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Abstract

In sub-Saharan Africa a large share of the energy use utilize biomass as a fuel. In some countries more than 90 percent of the energy use is biomass. This energy is primarily used for cooking, heating and drying. Cooking food on an open fire or using a traditional stove will combust the firewood inefficiently and leads to pollution in the form of particulate matter, carbon monoxide and other hazardous pollutants. Indoor pollution has serious health effects and especially women and children are affected by this since they spend more time in the kitchens compared to men.

More efficient combustion would lead to less harmful pollution to women and children in these rural areas. There are different kinds of stoves on the market and one of them is the gasifier stove which allows the biomass to go through pyrolysis in a separate step before complete combustion. If the charred biomass is harvested before complete combustion it can be saved for later use. This stove will result in cleaner and more energy efficient combustion compared to the traditional 3-stone-fire.

The aim of this study has been to evaluate the charred biomass harvested from this gasifier stove in terms of energy use efficiency, emissions and cooking time. The charred biomass was compared to conventional charcoal bought at the local market. The charred biomass investigated is charred Grevillea prunings from the *Grevillea Robusta tree*, charred coconut husks (*Cocos nucifera*) and charred maize cobs (*Zea mays*). They were tested by cooking a meal consisting of two dishes at five different households for different kinds of charred biomass and conventional charcoal as a reference.

Using charred Grevillea prunings gives an energy saving up to 31 percent while charred coconut husks gives up to 11 percent energy saved compared to the 3-stone-fire. Charred maize cobs was only up to 2 percent more energy efficient than conventional charcoal due to its low energy density and fast burning rate. In most cases there was no significant difference between the emissions of the different charred fuel types. Only charred maize cobs resulted in significantly higher emissions than the other fuels. Household B deviated from the others households and had higher emissions. In conclusion the different types of charred biomass are good fuels for cooking. Charred maize cobs are less valuable since they require a higher rate of refilling of fuel during cooking and do not result in better energy use efficiency compared to conventional charcoal.

There were no significant differences between the different types of charred biomass and conventional charcoal in emissions except for a few cases where charred maize cobs had a slightly higher level of emission compared to the others. CO_2- levels were so low that there was no risk of harmful concentrations in any way. $PM_{2.5}$-emissions levels were safe, but the CO-emissions levels for charred maize cobs were close to levels were symptoms might show.

Sammanfattning

I Afrika söder om Sahara kommer en stor del av energianvändningen från biomassa och i vissa länder kommer mer än 90 procent av energianvändningen från biomassa. Energin går i störst utsträckning till matlagning, uppvärmning och torkning. Att laga mat över öppen eld eller med mer traditionella spisar förbränner bränslet på ett ineffektivt sätt och leder till utsläpp i form av partiklar, kolmonoxid och andra hälsofarliga ämnen. Luftföroreningar inomhus har skadliga effekter på hälsan och drabbar mest barn och kvinnor eftersom de spenderar mest tid i köken.

En spis med effektivare förbränning skulle ge minskade utsläpp och minskad energiåtgång. Det finns olika sorters spisar på marknaden och en utav dessa är en förgasningsspis, vilket är en spis som förgasar bränslet så att pyrolys sker och bränslet förkolnar innan det genomgår total förbränning. Man kan "skörda" kolet innan det har förbränts fullständigt så att man får svartkol som kan sparas och användas i ett senare skede. Fördelen med en sådan här spis är att det sker en effektivare förbränning och därmed har mindre utsläpp.

Målet med det här projektet har varit att utvärdera svartkol som energikälla sett till energieffektivitet, utsläpp och matlagningstid. Svartkolet jämfördes med konventionellt träkol som inhandlades på den lokala marknaden. Testerna utfördes i köken hemma hos fem bönder där varje bränsle användes för matlagning av två rätter, Ugali (majsmjöl med vatten kokas till en "gröt") och Sukuma Wiki (grönkål, rödlök och tomater steks i kokosnötsfett). Bränslena som utvärderades var svartkol av Grevillea-kvistar och -grenar, majskolvar samt kokosnötskal med konventionellt träkol som referens.

Svartkol från Grevillea-kvistar och -grenar gav störst energibesparing, med upp till 31 procent besparing jämfört med konventionellt träkol. Svartkol från kokosnötskal gav en besparing på upp till 11 procent medan svartkol från majskolvar endast gav en besparing på upp till 2 procent. Anledning till att majskolvar hade så låg besparing var svartkolets låga energidensitet och dess höga effekt vid förbränning i spisarna (avgiven värme per tidsenhet). I de flesta fallen var det ingen signifikant skillnad i utsläpp mellan bränslena eller mellan hushållen. I de fall då en signifikant skillnad fanns var det att svartkol från majskolvar hade lite högre utsläpp än de andra bränslena och mellan hushållen stod hushåll B för lite högre utsläpp än de övriga hushållen.

Sammanfattningsvis kan man säga att svartkol fungerar bra som ett bränsle för matlagning där svartkol från Grevillea-kvistar och -grenar visade sig bäst och svartkol från majskolvar sämre då det var likvärdigt med konventionellt kol. Anledningen till att svartkol från majskolvar inte fungerar så bra som de andra är att man måste fylla på med bränsle flera gånger under matlagningen och därmed sänker temperaturen i spisen. Påfyllningen behövdes inte i lika stor utsträckning med de andra bränslena. Utsläppen från de olika bränslena var likartade med något högre utsläpp från svartkolet från majskolvar.

Executive summary

Charred biomass produced with a gasifier and then used as a fuel for cooking in a Kenya ceramic Jiko stove has been evaluated in terms of energy efficiency, emissions and energy density. When comparing the different charred biomasses to conventional charcoal in terms of energy efficiency, charred Grevillea pruning shows the most promise with 7 675 ± 358.4 kJ per cooked meal compared to 11 160 ± 1 448 kJ per cooked meal for conventional charcoal. This is an improvement of 31 percent in saved energy. For charred coconut husks the amount of energy saved was 11 percent with 9 837 ± 1 826 kJ per cooked meal. Charred maize cobs were the least energy efficient with only 2 percent saved energy cost for one meal.

There were no significant differences between the different types of charred biomass and conventional charcoal in emissions except for a few cases where charred maize cobs had a slightly higher level of emission compared to the others. CO_2- levels were so low that there was no risk of harmful concentrations in any way. $PM_{2.5}$-emissions levels were safe, but the CO-emissions levels for charred maize cobs were close to levels were symptoms might show.

The conclusion is that the different types of charred biomass are useful substitutions as a fuel for cooking when compared to conventional charcoal in terms of fuel properties and had higher or similar energy use efficiency.

Acknowledgement
This master thesis was written as a part of the research program, “Biochar and smallholder farmers in Kenya”, in collaboration with the World Agroforestry Center (ICRAF), the Swedish University of Agricultural Sciences (SLU), IITA (International Institute of Tropical Agriculture) and Lund’s University. This master thesis is the final step to gain the degree of MSc in Energy Systems Engineering, at Uppsala University and the Swedish University of Agricultural Sciences (SLU). The field study was done in Embu, Kenya and the preparation at the office of ICRAF in Nairobi, Kenya. The field study was sponsored by the minor field study program financed by SIDA.

The supervisor for the project in Kenya was Ph.D Mary Njenga from ICRAF and the supervisor in Sweden was Ph.D Cecilia Sundberg from SLU. I would like to thank both Dr. Mary Njenga and Dr. Cecilia Sundberg for their help and guidance in this project. Their expertise and experience has been an invaluable help to complete this project and deliver these results.

I would like to thank ICRAF for the attachment there and their help and support to make my stay in Kenya easier. I would also like to thank Gunnar Larsson and Martin Karlsson for their feedback on this master thesis. A special thanks to Barbara Njeri for being a valuable asset in the field, a good host in this new environment and for translating the communication with the farmers on site.

Content

1 Introduction

1.1 Background

Sub-Saharan Africa (SSA) is today a large consumer of biomass and in some of the SSA-countries biomass represents more than 90 percent of their total energy use. This energy is primarily used for cooking, heating and drying. SSA is not as electricity dependent as the developed countries in the world and the availability of electricity is not as secure and reliable as in more developed countries (Kebede, et al., 2010). In Kenya's rural areas the main source of energy is firewood for almost all households. In 2005, 68 percent of all households in the country used firewood as its main source for cooking fuel. The advantage with firewood is that it can be used for both cooking and space heating. High costs and insufficient supply chains for alternative energy sources are problems that further increase the firewood's advantage. Biomass is expected to remain the main source of energy since the trend is that higher income leads to "fuel stacking". Fuel stacking is when the households use multiple energy sources to meet their energy demands, so instead of relying on one single source of fuel they have several (Nyambane, et al., no date).

Using biomass on an open fire or a traditional stove is an ineffective way of combusting the material and it leads to pollution in the form of particulate matter, carbon monoxide and other hazardous particles and gases. The use of biomass for cooking with incomplete combustion of the fuel has led to a lot of indoor pollution. There are different levels of pollution depending on which biomass is combusted. There is an energy ladder that shows which biomass type produce high levels of pollution and which goes through a more complete combustion. At the bottom of this ladder are found collected grass, twigs and dried animal dung that have a bigger portion of incomplete combustion. Crop residues, charcoal and wood are higher up on this ladder and yield less pollution (Fullerton, et al., 2008).

Indoor pollution has serious health effects on the people living in rural areas and especially on women and children since they spend most time at home and in the kitchen. Children living under these conditions are two to three times more likely to catch acute lower respiratory tract infection and childhood pneumonia is directly correlated with indoor cooking smoke. These diseases are just some of the respiratory illnesses caused by indoor cooking smoke (Fullerton, et al., 2008).

Gasifier stoves are one type of advanced stove types for biomass combustion that improves the emission levels and also enables a more effective combustion. These stoves allow the biomass material to go through pyrolysis with low oxygen supply and thus produce charcoal. The typical gasifier stove will then combust the charred biomass as well, but they can also be used to produce charcoal that can be saved for future use. The effects of these changes are a cleaner combustion and a more effective use of energy (Anderson and Reed, 2004).

This master thesis has been done as a part of a research project where the aim is to evaluate charred biomass's potential role in the community of smallholder farmers in Kenya. Charcoal from biomass has the potential to be used as a fuel or as a soil amendment. Both options will be evaluated in a research project with participants from World Agroforestry Center (ICRAF), the Swedish University of Agricultural Sciences (SLU), IITA (International Institute of Tropical Agriculture) and Lund's University. Five households were selected to be a part of this research project and its different stages. A bachelor thesis has been produced by Hanna Helander and Lovisa Larsson as an earlier stage in this research project (Helander and Larsson, 2014). The aim of their thesis was to compare a bio-char producing gasifier stove with a three-stone fire and an improved cooking stove with regards to energy use efficiency and indoor emissions. This master thesis will investigate the option of using biochar as fuel and not as a soil amendment. The biochar will be referred to as charred biomass since it is not going to be used as a soil amendment and to follow the nomenclature used in this field. The bachelor thesis work done during the earlier stage of this research project will be referred to as Trial 1 and this master thesis will be referred to as Trial 2.

1.2 Aim

The study aims to evaluate charred biomass produced in gasifier stoves using three different types of feedstock. Charred biomass from different feedstock will be compared to each other and to traditional charcoal when used as a fuel for cooking by smallholder farmers in Kenya. Bulk density, energy density, energy efficiency and emissions will be evaluated. The emissions from the different types of charred biomass will be compared to the emissions from the charcoal to see if there is any significant difference between them in terms of $PM_{2.5}$, CO and CO_2.

1.3 Research questions

Research questions were defined to guide the work of gathering data to fulfill the aim of this project. The following questions were formulated:

- What amount of fuel and time is needed for cooking a standard meal?
- How does the charred biomass perform as a fuel compared to conventional charcoal in terms of energy efficiency, calorific value, energy density and bulk density?
- What emission levels are the rural farmers of Embu exposed to during their cooking with charred biomass from the three different feedstock compared to conventional charcoal from the local market as a fuel?

2 Theory

2.1 Process of producing charred biomass in a gasifier stove

Charcoal properties such as moisture content, volatile matter, fixed carbon content and ash content are used to determine the quality of charcoal. The moisture content is usually between 5 and 10 percent after the charcoal has interacted with the moisture in the air. The volatile matter consists of substances other than water that are given off as gas or vapor during combustion. This is tarry residues or short-chain hydrocarbons. The fixed carbon content is usually between 50 and 95 percent. Ash content is the residue after all the combustible matter has been burned away. This usually consists of clay and minerals etc., that occurs in the biomass naturally or as contamination attached to the biomass (FAO).

The biomass will be partly combusted in the gasifier. When the biomass has been ignited, the released heat will dry the biomass as the water evaporates. When the temperature rises volatile matter will start to evaporate from the fuel and since the biomass is ignited at the top, the bottom will catch fire last. The airflow is limited in the gasifier so the biomass will go through combustion with low oxygen supply.

The air/fuel ratio is the mass of air divided with the mass of fuel in the combustion process. An air/fuel equivalence ratio is the actual air/fuel ratio divided with the air/fuel ratio needed for complete combustion, as shown in equation 2.2.1.

$$\Phi = \text{actual air fuel ratio/ air fuel ratio needed for complete combustion} \quad (2.2.1)$$

The fuel can only go through complete combustion if the equivalence ratio is above one, $\Phi > 1$. If it is hot enough and Φ is between 0 and 0.25 the fuel can go through pyrolysis. If it is hot enough the equivalence ratio is above 0.25 it will go through gasification (Reed and Desrosiers, 2014). If the temperature rises above 400 ˚C and pyrolysis has begun the biomass will be transformed to charcoal (The Biomass Centre, Pyrolysis no date). The temperature will continue rising in the gasifier and low temperature gasification will start to produce high levels of hydrocarbon gases which can be combusted directly for heating (The Biomass Centre, Gasification, no date).

In Figure 1 the temperature during combustion of normalized biomass is plotted against the equivalence ratio. The normalized biomass is a mean of different types of biomass since they differ within the group. When the actual air fuel ratio goes up then the equivalence ratio goes up, making the temperature rise and the pyrolysis makes a transition to gasification (Reed and Desrosiers, 2014).

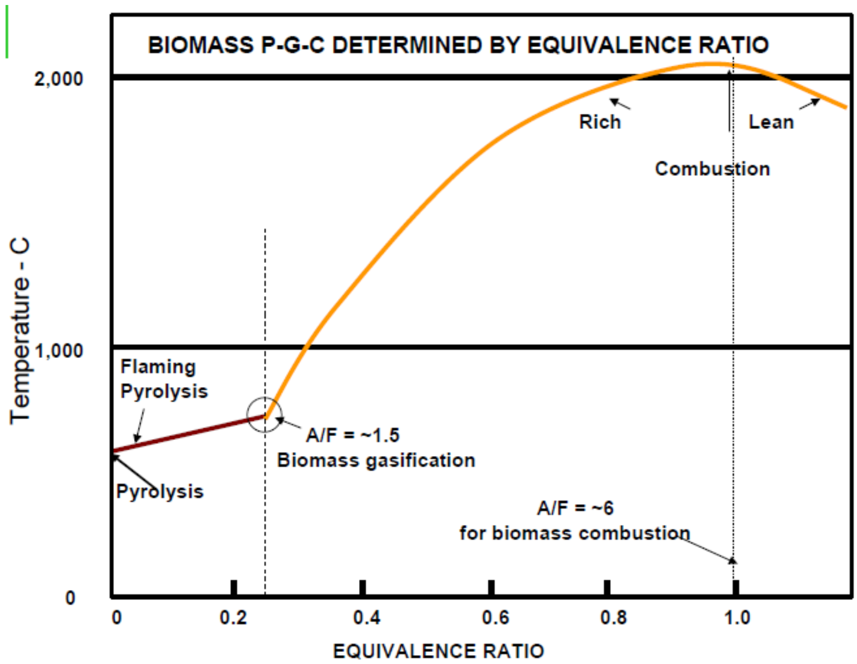

Figure 1. Equivalence ratio for combustion of biomass and the equilibrium temperature. A/F is the air/fuel ratio and P-G-C stands for pyrolysis, gasification and combustion of the fuel (Reed, 2005).

