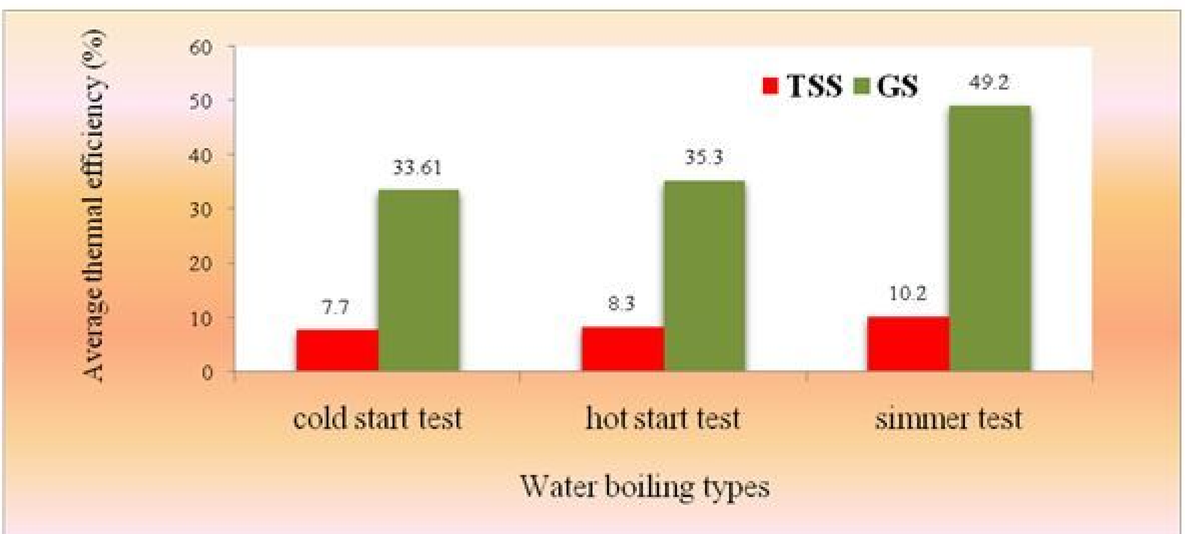


Figure 6

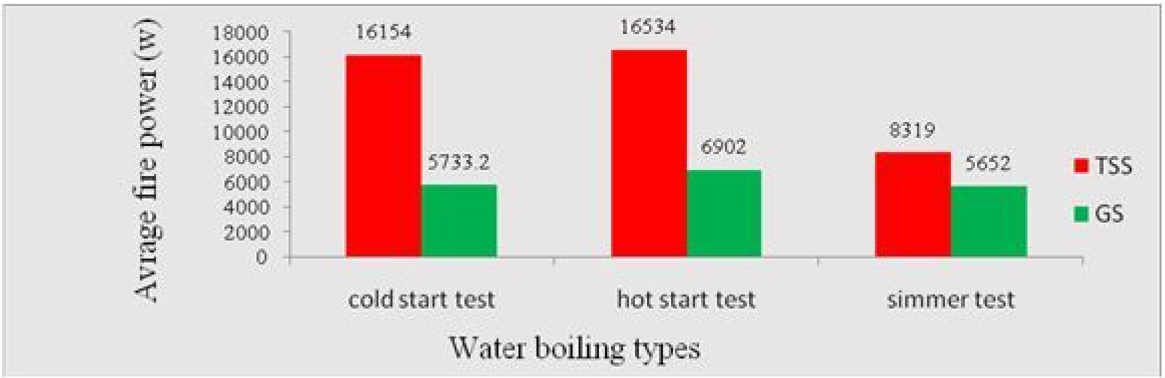


Figure 7