2.2 $PM_{2.5}$, CO and CO_2

Particulate matter is a term that covers particles and small liquid droplets. It can consist of acids, organic chemicals, heavy metals or dust particles. PM can be measured as either PM_{10} or $PM_{2.5}$. $PM_{2.5}$ is called "fine particles" and measures particles smaller than 2.5 μm in diameter, whilst PM_{10} measures particles smaller than 10 μm (EPA, PM, 2013). They are a health risk since they can travel far into the lungs and there is a risk of the particles staying there since they are so small and can get so far into the lungs. Exposure to $PM_{2.5}$ can lead to lung diseases such as lung cancer, respiratory problems and decreased lung function (DEQA, no date).

The guidelines for $PM_{2.5}$ are 10 $\mu g/m^3$ as a yearly mean and 25 $\mu g/m^3$ as a 24-hour mean (World Health Organization, 2005). This master thesis will use the 24-hour mean as the hazardous level of exposure for $PM_{2.5}$ since the exposure is considered short term. The total cooking time during the day is shorter than 24 hours, but if the emission levels are lower than the 24-hour mean one can assume that it is safe to be exposed to these levels during the few hours of cooking.

Carbon monoxide (CO) is a toxic gas that is both odorless and colorless. CO can cause fatigue for healthy people and pain in the chest for people with heart problems already at comparatively low concentrations (~25 ppm). At a moderate CO-level (~50 ppm) symptoms are for example decreased brain function and impaired vision. Exposure to a higher concentration can cause dizziness, nausea, headaches among other symptoms and if the level is high enough it might be fatal. Average levels in homes with electrical stoves vary between 0.5 and 5 ppm and for homes with gas stoves the levels vary between 5 and 15 ppm (EPA, CO, 2013). For short-term exposure (less than three hours) symptoms become noticeable above 70 ppm (New Hampshire, 2007).

Carbon dioxide (CO_2) is a greenhouse gas emitted from different types of human activity. It is a gas that occurs naturally in the Earth's atmosphere as a part of the natural carbon cycle between oceans, plants, animals and the atmosphere. The combustion of fossil fuels and the deforestation (forests are a natural sink for CO_2) has increased the concentration of CO_2 in the atmosphere (EPA, CO_2, 2014).

The lifetime of CO_2 in the atmosphere is hard to define since there is an exchange of CO_2 between the ocean, the land and the atmosphere that is hard to track. The oceans sediment CO_2 in the ocean floor, but the process is slow which makes the natural sinks such as forest the only way to reduce the concentration of CO_2 naturally in the atmosphere (EPA, CO_2, 2014).

Dangerous levels of CO_2 is 30 000 ppm for 15 minutes exposure and 10 000 ppm for an 8 hour exposure (Minnesota department of health, 2013).

2.3 Kruskal-Wallis test

The emissions from the different fuel types were compared to each other to determine if one or more fuel types differ from each other. If the different fuel types are similar in terms of energy properties, but differ greatly in terms of emissions, then this could be an important factor to consider. The results from the comparison have to have statistical significance for scientific reasons and a statistical test has to be performed.

ANOVA (Analysis of Variance) is a test which can determine if there is a significant difference between the means of more than two datasets. ANOVA will either confirm or discard the hypothesis that the means of the different datasets are equal. One of the assumptions is that the data has to be normal standard distributed for the test to work. (Explorable, no date).

The Kruskal-Wallis test is a non-parametric test which can be used instead of ANOVA when the data is not normally distributed. Kruskal-Wallis converts the observations into a ranked value based on its size. So the smallest value is ranked 1, the second smallest value is ranked 2 and it continues this way through the whole dataset. If there are two or more values that are equal they get an average rank. An example is if the fifth to the eight smallest values have equal values, they would all receive the rank of 6.5. There is a loss of information in the dataset when the observation values are converted into ranks, which cannot be avoided (McDonald, 2009).

The test will control if the null hypothesis can be rejected or not. The null hypothesis is defined such that a random chosen observation from one dataset has a 50 % probability of being greater than an observation chosen at random from another dataset. If the null hypothesis is rejected that means that the data is distributed differently in the different groups (McDonald, 2009).

When all the groups and their observations have been ranked, the sums of each group ranking values are calculated. When this is done, the test statistic K is calculated with the formula in equation 2.3.1. The variable n_i is the number of observations in group i, r_{ij} is the rank of observation j in the group i and N is the total number of observations. If there are no ties in the dataset the denominator is exchanged for exactly (N-1)N(N+1)/12 and $\hat{r}$ =(N+1)/2 and the K-value is calculated with the formula in equation 2.3.2. When ties occur between observations the test statistic K has to be divided with L from equation 2.3.3. G is the number of groupings with different tied ranks and t_i is the number of tied values in group i that are tied a specific value (Boundless, no date).

$$K = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_{i\cdot} - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \bar{r})^2}, \quad (2.3.1)$$

$$K = \frac{12}{N(N+1)}\sum_{i=1}^{g}(n_i)\left(\bar{r}_i - \frac{N+1}{2}\right)^2 = \frac{12}{N(N+1)}\sum_{i=1}^{g} n_i\bar{r}_i^{\,2} - 3(N+1) \quad (2.3.2)$$

$$L = 1 - \frac{\sum_{i=1}^{G}(t_i^3 - t_i)}{N^3 - N} \quad (2.3.3)$$

When this has been done, the probability value (P-value) is approximated with the K-value and chi squared χ^2_{g-1}. The critical value of chi squared, χ^2_{g-1}, can be found in a chi-squared-distribution-table when the level of significance is decided (0.05 in this study) and the right degree of freedom has been calculated (number of groups – 1). The null hypothesis is rejected if $K \geq \chi^2_{g-1}$. If there is any significance then there is a difference between at least two of the datasets. If the test is not significant, the null hypothesis can be accepted and there is no difference in the distribution of the observations in the different datasets (Boundless, no date).

If the null hypothesis is rejected a post-hoc can be done to indentify which group of observations is different from the rest of the groups. One post-hoc method is Tukey’s honestly significant difference test. The method will compute the significant difference between two different means using a q-distribution. The q-distribution defined by Student will give the largest difference of a set of means which originates from the same population (Abdi and Williams, 2010). This post-hoc can be done in Matlab using the *multcompare* function which uses Tukey’s HSD as a default and has 95 % confidence interval as a default.

3 Method

The first part of the field work was the production of the different types of charred biomass. The second part of the field work was the cooking tests. The production of charred biomass was done with gasifier stoves and no measurements were done during this part of the field work. After enough charred biomass was produced the cooking tests begun and the Kenya ceramic Jiko stove was used for this second part of the field work.

3.1 Equipment and feedstock

The feedstock that was used for the experiments consisted of Grevillea Robusta prunings, maize cobs and coconut husks. The Grevillea prunings are a local feedstock which is available all year around and comes from the *Grevillea Robusta tree.* The maize cobs (*Zea mays*) are locally produced, but the ones used in this study were from Kisumu, and maize cobs are only available some parts of the year. The coconut husks (*Cocos nucifera*) were brought from the coast so that the results of this study were applicable to various regions in Kenya. The charcoal was purchased at the local market in Kibugu, but was produced in Mbeere.

Five households were used and named in alphabetical order from Household A to Household E. The kitchens are represented in Figure 2. All kitchens were separated from the main building except for Household E that was attached to the main building. Household B had the kitchen as a part of another building and one of the doors (marked indoor in Figure 2) led to the rest of the small building. This master thesis has a different order of the households compared to the bachelor thesis from Trial 1 (Helander and Larsson, 2014). They are connected in this order (trial 2 – trial 1), Household A – C, Household B – D, Household C – A, Household D – B and Household E – E.

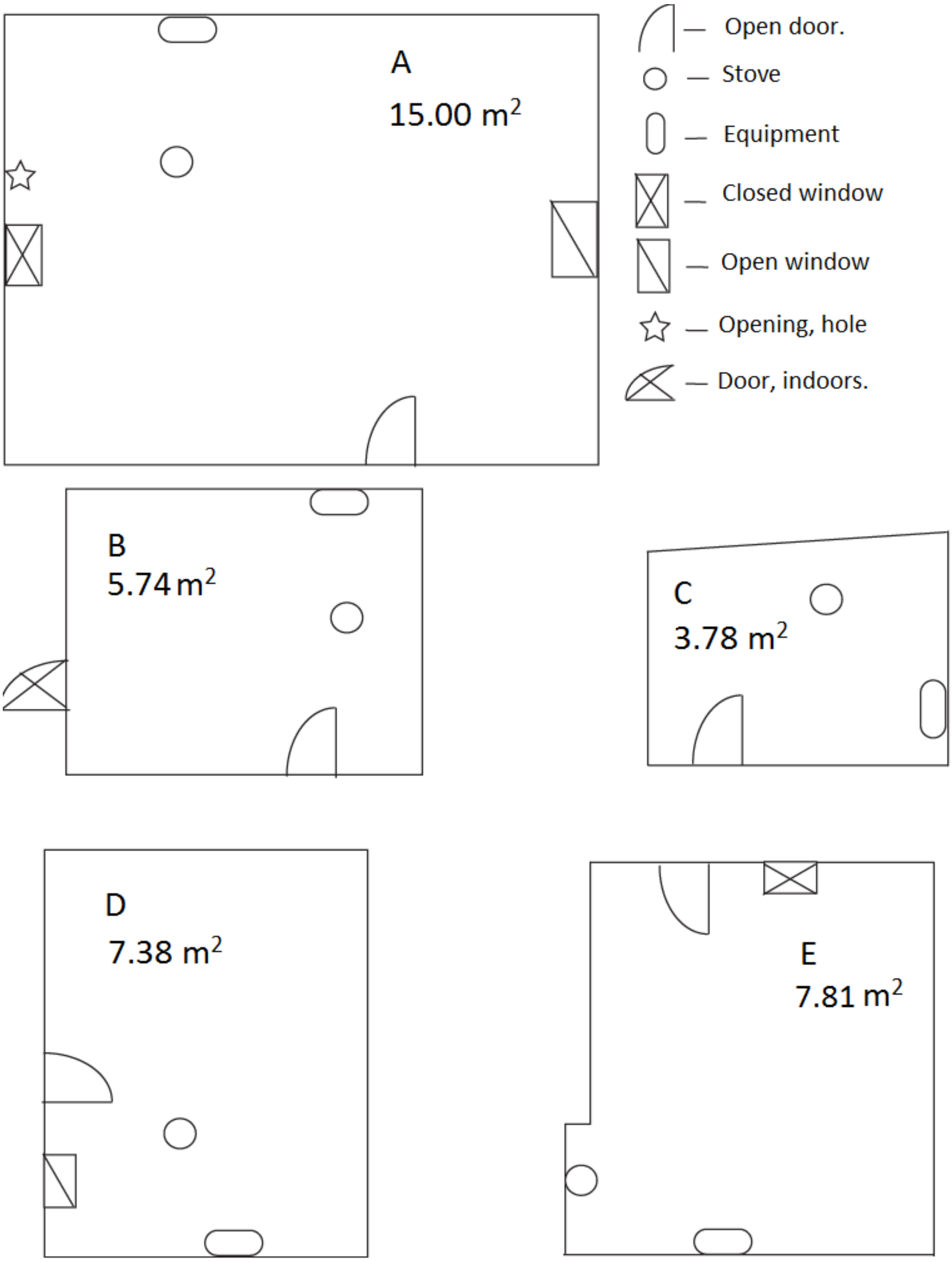

Figure 2. Schematics over the different households and they are in scale in reference to each other.

The equipment used for the experiments performed by this study:

- The temperature measurement was done with a thermometer and a thermocouple that could handle temperatures up to 1 400 ˚C. The point of the thermometer was placed between the stove and the pot, above the charcoal. The thermometer had a measurement range from -50 ˚C up to 1 300 ˚C. The accuracy was ± 0.5% rdg (reading, the temperature measured) +1 ˚C (Clas Ohlson). The thermocouple could measure up to 1 200 ˚C and the accuracy for temperatures between – 40 ˚C and 375 ˚C was ± 1.5 ˚C. For temperatures between 375 ˚C and 1 000 ˚C the accuracy was 0.004 times the measured temperature. (Jonas Bertilsson, Pentronic).

- A UCB particle monitor was used in this study to monitor the $PM_{2.5}$ level during the cooking process. It combines ionization chamber sensing and optical scattering sensing, which a commercial smoke detector uses. It has been modified to send real-time signals, so that real-time monitoring and measurements can be done. When launched it had a zeroing time of at least 30 minutes, the monitor was put inside a closed zip lock bag inside a sealed airtight container. The concentration was recorded in mg/m^3 (Household Environmental Monitoring).
- A EL-USB-CO logger from Lascar Electronics was used to monitor the CO-level in the kitchen during the cooking process. The measurement range is between 0 and 1 000 ppm and the operating temperature is between -10 ˚C and 40 ˚C. The measurements were recorded every 10 seconds. It can store up to 32 510 measurements which is more than enough for one cooking process (Lascar).
- To measure the CO_2-concentration during the cooking process a HOBO-CO_2-datalogger from Onset was used. The measurement was in ppm and the device had a measurement accuracy of 50 ppm or 5 % of the measurement value (the largest value). The measurement range was between 0 and 2 500 ppm and measurements were recorded every 5 seconds (Onset).
- A kitchen scale was used to measure the fuel weight during this study. The scale had a capacity of 3 kg and the accuracy was ± 1 g (Kjell & company).
- The gasifier stove in galvanized steel was made of three different parts. The gasifier had one outer shell, a bucket for the fuel that went inside the outer shell and a top lid with one hole in the middle. See Figure 3 for the dimensions. The bucket when inside the gasifier is 5 cm above ground. The bucket was used to harvest the charred biomass.

Kenya Ceramic Jiko Stove is a common charcoal stove and the one used in this study had the dimensions as described in Table 1 and was assembled as shown in Figure 4.

Table 1. Dimensions of the Kenya Ceramic Jiko stove

Part	Size
Outer diameter	25 cm
Inner diameter	18.5 cm
Height (the whole stove)	17.5 cm
Depth (fire box)	7 cm
Air inlet	3 cm x 7 cm

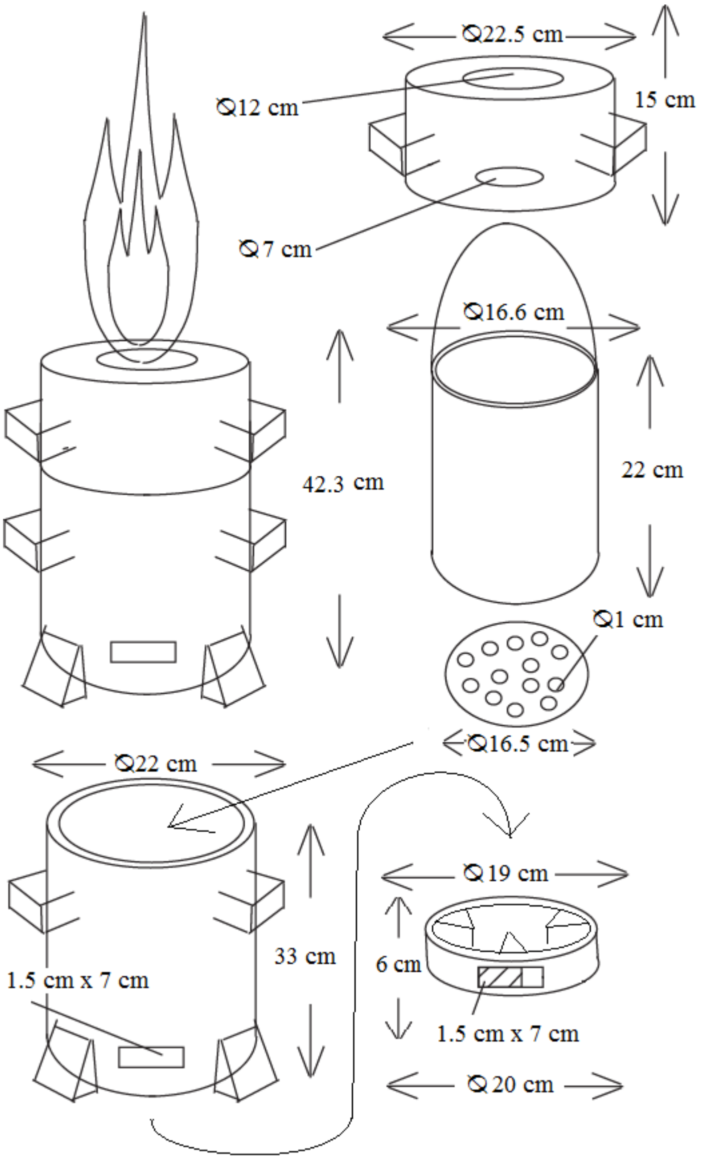

Figure 3. Dimensions of the Gasifier stove.

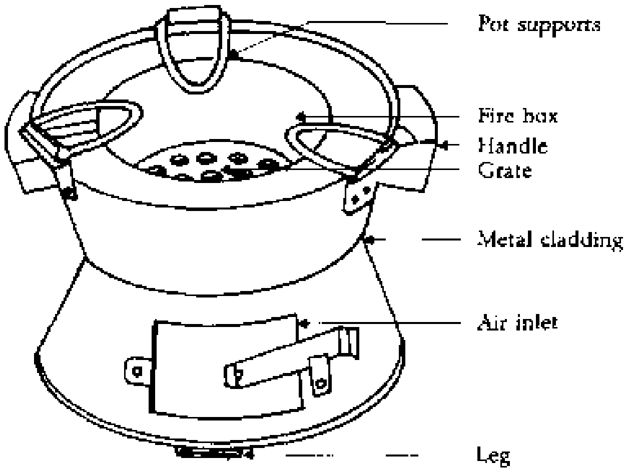

Figure 4. Kenya ceramic Jiko (Kengo Wood energy)

3.2 Pre-cooking steps

Charred biomass was produced in the gasifier stoves in order to be able to perform the cooking tests. All the charred biomass was produced in the kitchen of one of the five households that were a part of this study to mimic the charred biomass that would be produced by the farmers if they use the gasifiers. The kitchen used for production was Household A in Figure 2. The gasifier was filled with the chosen feedstock and then lit outside of the kitchen. Dry sticks of Grevillea Robusta prunings and some dry material like leaves and branches from bushes which were to be found around the kitchen were used as lighting material. When the gasifier caught fire it was carried inside the kitchen and a pot with water was put on it to boil so to mimic the way it will be used by the farmers under normal circumstances. When the flame in the gasifier burned out the charred biomass was harvested by emptying the bucket in a pot. A lid was put on the pot to cut the oxygen supply and the pot was then put in a basin filled with water to cool. When the charred biomass cooled to room temperature it was put in a carton box for safekeeping for the tests. Three different boxes were used to store the three different types of charred biomass.

When at least one kg of one type of charred biomass had been produced, a cooking test was performed in the household where the production was done, in order to estimate how much charred biomass needed to be produced for the entire set of cooking tests. The cooking test was performed the day after production when the emissions from the production were aired out as not to affect the test.

The weight of the charred biomass/charcoal was measured with the kitchen scale. **The weather and cooking conditions** were recorded before each cooking test to see if any special source of error could be found later in the results. There might have been a rainy day (higher moisture content) or some changes in the kitchen (stove moved around in the kitchen etc.). A field work sheet was produced and printed for the record keeping during the cooking process in the field. The field work sheet can be found in Appendix A1. The kitchens were prepared so that they were at the same conditions as the kitchens in the first stage of the research project (Helander and Larsson, 2014). Doors and windows were to be open and closed in accordance to Figure 2 in Section 1.4.

The bulk density was determined by filling up a container with a known volume of the different types of fuel and weighing the container before and after it was filled. The volume of the container was 4 450 ml ± 10 ml. The measurement was done five times for each fuel type. To determine the bulk density the mean weight of each fuel type was divided by the volume of the container as in equation 3.2.1.

Bulk density = mean weight for five tests / volume of container $[g]/[dm^3] = [g/dm^3]$ (3.2.1)

3.2.1 Charred biomass production from Grevillea prunings, maize cobs and coconut husks

To calculate how much charred biomass was needed per cooking test a complete cooking test was performed in Household A for each type of charred biomass. To be sure that the amounts of charred biomass per cooking test ($A_{PERCOOK}$) was enough it was set to the double the amount that was used during the first cooking test. When charred Grevillea prunings was used the test consumed 390 g and in order to make sure that enough charred Grevillea prunings were produced the amount needed per cooking test was set to 800 g. A_{TESTS} in eq. 3.2.1.1 was set to four tests per feedstock since there were only four households left in which to perform the cooking test. The extra charred biomass (A_{EXTRA}) was produced so that the bulk density test could be performed and used as a backup in case that more charred biomass was needed than the estimated $A_{PERCOOKING}$ per cooking test. A_{EXTRA} was set to 1 kg. As equation 3.2.1.1 shows the total amount of charred Grevillea prunings needed (A_{TOT1}) was estimated to be 4 200 g.

$$A_{TOT} = A_{PERCOOKING} * A_{TESTS} + A_{EXTRA} \quad (3.2.1.1)$$

$$A_{TOT1} = 800 * 4 + 1\,000 = 4\,200 \text{ g}$$

The same procedure was used for maize cobs and the coconut husks. The difference is that for maize cobs $A_{PERCOOKING}$ was set to 1 000 g since 449 g of charred maize cobs were used during the first cooking test. The total amount of charred maize cobs needed (A_{TOT2}) was estimated to be 5 000g.

$$A_{TOT2} = 1\,000 * 4 + 1\,000 = 5\,000 \text{ g}$$

For coconut husks $A_{PERCOOKING}$ was set to 800 g since 379 g of charred coconut husks were used during the first cooking test. The total amount of charred coconut husks needed (A_{TOT3}) was estimated to 4 200 g.

$$A_{TOT3} = 800 * 4 + 1\,000 = 4\,200 \text{ g}$$

3.3 Cooking test

The cooking test was performed in five households, with three different types of charred biomass, charred Grevillea prunings, charred maize cobs and charred coconut husks and with conventional charcoal from the market in Embu used as a reference. The raw material from which the conventional charcoal was produced is unknown, but all the conventional charcoal was produced from the same raw material. A Kenya Ceramic Jiko stove was used for the cooking tests. The same households that were used in the earlier stage of this research project (Helander and Larsson, 2014), were used in this study. The time when the cooking started and finished (after the ignition of the fuel) was documented. The order in which the trials were done was randomized using Matlab's function *rand* except for the tests at Household A since they were already done during the production days. Some changes had to be done to the list to match the work schedule of the farmers. See Appendix A2 for the final randomized list. During the trials the following parameters were observed:

- Time to cook a standard meal
- Amount of fuel used per cooking test
- Amount of food cooked
- If fuel had to be added during the process and if so how many times it was necessary for one meal.
- Emissions formed (CO_2, CO and $PM_{2.5}$)

- The flame temperature during cooking

A standard meal was defined as Ugali and Sukuma Wiki. One pot was used for cooking the Sukuma Wiki and a different pot was used for Ugali. These are traditional dishes consisting of a kind maize porridge (Ugali) and fried kale, tomatoes and onions (Sukuma Wiki). The pot for Ugali had to be changed to a thicker pot since cooking Ugali requires a thicker pot than Sukuma Wiki. For each cooking test the same amount of the ingredients were used. The amounts were 1 kg of Soko maize flour, two bags of kale from the local market always prepared in the same way (about 700 g), three tomatoes (200 g - 300 g), two red onions (80 g - 120 g) and the Sukuma Wiki was fried in coconut fat (~ 80 g).

The whole cooking process was measured from when the fuel was ignited until dish two was finished. The time was recorded when:

- the stove was ignited (outside so no emissions were recorded from this step)
- the stove caught fire (also considered start of boiling time)
- the cold water boiled
- dish one started
- dish one finished
- dish two started
- dish two finished (considered the end of the total cooking time)

The total cooking time was the time from that the stove caught fire until dish two was finished.

The measurement of emissions was done with the equipment hanging one and a half meter above the ground and one meter to the side of the stove, to simulate the location of the person cooking in relation to the stove. The measurements started 30 min before the cooking started and ended 30 minutes after the cooking had ended. In the data analysis, data from the total cooking time were used. To measure the temperature the thermometer and the thermocouple were used. CO was measured with the EL-USB-CO logger, particulate matter ($PM_{2.5}$) was measured with UCB particle monitor and CO_2 was measured with the CO_2-datalogger.

The flame temperature was measured during the whole cooking process in eight minute intervals. **The amount of fuel** used was determined by weighing the pre-prepared fuel before and after the cooking process. In case of reload of fuel it would be taken from the already prepared amount of fuel which was prepared to be more than enough for cooking a meal. If adding of fuel was necessary, the time when it was added was recorded in the field work sheet.

3.4 Energy use efficiency

The energy use efficiency was determined in the unit amount of energy [kJ] used per cooking test using equation 3.4.1. The amount of energy used per cooking test was determined and the different types of charred biomass were compared to the reference charcoal from the local market. The amount of energy used per cooking test was defined in two different ways, gross fuel and net fuel. Gross fuel is when all the fuel used during the cooking test is considered to be used including the amount of fuel left in the stove. The net fuel is when the fuel left in the stove is considered to have the same fuel quality as before the cooking test and then considered unused.

Energy used per cooking test [kJ /per cooking test] = Amount of fuel (g) per cooking test * calorific value * 4.1816 [g * kCal/g* J/Cal] (3.4.1)

The mean energy use per cooking test was calculated for the four fuel types in the five different households using equation 3.4.2. The cooking process was assumed to be the same in the households independent of fuel used. The mean power released during cooking was calculated using equation 3.4.3. All the mean values were processed with the Kruskal-Wallis test to determine significant difference in mean between the fuels.

The mean energy use per cooking test was calculated using equation 3.4.2. The energy use for one type of fuel was summated for the five households it had been used in and divided with the number of households:

(∑ Energy used per cooking test in household (i)) / Total number of households (3.4.2)

Where i = [1, 2, 3, 4, 5].

The mean power can be calculated as the amount of energy used per cooking test divided by the time it took to cook the meal as in formula 3.4.3:

Mean power [kJ / sec] = (∑ (Energy used per cooking test / total cooking time)) / Total number of households (3.4.3)

The amount of energy used per cooking test can be calculated with formula 3.4.1 which is the mass of the total amount of fuel used during one cooking test multiplied with the calorific value of the fuel, which were analyzed in a research laboratory (KEFRI). The method for determining the calorific value was as follows:

The sample was grinded and one gram was taken and wrapped with tissue paper of known calorific value and weight. It was then tied with an ignition wire (platinum) of known calorific value. Both ends of the wire were then connected to bomb calorimeter electrodes and then placed in a bomb calorimeter and firmly closed. Thirty kg of oxygen was then led into the bomb and the bomb immersed into a cylinder filled with distilled water up to 2 100 g. The bomb calorimeter was calibrated with benzoic acid tablets of known calorific value (see Appendix B1 for further information of how the laboratory results were obtained).

The energy density was calculated using the bulk density, conversion value from calories to joules and the calorific value obtained in the laboratory results as in equation 3.4.4.

Energy density [kJ/m^3] = Bulk density * calorific value * 4.1816 [g/m^3*kCal/g*J/Cal] (3.4.4)

The energy balance for using the gasifier and the produced charred biomass for cooking can be calculated with equation 3.4.5.

Mean energy used per cooked meal / (1 + a) (3.4.5)

The energy used per cooking test is used to cook a meal and to produce charred biomass. A mean energy use is calculated for each type of fuel and it is divided with 1+a, a = produced amount of charred biomass / charred biomass needed to cook a meal. The meal cooked with the gasifier is represented with the value 1 and a is the number of meals the produced charred biomass can cook.

3.5 Emission data analysis

The emission data collected in the field had to be processed in Excel and Matlab since each dataset for CO, CO_2 and $PM_{2.5}$ contained a lot of information. For $PM_{2.5,}$ data was recorded once a minute during the cooking period. The corresponding sampling period for CO was 10 seconds and for CO_2 the sampling period was 5 seconds. The data only consisted of observations from directly after the stove was lit until the last dish was finished so the data did not include background data from before or after combustion.

The typical behaviors for the three different types of emissions were presented in graphs. The emission data for CO, CO_2 and $PM_{2.5}$ were processed using Matlab to plot the curves as concentration (Y-axis) versus time (X-axis) plots. To determine if there was a significant difference between the different households and the different types of fuel, an ANOVA or Kruskal-Wallis were performed. The preferable choice would be an ANOVA since it processes more information than the Kruskal-Wallis. One of the assumptions of ANOVA is that the data has to be standard normal distributed (Exploarable). One-way Kolmogorov-Smirnov test (Mathworks, kstest) and the Jarque-Bera test (Mathworks, jbtest) were used to evaluate whether the data were normal distributed. Five random measurements were chosen from each type of pollutant. Both tests showed that the data was not normal distributed. Therefore the Kruskal-Wallis test was selected as the method used to determine whether the data had a significantly different mean or not, since the ANOVA could not be applied here. The Kruskal-Wallis test rank the observations as explained in Section 2.3 and compare the mean ranks of each group against each other. If one group has a higher mean rank, then it would mean that those observations have higher values than the other groups. The Kruskal-Wallis test was done in Matlab using the function *kruskalwallis*.

The data for one cooking test consists of three datasets (one for each type of pollutant) with a different amount of data points depending on the type of pollutant. Each pollutant was tested on its own and not in combination with the other types of pollutants. The data was handled in three different ways before it was processed in the Kruskal-Wallis test as follows:

1. The mean value for each dataset was calculated and used as an observation, which meant that the 20 tests had 20 mean values for each emission. The mean was for the part of the dataset that corresponded to one complete cooking test (total cooking time).
2. The highest value was identified for each dataset in the interval for when the cooking test was performed resulting in 20 top values for the 20 tests for each emission.
3. The whole dataset in the interval of one complete cooking test was used as one observation which meant that for the 20 tests there were 20 vectors of data for each pollutant.

For the last alternative it can be interpreted as the number of observations is equal to the number of data points, which is not correct. The purpose was to compare the dynamic of the measurements. The Kruskal-Wallis test was done in two ways, one where the different groups were divided by type of fuel (4 types of fuel with 5 observations in each group) and the other where the different groups were divided by the household number (5 groups with 4 observations in each). When the Kruskal-Wallis test was performed, the results were presented in an ANOVA-table. If the Kruskal-Wallis test showed significant difference between the groups then Matlab performed a Tukey's HSD test to find which group was significantly different from the others. The Matlab function used is called *multcompare* and it uses Tukey's HSD as a default.

The emission for charred Grevillea prunings and conventional charcoal from Trial 2 were compared to the emission from the gasifier, the improved stove and the 3-stone-fire from Trial 1 when Grevillea prunings were used. The comparison was made for the mean value and the whole dataset for each cooking test. This was done for the $PM_{2.5}$-emission and the CO-emission separately.

4 Results for energy use efficiency

The results are divided into different sections as follows. The amount of fuel used for each test as well as the energy density and bulk density of the fuels are presented in Section 4.1. The energy use efficiency, the energy balance and the mean power are presented in Section 4.2. The time measurements for different steps of the cooking tests are presented in Section 4.3. A full table with the P-value for each Kruskal-Wallis test is presented in Appendix B2.

4.1 Amount of fuel used, energy density and bulk density test

The mean mass of net fuel used and the mean use of gross fuel for each fuel type is displayed in Table 2. There is a significant difference (P=0.0201) between charred Grevillea prunings and charred maize cobs for both net and gross fuel. There are no significant differences between the other combinations of fuel types. The whole amount of fuel used during the cooking test including the fuel left in the stove is presented in the fourth column of Table 2. There are no significant differences in the mean use of gross fuel. Raw data for fuel consumption for each household and fuel type can be found in Appendix C1. Figure 5 shows the amount of fuel that was left in the stove after a completed cooking test.