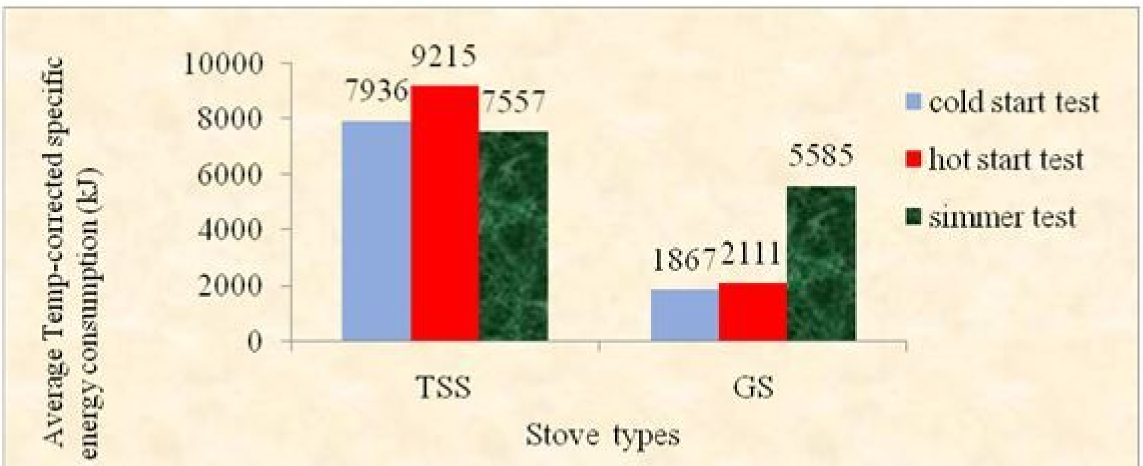


Figure 8

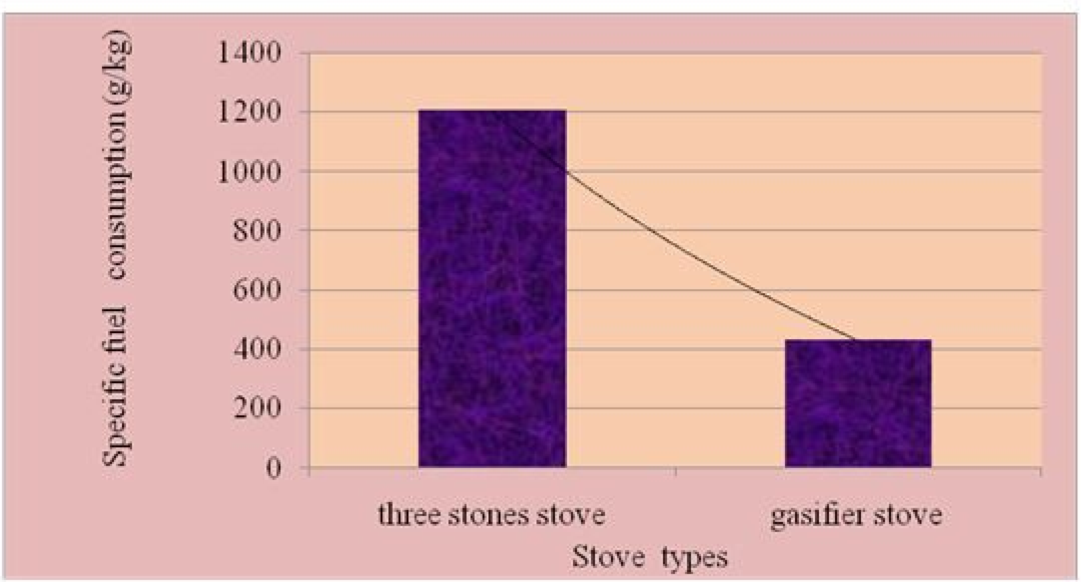


Figure 9