Table 2. Mean use of charred biomass per cooking test and the mean number of times it required adding

Fuel type	Mean net fuel used [g]	Standard deviation	Mean gross fuel used [g]	Standard deviation	Mean number of times of adding	Standard deviation
Grevillea	289	13.5	376	54.1	1.4	0.49
Coconut	310	57.6	395	57.0	0.6	0.49
Maize cobs	381	39.6	422	39.3	2.2	0.40
Charcoal	344	36.5	496	70.9	0	0

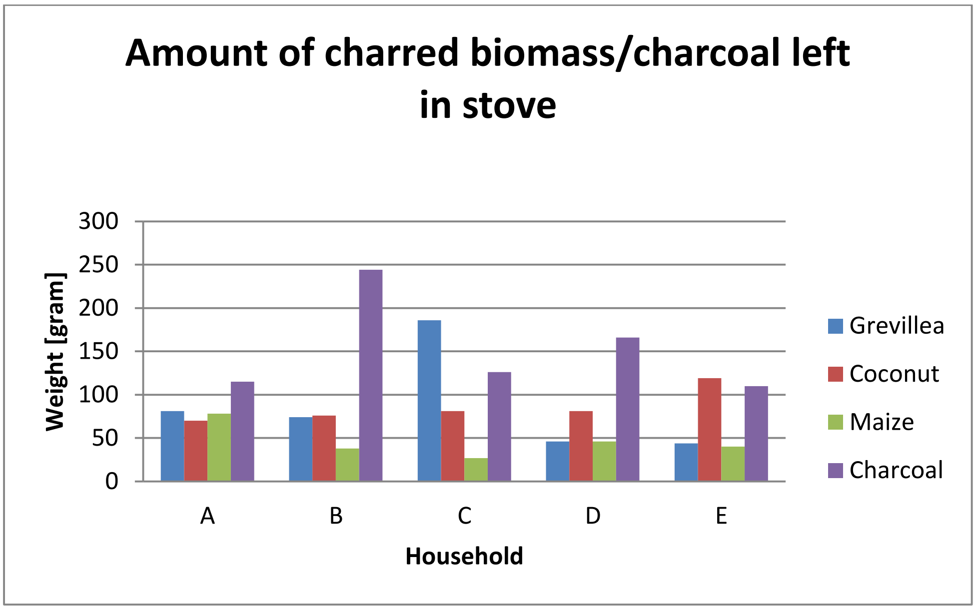

Figure 5. Amount of charred biomass or charcoal left in the stove after a completed cooking test.

The laboratory results from Kenya Forestry Research Institute Karura (KEFRI) performed by Moses Elima Lukibisi are presented in Table 3. The samples were from the different types of charred biomass and the conventional charcoal.

Table 3. Fuel properties of the different fuel types from laboratory results

Sample Name	MOISTURE CONTENT %	VOLATILE MATTER %	ASH CONTENT %	FIXED CARBON %	CALORIFIC VALUE Kcal/g
Maize Charcoal Cycle(2)	8.04	27.54	5.28	59.14	6.865
Coconut Shell Charcoal	5.78	19.84	4.71	69.67	7.584
Grevillea Charcoal Cycle(2)	6.73	31.84	5.15	56.28	6.342
Lump Charcoal Cycle 2	4.58	16.21	2.24	76.97	7.918

The calorific values from Table 3 are converted from calorific value [Kcal / g] to specific energy [MJ / kg] and are presented in Table 4.

Table 4. Specific energy for each charred biomass and charcoal [MJ/kg]

Type of fuel	Grevillea	Coconut	Maize	Charcoal
Specific energy	26.52	31.71	28.71	33.11

The bulk density for the different types of charred biomass and conventional charcoal are presented in Table 5. The bulk density for the different fuel types were calculated by using Equation 3.2.1 in Section 3.2. The raw data for Table 5 is found in Appendix C2. The bulk density for charred maize cobs is significantly different (P=0.0007) from charred coconut husks and conventional charcoal. There are no significant differences between the other combinations of fuel types.

Table 5. Calculated bulk density for the different types of charred biomass/charcoal

Type of fuel	Bulk density [g/dm^3]	Standard deviation	Significant difference
Grevillea prunings	137.0	7.55	No
Coconut	267.0	13.66	No
Maize cobs	99.10	3.34	Yes
Charcoal	277.5	15.39	No

The energy density for each fuel type is presented in Table 6, which was calculated using the calorific value from Table 3 and the bulk density from Table 5. Charred maize cobs are significantly different (P=0.0005) from charred coconut husks and conventional charcoal. Charred Grevillea prunings are also significantly different from conventional charcoal.

Table 6. Energy density based on calorific value from lab test and bulk density

Type of fuel	Energy density [kJ/dm^3]	Standard deviation
Grevillea	3 630	200.0
Coconut	8 467	433.3
Maize	2 840	95.8
Charcoal	9 188	509.6

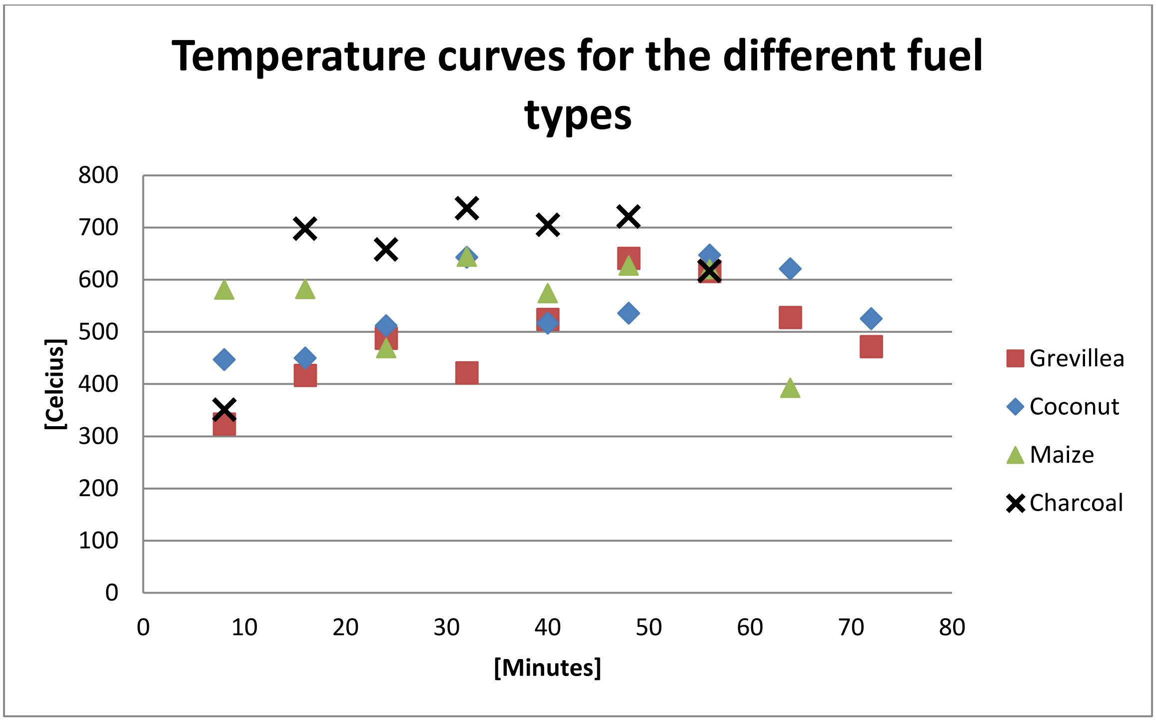

Figure 6. The temperature curves for 4 different tests, with 1 test for each fuel type.

Temperature curves representing each fuel type are presented Figure 6. Charred Grevillea prunings have a lower temperature for the most part of the cooking time and conventional charcoal has a higher temperature.

4.2 Mean energy use, mean energy balance and mean power

The mean energy consumption for cooking a meal in a Kenya ceramic Jiko stove with charred biomass produced from gasifiers is displayed in Table 7. The mean net energy use per cooking test for charred Grevillea prunings is significantly different (P=0.0298) from the corresponding value for conventional charcoal. The rest of the fuels do not have significantly different means from each other. There were no significant differences in the mean gross energy use.

Table 7. Mean net energy use per cooking test with charred biomass and charcoal

Fuel type	Mean net energy use [kJ]	Standard deviation	Mean gross energy use [kJ]	Standard deviation
Grevillea	7 675	358.4	9961	1 435
Coconut	9 837	1 826	12 530	1 809
Maize	10 940	1 136	12 100	1 130
Charcoal	11 160	1 448	15 860	2 986

Table 8 and Table 9 consist of data collected by Hanna Helander and Lovisa Larsson (Helander and Larsson, 2014). Table 8 shows how much energy was consumed to cook a meal and the yield of different types of charred biomass with the gasifier stove. There were no significant differences between the different feedstocks in terms of energy consumption, charred biomass production and amount feedstock used. Energy value is the product of the calorific value, the amount of feedstock used and the conversion value from calories to Joule.

Table 8. Mean energy consumption for producing charred biomass and cooking a meal with a gasifier stove

Type of fuel	Feedstock used [g]	Standard deviation	Charred biomass produced [g]	Standard deviation	Energy value [kJ]	Standard deviation
Grevillea	1 820	167.8	349	31.3	35 700	3 290
Coconut	1 654	330.1	390	89.0	34 700	6 920
Maize	1 514	261.8	317	61.4	28 500	4 930

The mean energy consumption between the different feedstock and the different stoves are presented in Table 9. There is a significant difference between maize cobs used in a gasifier and Grevillea used in a 3-stone-fire. Otherwise there were no significant differences between the different fuels and stoves in energy consumption. The energy consumption for gasifier stoves are in Table 9 presented with the energy value for the produced charred biomass subtracted from the total energy consumption for the gasifiers.

Table 9. Mean energy consumption per cooking test [kJ] with energy value for produced charred biomass subtracted from the gasifier tests.

Type of stove	Type of fuel	Energy cost per meal [kJ]
3-stone-fire	Grevillea	30 700
Improved stove	Grevillea	24 700
Gasifier	Grevillea	26 400
Gasifier	Coconut	22 300
Gasifier	Maize	19 400

The energy balance for using the gasifier stove in combination with the Kenya ceramic Jiko stove was between 16.3 - 18.4 MJ per meal (gross fuel, Table 10) and 15.3 MJ and 16.1 MJ per meal (net fuel, Table 11). There were no significant differences between the fuels in either the net fuel or the gross fuel case.

Table 10. Energy balance per meal for gross fuel

Type	Mean energy consumption per meal [MJ]	Standard deviation
Grevillea prunings	18.4	1.74
Coconut husks	17.3	3.10
Maize cobs	16.3	2.79

Table 11. Energy balance per meal for net fuel

Type	Mean energy consumption per meal [MJ]	Standard deviation
Grevillea prunings	16.1	1.21
Coconut husks	15.3	3.17
Maize cobs	15.5	2.66

The mean power that the stoves used is presented in Table 12, where charred Grevillea prunings have the lowest power with 1.98 kW and conventional charcoal has the highest power with 3.06 kW. The mean power with charred Grevillea prunings is significantly less (P=0.0029) than with charred maize cobs and conventional charcoal.

Table 12. Mean power during the total cooking time [kW]

Fuel type	Mean power	Standard deviation
Grevillea	1.98	0.110
Coconut	2.48	0.541
Maize	2.82	0.340
Charcoal	3.06	0.448

4.3 Cooking time

The mean total cooking and boiling time was similar for the different types of fuel, which Table 13 shows, but between the different households the mean total cooking and boiling time was quite different, which can be seen in Table 14. However, there are no significant differences in boiling time or total cooking time between the households or the fuel types. Household B had the fastest total cooking time and Household E had the longest total cooking time.

Table 13. Mean boiling time and mean cooking time (incl. boiling time, Dish 1 and Dish 2) for the different fuel types [min]				
Type	**Mean boiling time**	**Standard deviation**	**Mean cooking time**	**Standard deviation**
Grevillea	19.8	2.04	66	8.2
Coconut	20.6	3.01	66	11
Maize cobs	20.0	3.74	65	2.8
Charcoal	19.2	2.93	62	6.6

Table 14. Mean boiling time and mean total cooking time for the different households [min]				
Household	**Mean boiling time**	**Standard deviation**	**Mean total cooking time**	**Standard deviation**
A	17.8	0.829	65	7.4
B	18.8	1.48	53.8	6.67
C	22.5	3.28	62.8	4.61
D	18.8	3.11	63	4.9
E	21.8	2.28	70.8	4.84

The mean cooking times for Dish 1 and Dish 2 depending on fuel type are presented in Table 15. There are no significant differences between the different fuel types for either Dish 1 or Dish 2.

Table 15. Mean cooking time Dish 1 and Dish 2 for each fuel type [min]				
Type	**Dish 1**	**Standard deviation**	**Dish 2**	**Standard deviation**
Grevillea	15	6.0	25	3.2
Coconut	16	8.1	25	3.4
Maize cobs	13	1.9	23	1.4
Charcoal	15	8.7	22	3.1

The mean cooking time for Dish 1 and Dish 2 are presented in Table 16. There is a significant difference (P=0.0135) between Household A and Households B and C for Dish 1. There are no significant differences between the households for Dish 2.

Table 16. Mean cooking time Dish 1 and Dish 2 for each household [min]				
Household	**Dish 1**	**Standard deviation**	**Dish 2**	**Standard deviation**
A	25.3	6.6	22	2.2
B	9	2	23	3.0
C	10.3	0.83	22	2.2
D	14.3	3.27	27	1.9
E	15.3	3.27	26	2.6

5 Emission results for Trial 2

The emission for the different types of charred biomass (Trial 2) has been evaluated and compared to each other. This section has been divided into two different subsections for each type of pollutant except for CO_2-emissions and one subsection for comparison with Trial 1. The data from the CO2-measurements could not be analyzed properly, due to a lack of data since two measurements failed for the CO_2-emission because of technical difficulties with the equipment. Figure 7 shows five tests chosen at random and the CO_2-concentration during these tests. The levels varied between ~350 ppm and ~800 ppm.

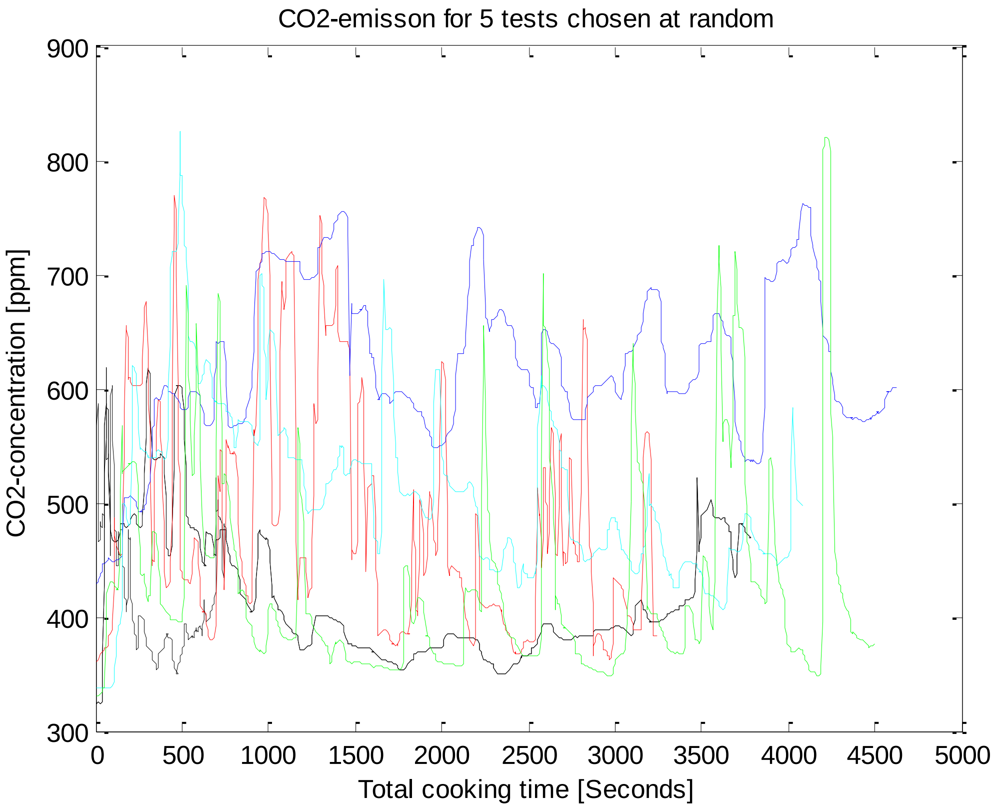

Figure 7. CO_2-emission curves for five cooking tests chosen at random. 1 step in the x-axis represents 5 seconds.

5.1 $PM_{2.5}$-emission data

The Kruskal-Wallis test was performed on the mean value, top value and the whole data set for the $PM_{2.5}$-emission to determine if there were any significant differences. The $PM_{2.5}$-emissions curves for five different tests (chosen at random) are presented in Figure 8. The mean emission level throughout the cooking time over all tests for $PM_{2.5}$ is 76.3 μg/m^3.

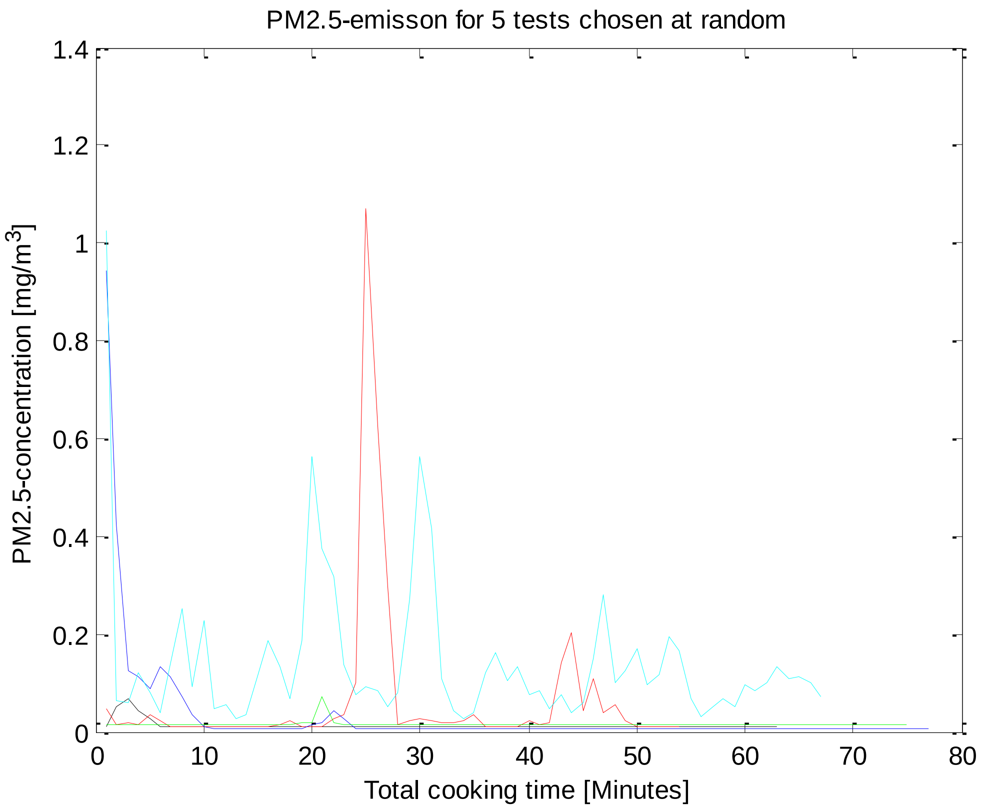

Figure 8. $PM_{2.5}$-emission curves for five cooking tests chosen at random. The Y-axis shows the $PM_{2.5}$-concentration levels in the kitchens during cooking. The X-axis shows the total cooking time [Minutes] from when the combustion began until Dish 2 was finished.

5.1.1 Comparison of the mean value of $PM_{2.5}$-emission for each cooking test

The mean value for all the $PM_{2.5}$-measurements done under one cooking test (the whole cooking time) was calculated for all 20 cooking tests. The mean values for each fuel type is presented in Figure 9. A significant difference was found between the different fuel types (P=0.034) which can be seen in Appendix B2, but the post-hoc (Tukey's HSD) could not find which one. Maize has the highest mean, but also has a large variance (Figure 10).

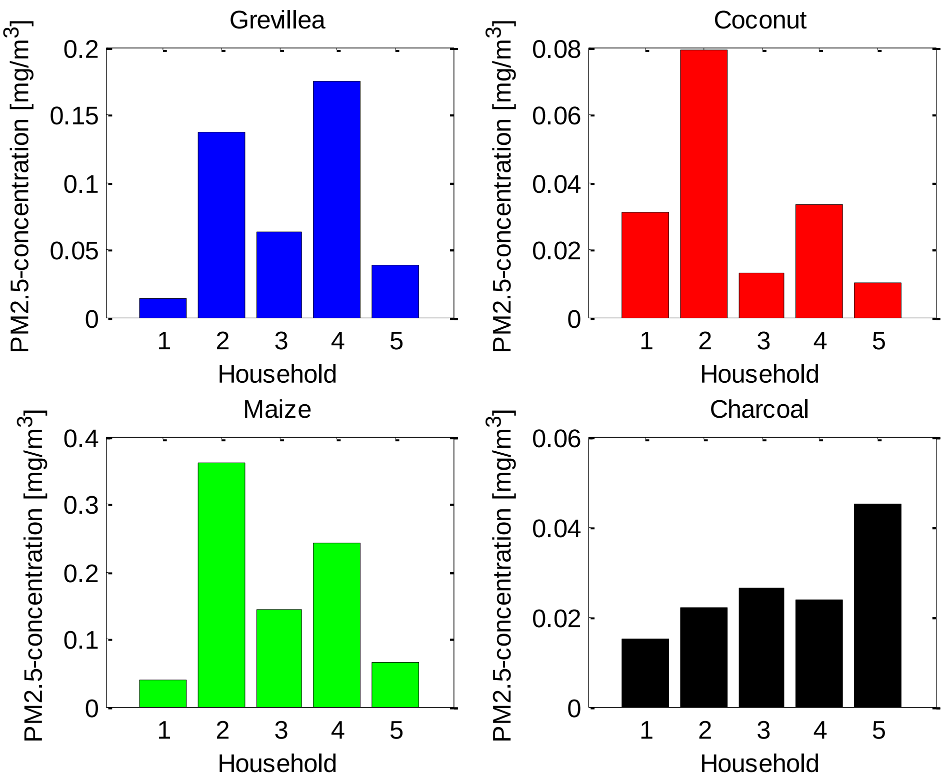

Figure 9. Mean ranks for the different types of fuel, each observation corresponds to the mean value of one household. Observation 1, 2, 3, 4 and 5 corresponds to household A, B, C, D, and E in that order.

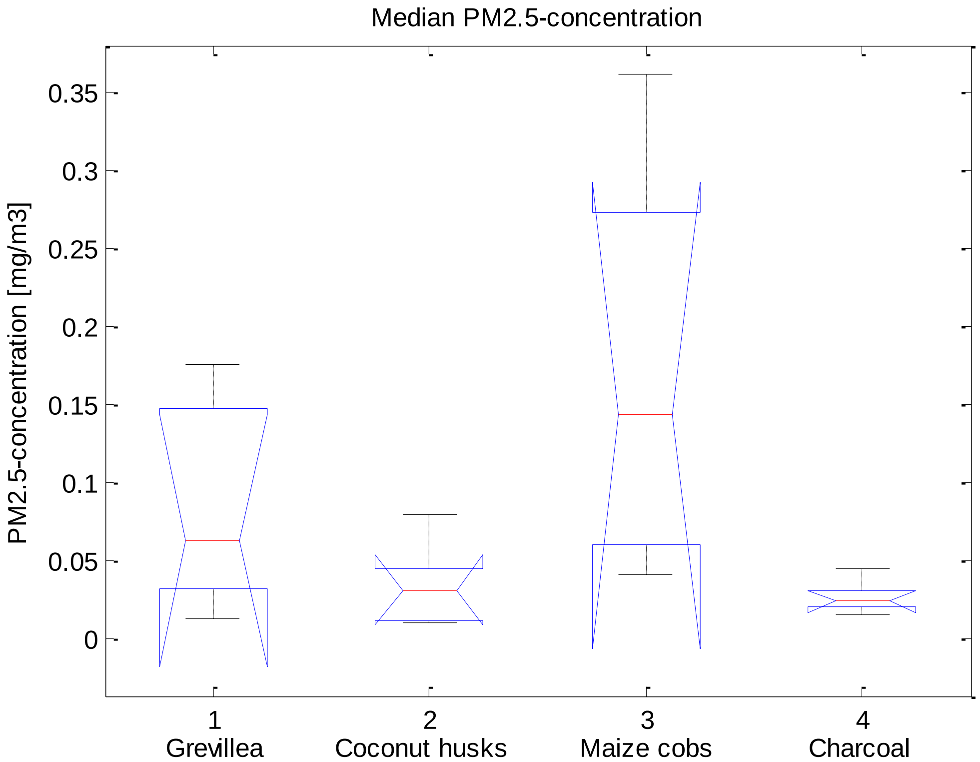

Figure 10. A box plot showing the median for each fuel (in red), the 25th and 75th percentiles (in blue) and max and min value (in black).

There were no significant differences between the households, but charred maize cobs have the highest value in each household. The mean values for the households are presented in Figure 11.

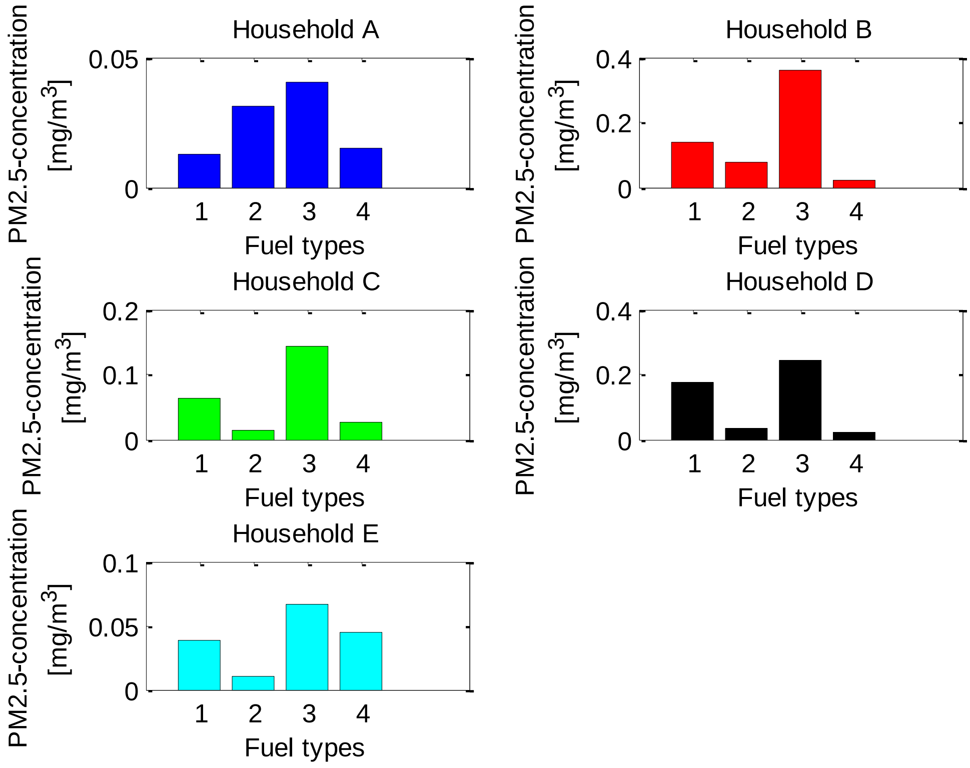

Figure 11. Mean ranks for each household with observation 1 representing charred Grevillea prunings, observation 2 represents charred coconut husks, observation 3 represents charred maize cobs and observation 4 represents conventional charcoal.

5.1.2 Comparison of the top value of $PM_{2.5}$-emission for each cooking test

There are no significant differences between the fuel types or the households in terms of top values (data in Appendix B2). The top values for the different fuel types are presented in Figure 12 and for the different households in Figure 13.

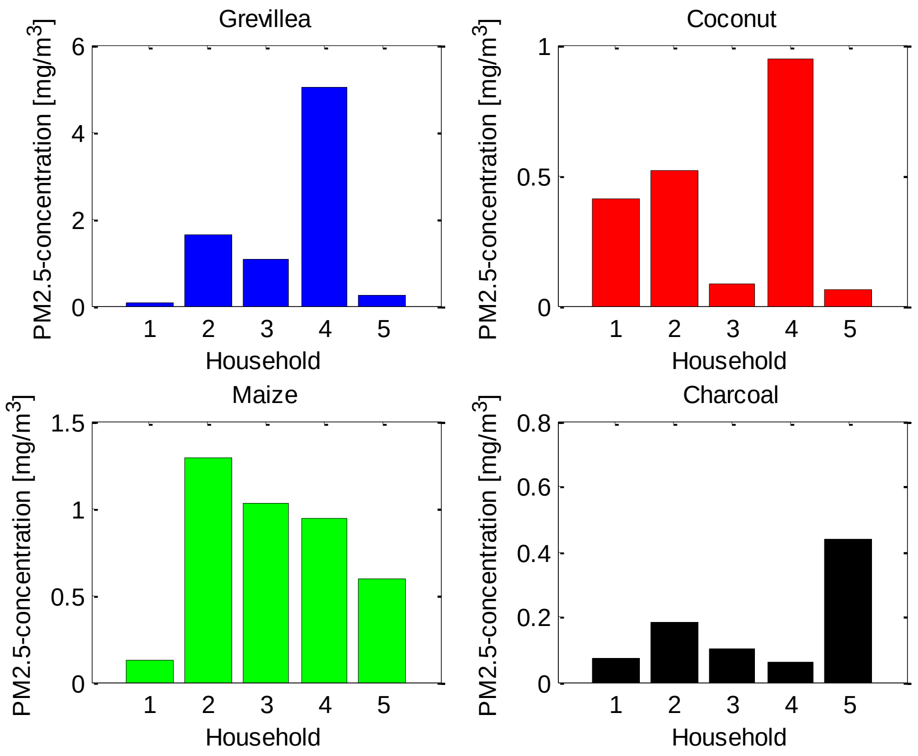

Figure 12. Top values for the different types of fuel. Observation 1, 2, 3, 4 and 5 corresponds to Household A, B, C, D, and E in that order.

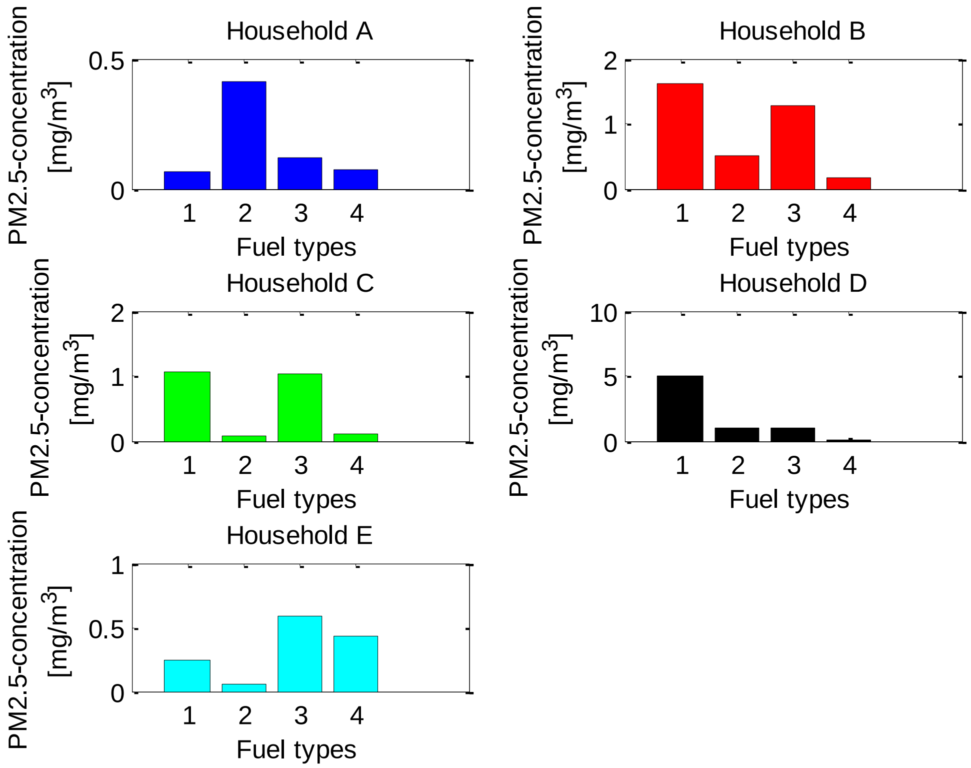

Figure 13. Top value for each household where observation 1 represents charred Grevillea prunings, observation 2 represents charred coconut husks, observation 3 represents charred maize cobs and observation 4 represents conventional charcoal.