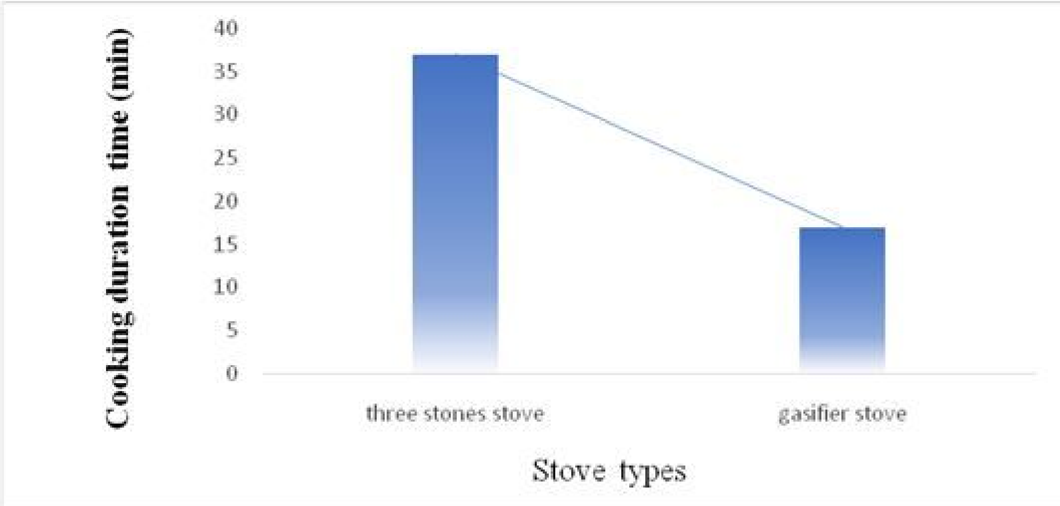
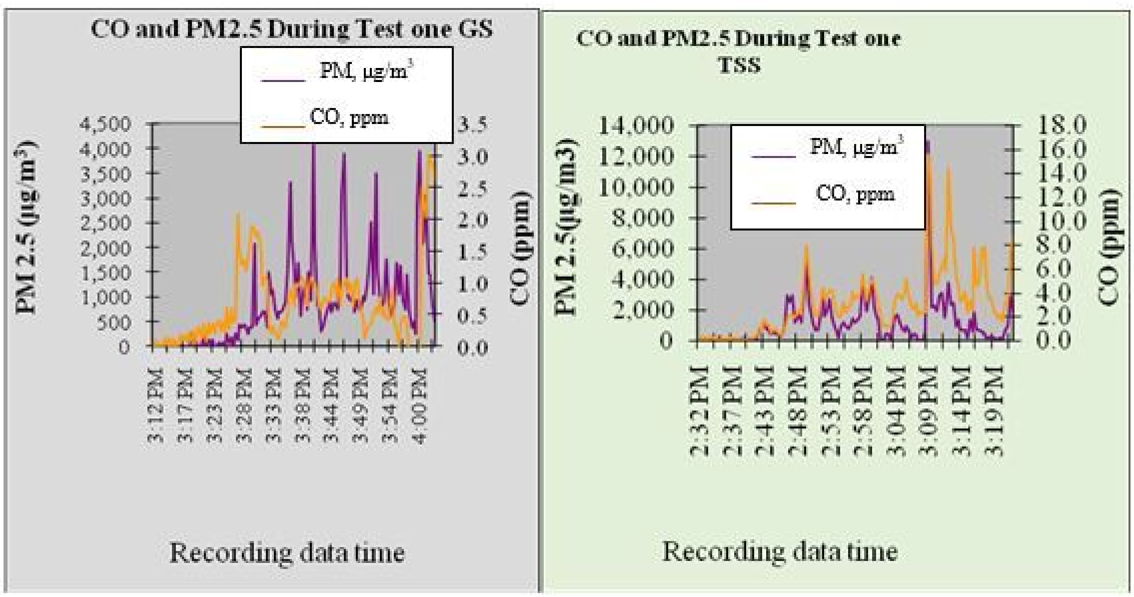
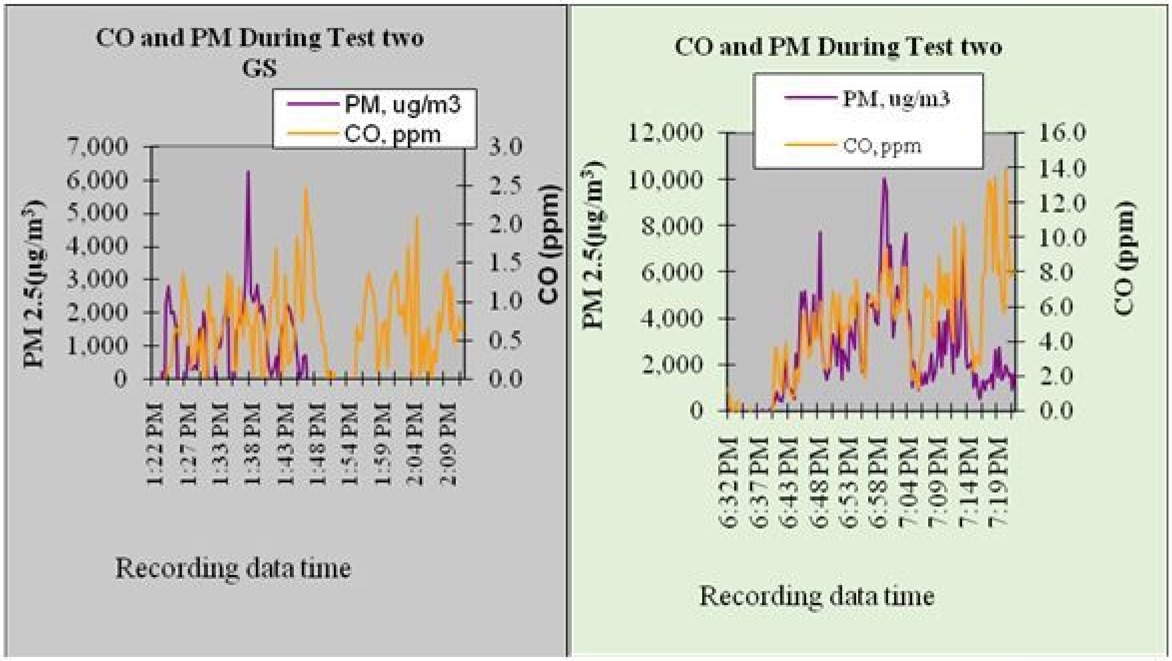