5.1.3 Comparison of the complete dataset for $PM_{2.5}$-emission for each cooking test

Figure 14 shows how the $PM_{2.5}$-concentration varies during the five tests for each fuel type. There is a clear significant difference between different fuel types in terms of mean rank for all the measurements taken during the cooking tests. Charred maize cobs high values differ the most from the other fuel types (see Figure 15) and charred Grevillea prunings also differ from the other fuel types. Charred coconut husks and conventional charcoal do not differ significantly from each other and have the lowest values of the different fuel types. In Figure 15 the X-axis is the rank value and this value gives no indication on its own if the value is high or low. It is only in comparison to the other rank values that one can see if the value is high or low since the rank value depends on how many measurements has been done. For a 100 data points the rank will be between 0 and 100, but for a 1 000 data points they will be ranked between 0 and 1 000.

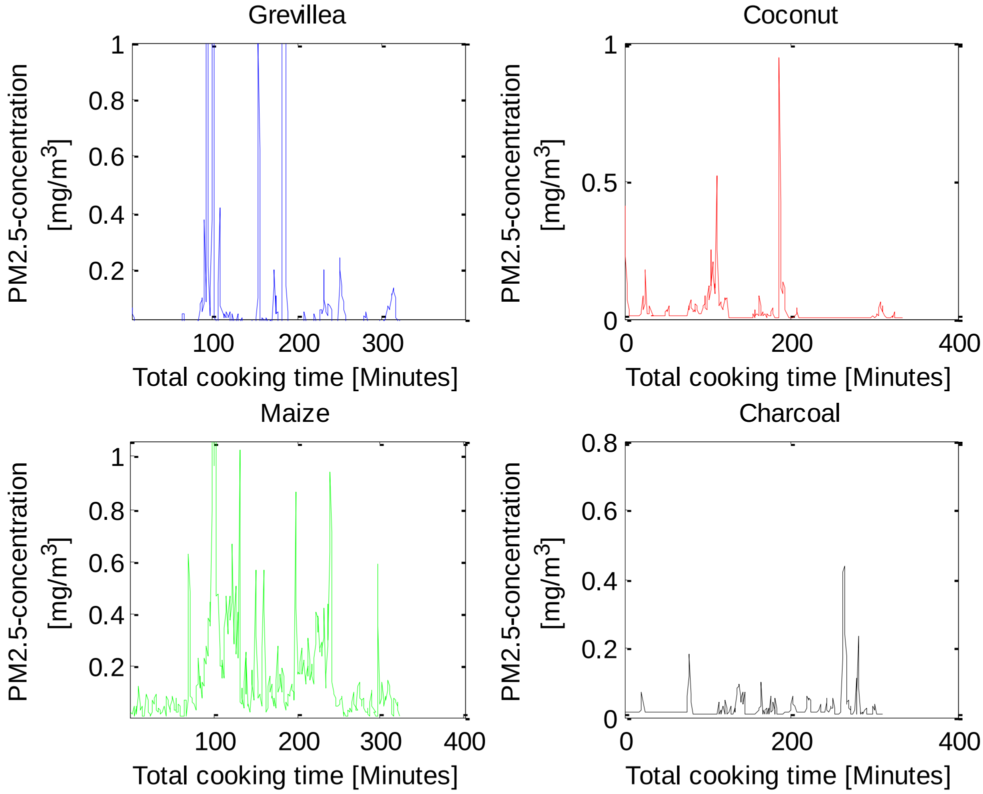

Figure 14. Observations for the different types of fuel with five emission curves following each other with the emission curve of Household A first and in alphabetical order until the emission curve for Household E.

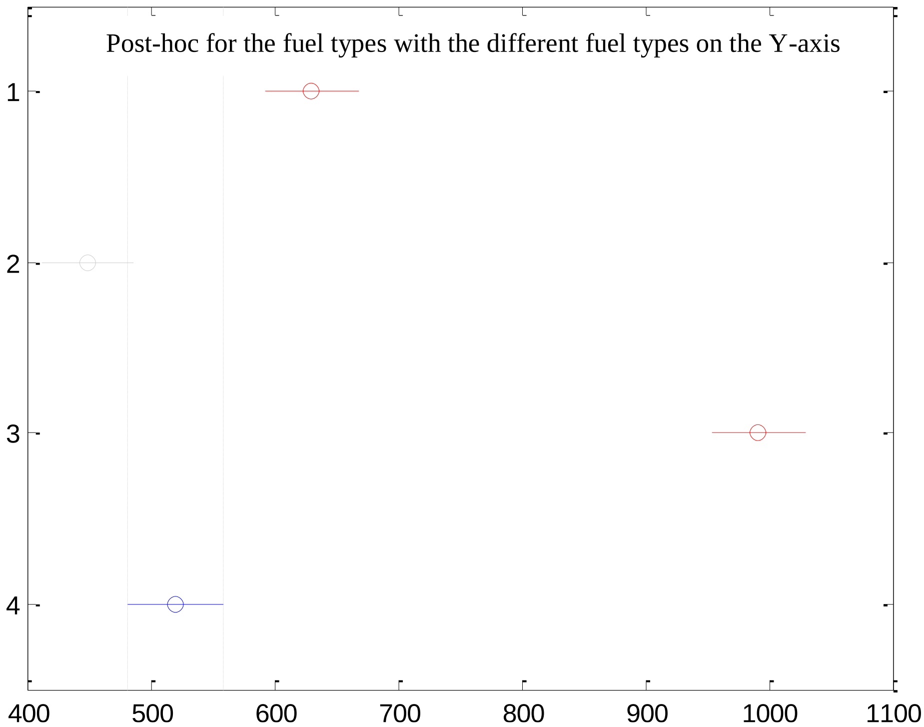

Figure 15. Observation 1 represents Grevillea prunings, observation 2 represents charred coconut husks, observation 3 represents charred maize cobs and observation 4 represents conventional charcoal. The median rank is on the X-axis and red marker means significantly different from the blue marker and grey marker means not significantly different from the blue marker.

Figure 16 shows how the CO-concentration varies during the five tests for each fuel type. A significant difference was found between the households. The post-hoc showed that Household B was significantly different from the others, as Figure 17 displays. Household E was also significantly different from all other households except Household A. Household A, Household C and Household D are not significantly different from each other.

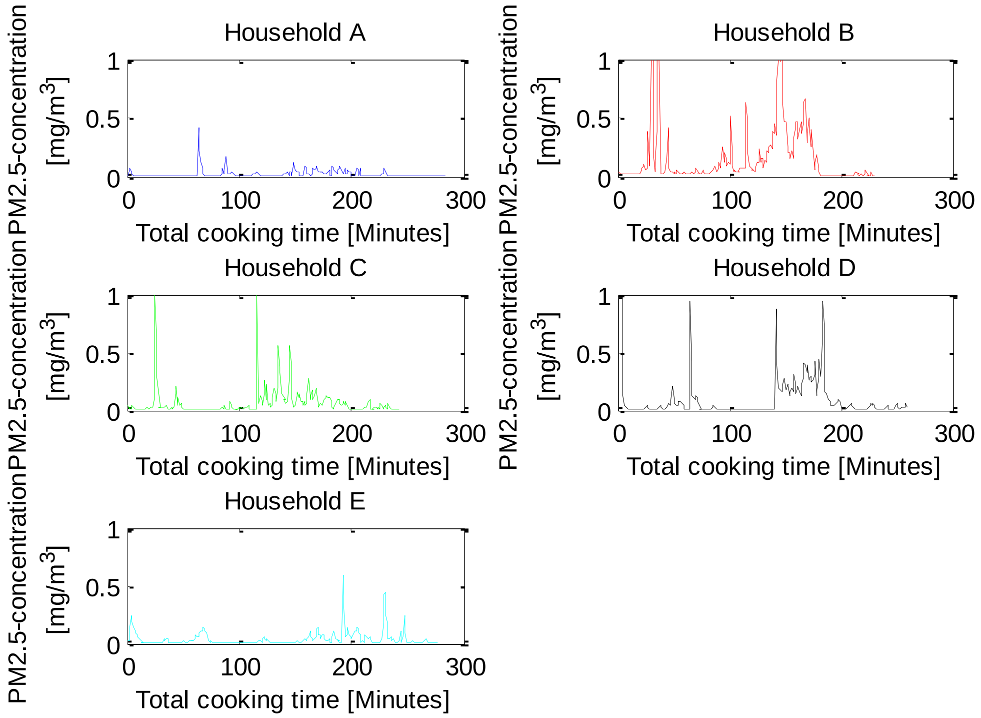

Figure 16. Observations for the different households with four emission curves following each other with the emission curve of charred Grevillea prunings first, charred coconut husks next, charred maize cobs after that and the emission curve for conventional charcoal last.

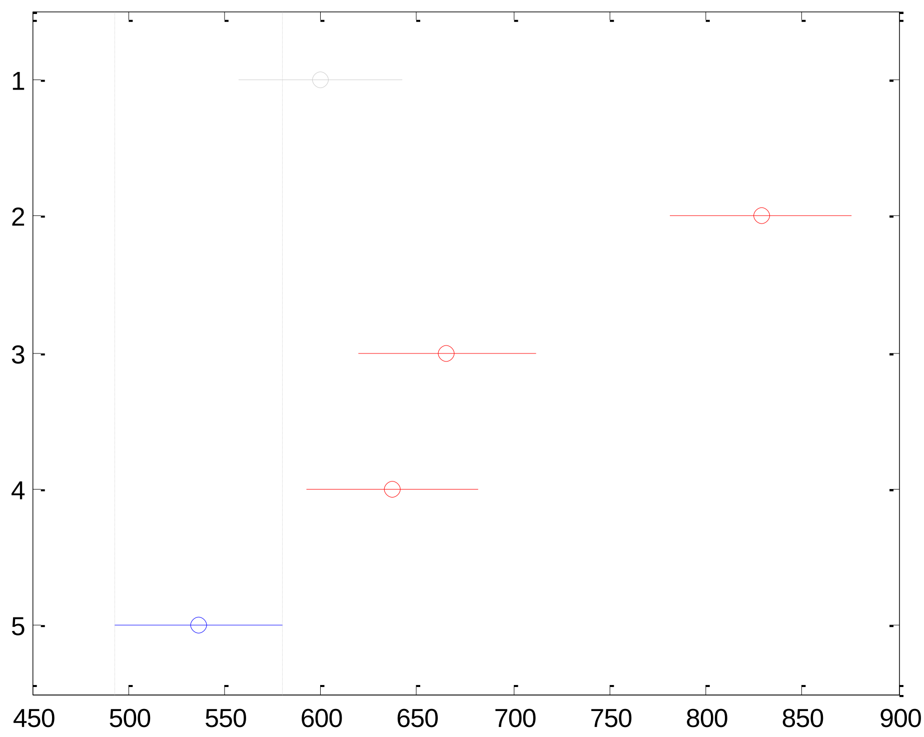

Figure 17. Post-hoc for the different households with the different households on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to household A, B, C, D, and E in that order on the Y-axis. The median rank is on the X-axis and red marker means significantly different from the blue marker and grey marker means not significantly different from the blue marker.

5.2 CO-emission data

The Kruskal-Wallis test was performed on the mean value, top value and the whole data set for the CO-emission for all fuel types to determine any significant differences. The CO-emissions curves for five different tests (chosen at random) are presented in Figure 18.

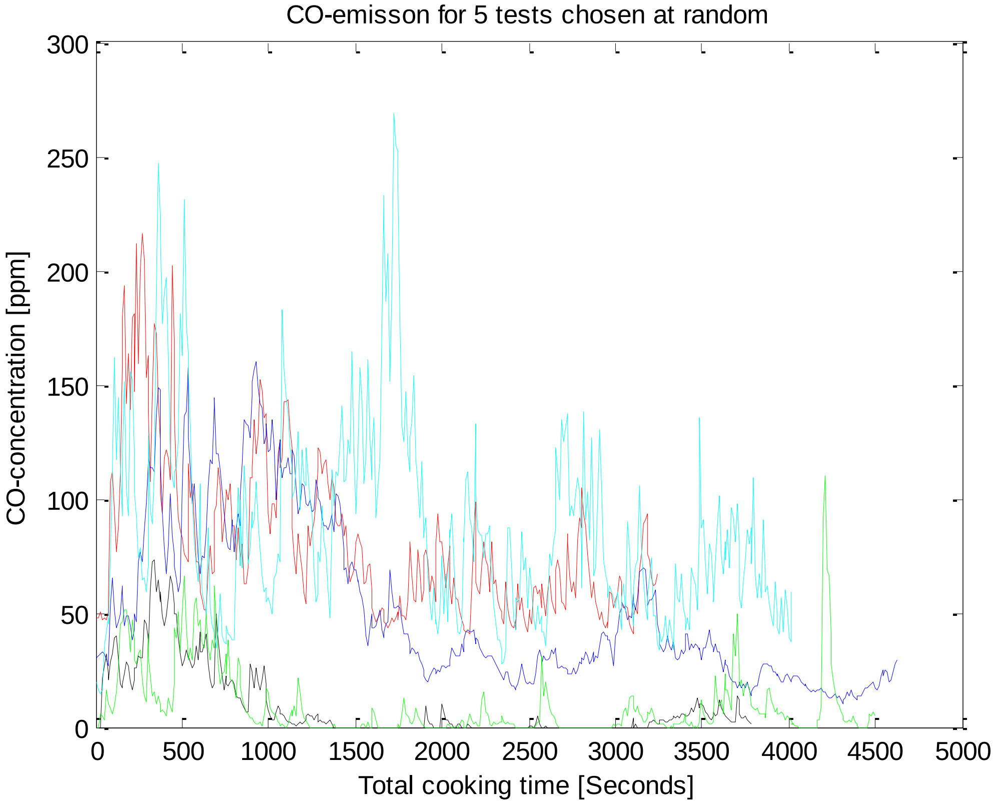

Figure 18. CO-emission curves for five cooking tests chosen at random. 1 step in the x-axis represents 10 seconds.

5.2.1 Comparison of the mean value of CO-emission for each cooking test

There were no significant differences in mean values (one mean for each cooking test) for the different types of fuel. No significant difference was found between the different households mean value of CO-emission during the cooking test. As the box plot in Figure 19 presents Household B seems to have a higher median than the other households.

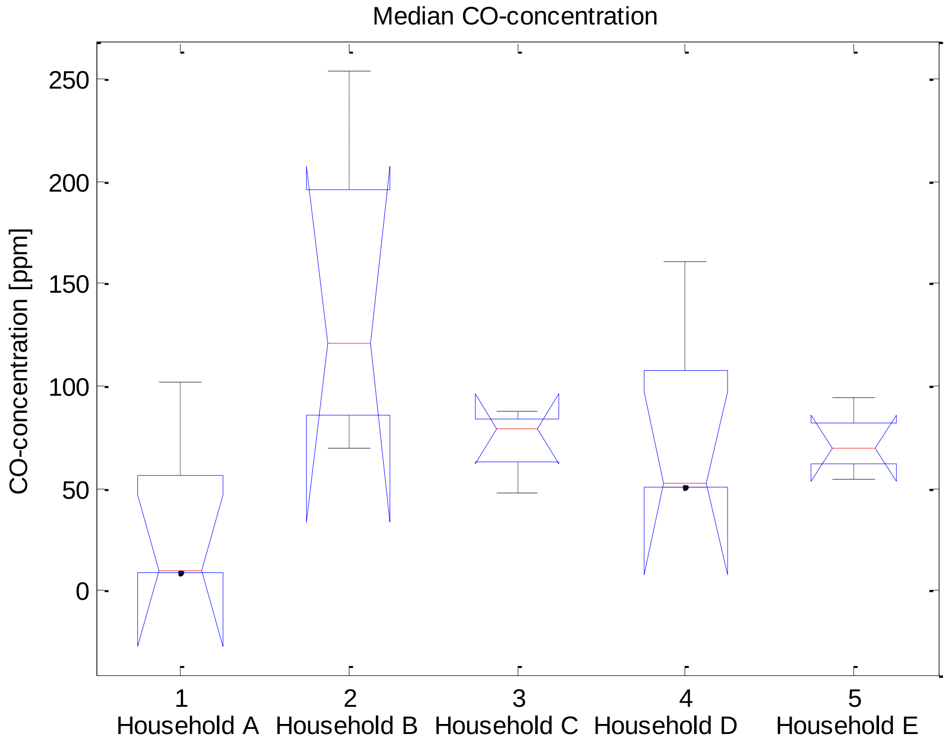

Figure 19. Box plot showing the median for each household (in red), the 25th and 75th percentiles (in blue) and max and min value (in black).

5.2.2 Comparison of the top value of CO-emission for each cooking test

The top values for the different fuel types are displayed in Figure 20. There is a significant difference between the top values of charred coconut husks and charred maize cobs which can be seen in Figure 21.

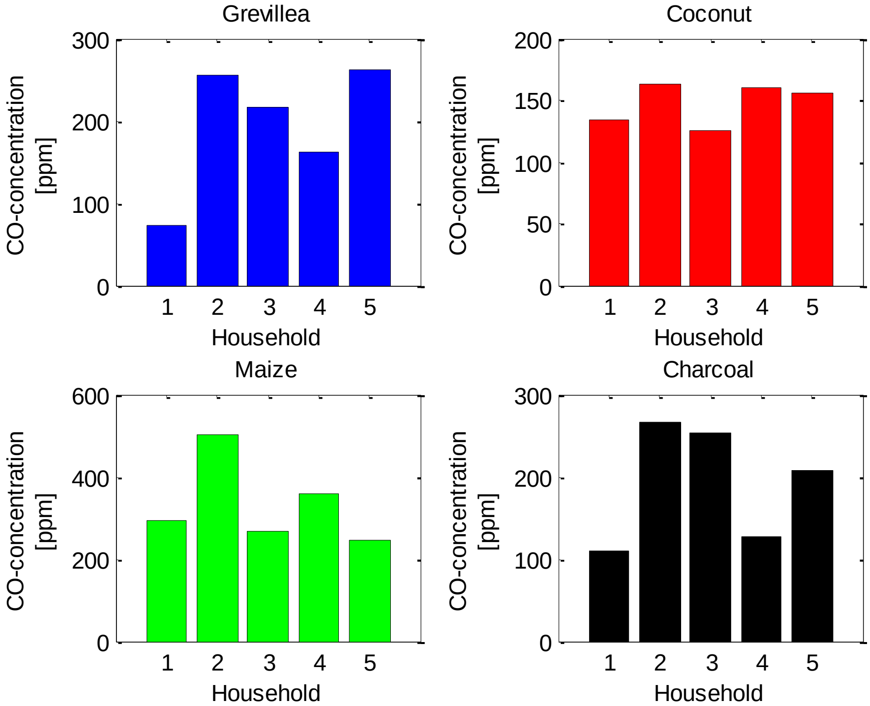

Figure 20. Top value for the different types of fuel, each observation corresponds to the top value of one household.

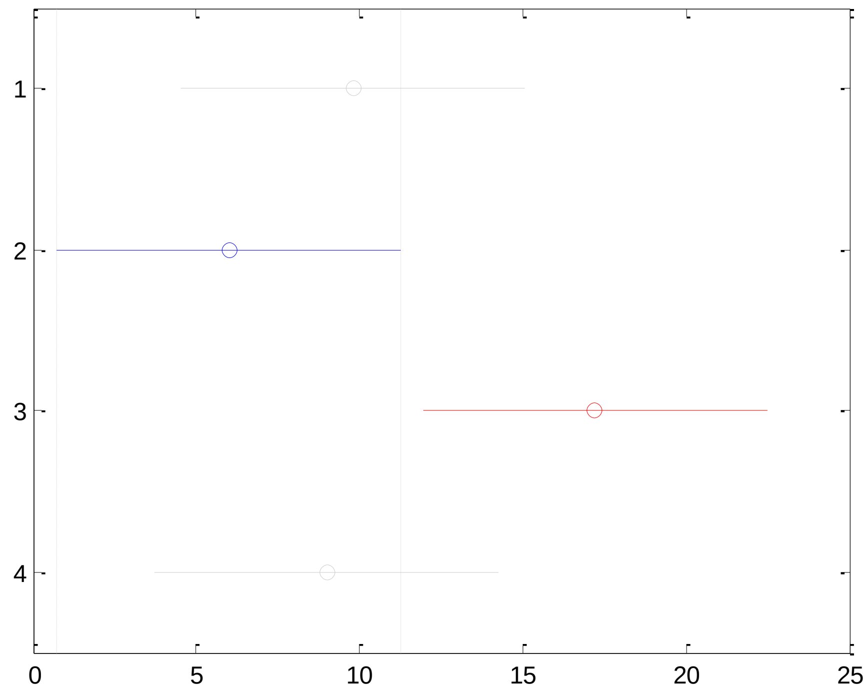

Figure 21. Post-hoc for the fuel types with the different fuel types on the Y-axis. Observation 1 represents Grevillea prunings, Observation 2 represents charred coconut husks, Observation 3 represents charred maize cobs and Observation 4 represents conventional charcoal. The rank value is on the X-axis.

There are no significant differences between the top values for the households. The top values for each household is presented in Figure 22.

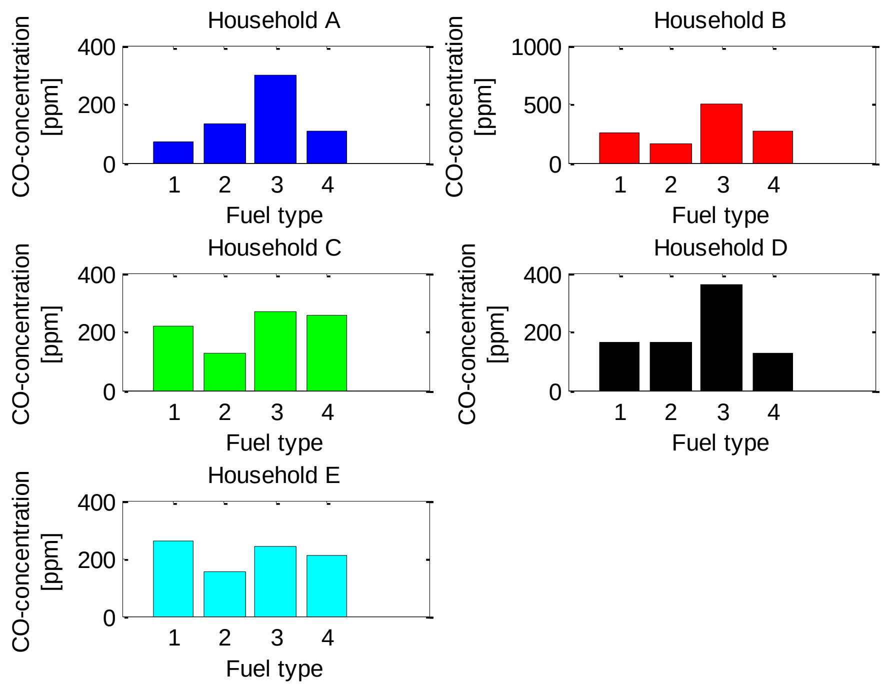

Figure 22. Top values for each household with observation 1 representing charred Grevillea prunings, observation 2 represents charred coconut husks, observation 3 represents charred maize cobs and observation 4 represents conventional charcoal.

5.2.3 Comparison of the complete dataset of CO-emission for each cooking test

There are significant differences between the different fuel types in terms of CO-emission levels. The CO-emissions have been presented for each fuel type in Figure 23. As the post-hoc shows in Figure 24 all the fuel types differ significantly from each other and charred maize cobs have the highest levels of CO-emission throughout the tests. This can be seen in Figure 23 where the green line is higher most of the time. The lowest CO-emissions levels throughout the tests are found when using charred coconut husks which are the red line in Figure 23.

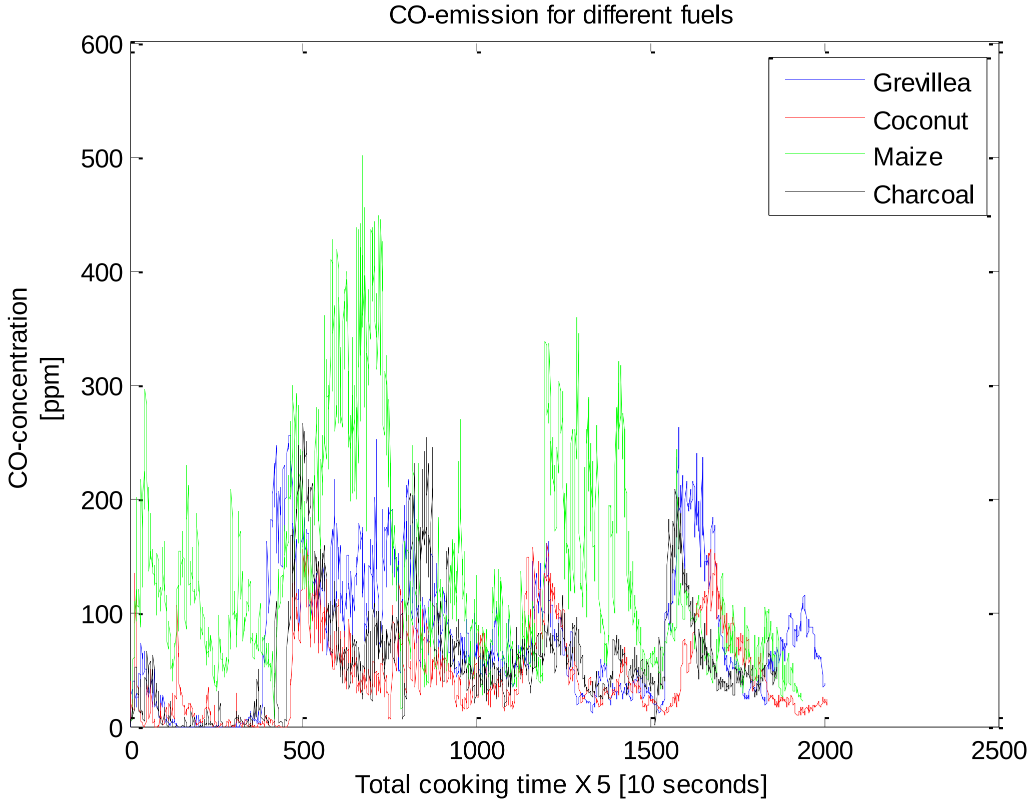

Figure 23. All the measurements taken during the cooking test are presented with the emission curves displayed in a row with household A first and household E last in alphabetical order. They are grouped after fuel type.

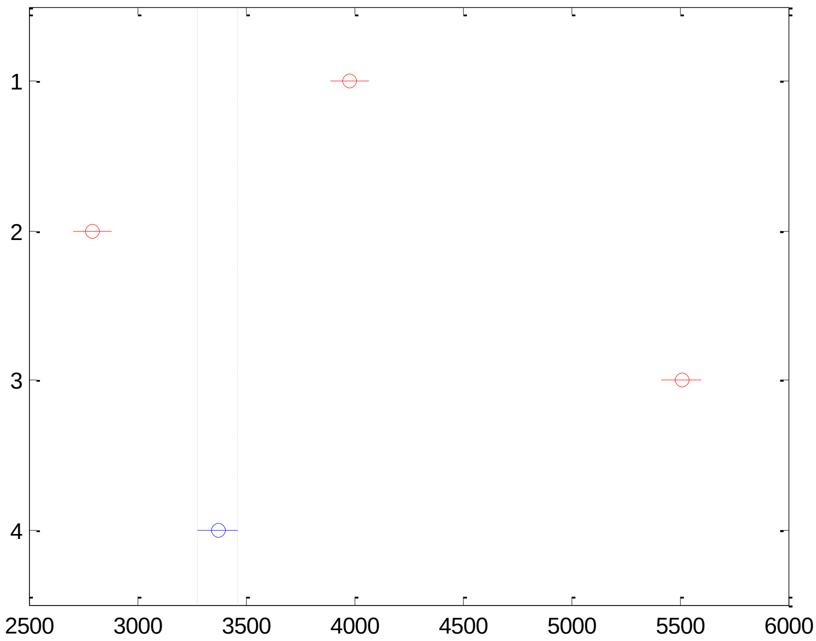

Figure 24. Post-hoc for the fuel types with the different fuel types on the Y-axis. Observation 1 represents Grevillea prunings, observation 2 represents charred coconut husks, observation 3 represents charred maize cobs and observation 4 represents conventional charcoal. The median rank is on the X-axis and red marker means significantly different from the blue marker and grey marker means not significantly different from the blue marker.

There are significant differences between the different households in terms of CO-emission levels which are presented in Figure 25. Household B has the highest levels of CO-emission independent of fuel type, which can be seen in Figure 26 and as the red line in Figure 25. Household A has the lowest levels of CO-emission which can be seen in Figure 26 and as the blue line in Figure 25. Household C and Household D are however not significantly different from each other, which can be seen in Figure 26.

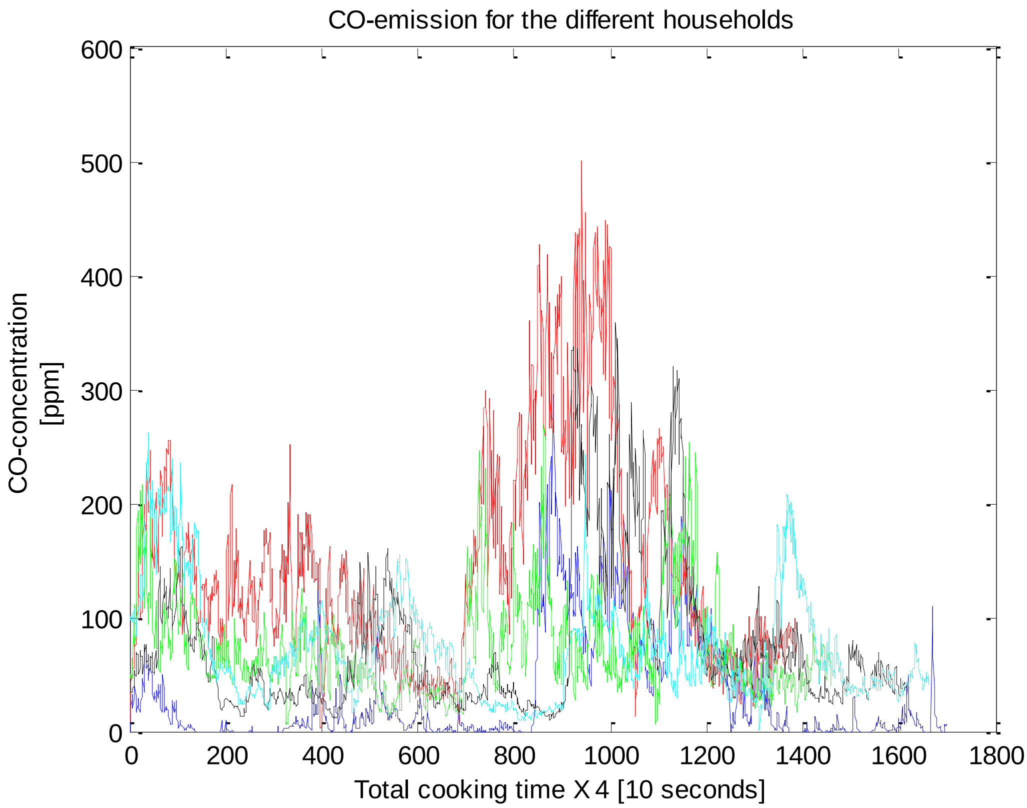

Figure 25. All the measurements taken during the cooking tests are displayed on a row with charred Grevillea prunings first, followed by charred coconut husks, charred maize cobs and lastly conventional charcoal. They are grouped after household.