Figure 10



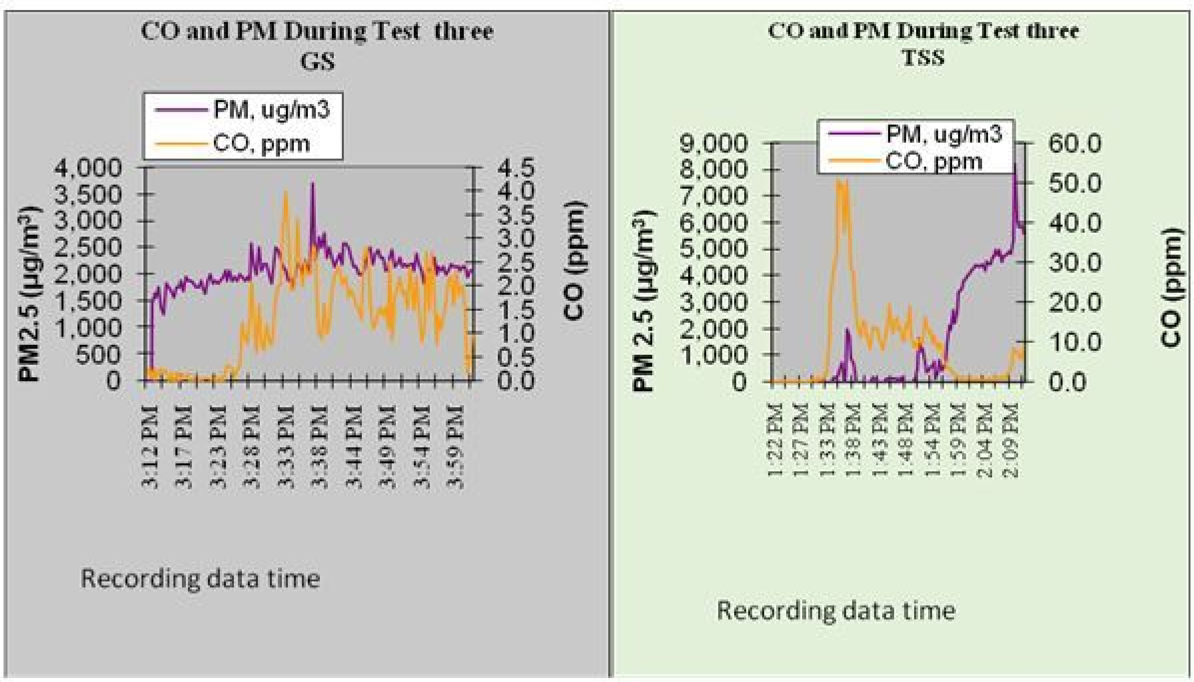
(a) Gasifier stove (GS) (b) three stones stove(TSS)

Figure 11



(a) Stove type: Gasifier stove (GS) (b) Stove type: Three stones stove (TSS)

Figure 12



(a) Gasifier stove(GS) (b) Three stones stove(TSS)

Figure 13

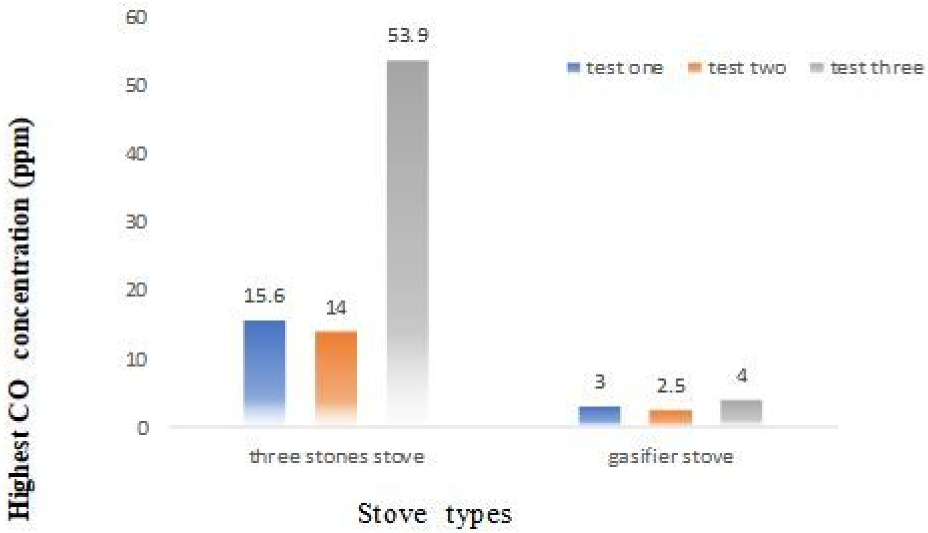

60
50
40
30
20
10
0
53.9
15.6
14
3
2.5
4
test one
test two
test three
Highest CO concentration (ppm)
three stones stove
gasifier stove
Stove types

Figure 14