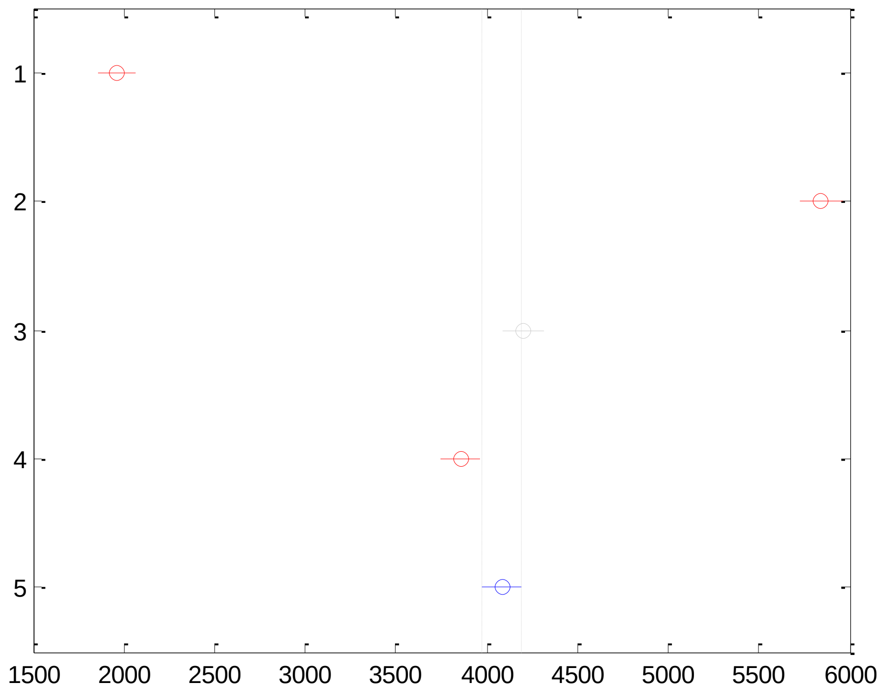

Figure 26. A post-hoc for the different households with the different households on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to household A, B, C, D, and E in that order on the Y-axis. The rank value is on the X-axis.

5.3 Comparing emission data for Trial 1 and Trial 2

The emission from the production of charred biomass (Trial 1) has been evaluated and compared to the emission data from the combustion of charred biomass (Trial 2). The purpose was to get an overview of the pollution associated with producing and using charred biomass for household cooking. The emission results from this thesis were compared to raw Grevillea prunings used as a fuel in two different types of stoves. The 3-stone-fire and the improved cooking stove that were used in Trial 1 were used for comparison and the data came from that thesis (Helander and Larsson, 2014).

5.3.1 Comparison of the mean value and the complete dataset for $PM_{2.5}$-emission

The mean value for each cooking test and stove type can be seen in Figure 27. The post-hoc in Figure 28 shows that the mean value for the charred Grevillea prunings was significantly lower than the improved stove with Grevillea prunings used as fuel (P=0.0005). The mean value for conventional charcoal was significantly lower than both for the improved stove and for the 3-stone-fire with Grevillea used as a fuel. Charred Grevillea prunings and conventional charcoal were used in Trial 2 in a Kenya ceramic Jiko stove.

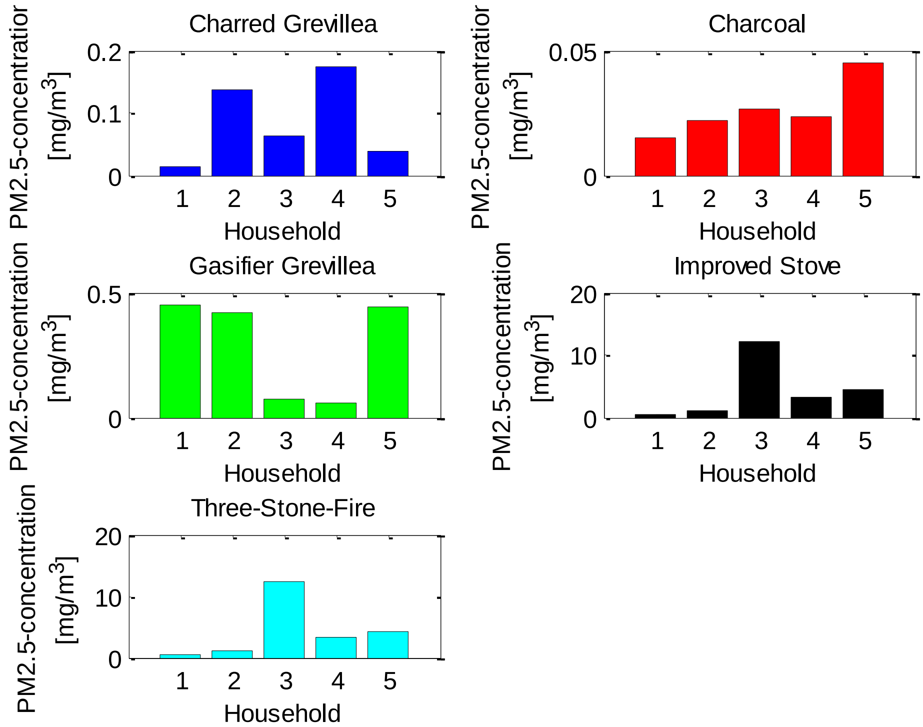

Figure 27. Mean value for the concentration level for each fuel and stove. The households are on the X-axis with number 1, 2, 3, 4 and 5 corresponding to household A, B, C, D and E in that order.

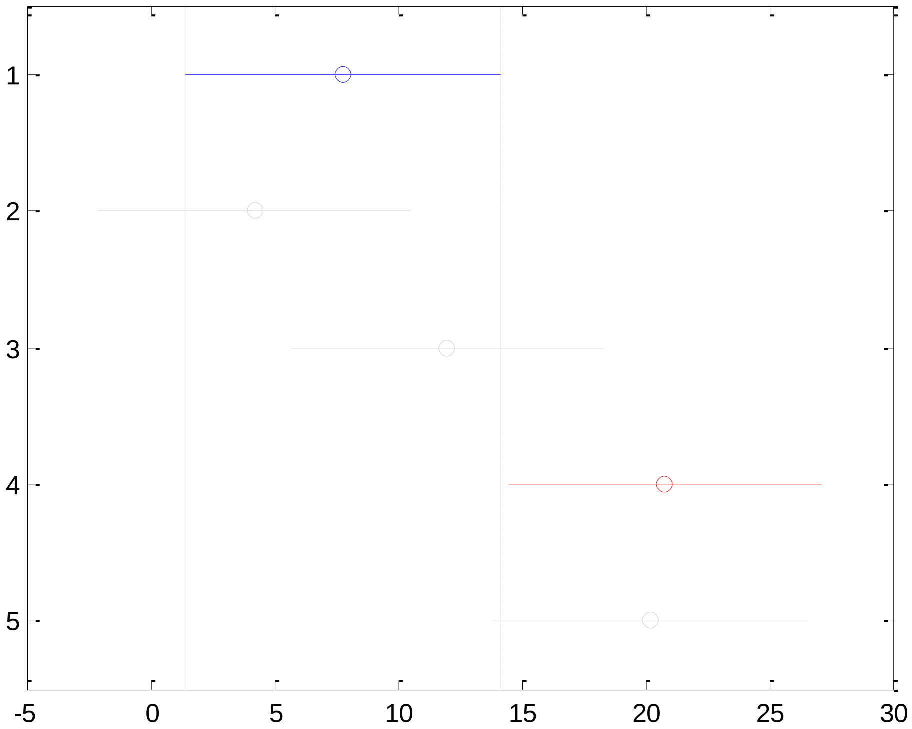

Figure 28. Post-hoc with the different stoves and fuel types on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to charred Grevillea prunings, conventional charcoal, gasifier with Grevillea prunings, improved cooking stove with Grevillea prunings and 3-stone-fire with Grevillea prunings in that order on the Y-axis. The rank value is on the X-axis.

The improved cooking stove and the 3-stone-fire had high emission levels and there were no significant differences between them, but there were significant differences between them and the others. The charred Grevillea prunings and conventional charcoal had low levels and no significant differences between them, but there were significant differences between them and the others. The gasifier with Grevillea prunings was significant different from all other stove types and had emission levels between them. This can be observed in Figure 29.

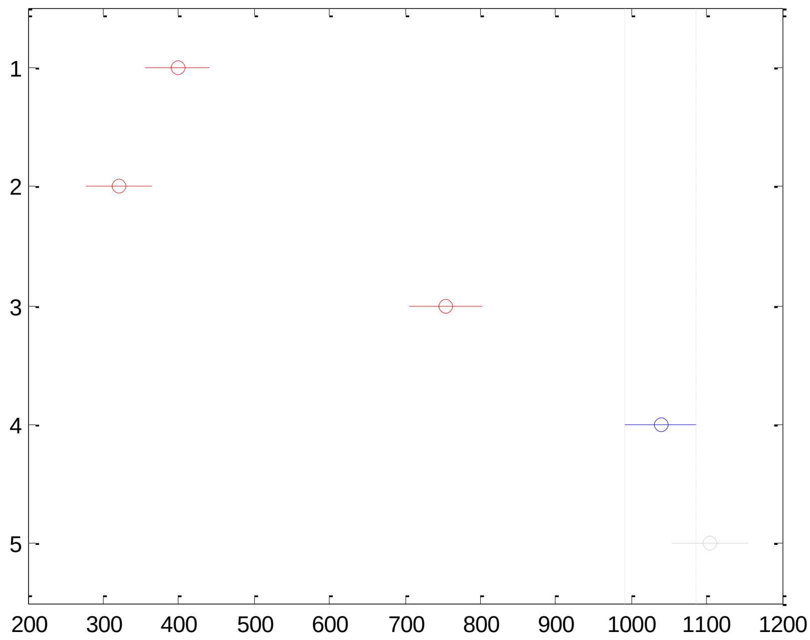

Figure 29. Post-hoc with the different stoves and fuel types on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to charred Grevillea prunings, conventional charcoal, gasifier with Grevillea prunings, improved stove with Grevillea prunings and 3-stone-fire with Grevillea prunings in that order on the Y-axis. The rank value is on the X-axis.

5.3.2 Comparison of the mean value and the complete dataset for CO-emission

The mean value for each cooking test and stove type can be seen in Figure 30. The mean value for charred Grevillea prunings and conventional charcoal were high and were not significantly different from each other. Charred Grevillea prunings and conventional charcoal were significantly higher (P=0.0225) than raw Grevillea prunings used as a fuel in the gasifier (Figure 31).

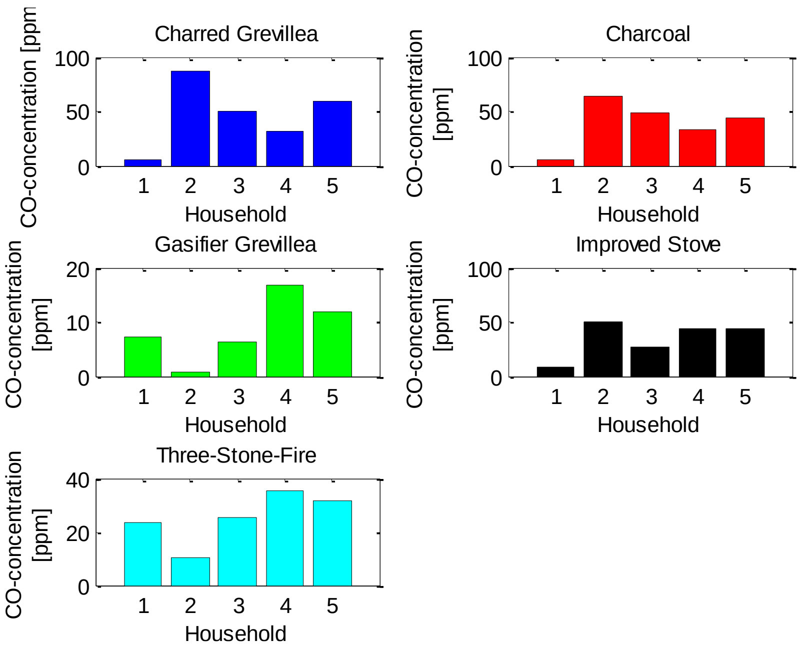

Figure 30. The mean value for the concentration level of each fuel and stove. The households are on the X-axis with number 1, 2, 3, 4 and 5 corresponding to household A, B, C, D and E in that order.

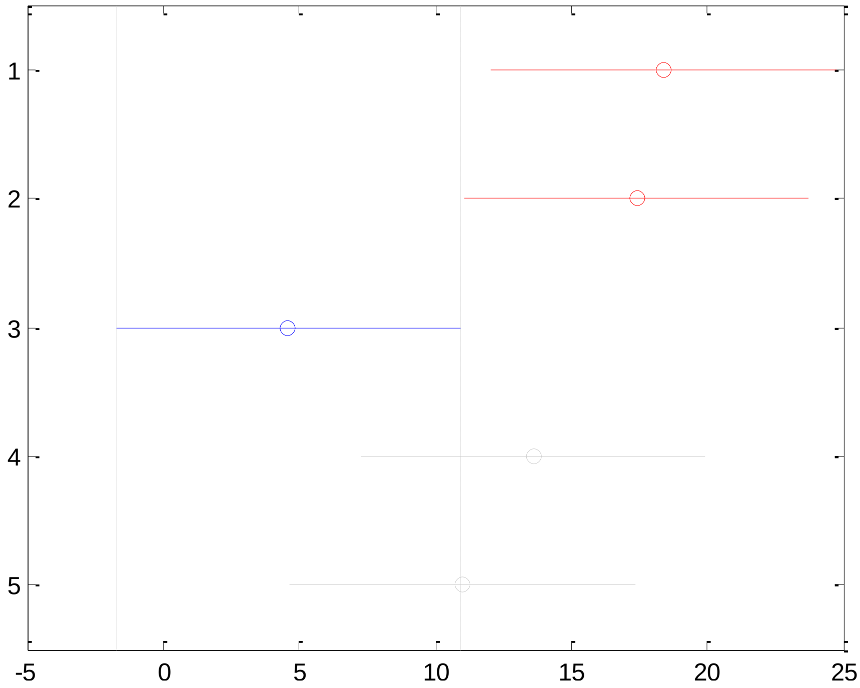

Figure 31. A post-hoc with the different stoves and fuel types on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to charred Grevillea prunings, conventional charcoal, gasifier with Grevillea prunings, improved stove with Grevillea prunings and 3-stone-fire with Grevillea prunings in that order on the Y-axis. The rank value is on the X-axis.

The emission levels were significantly different from each other for all except the improved stove and the 3-stone-fire. Charred Grevillea prunings and conventional charcoal had the highest emission levels and the gasifier had the lowest emission levels. This can be observed in Figure 32.

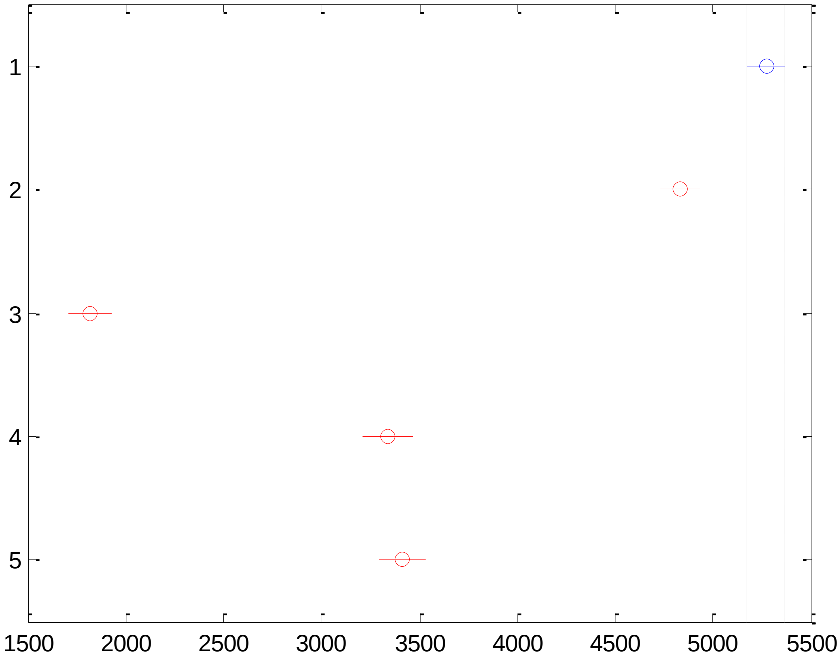

Figure 32. A post-hoc with the different stoves and fuel types on the Y-axis. Observation 1, 2, 3, 4 and 5 corresponds to charred Grevillea prunings, conventional charcoal, gasifier with Grevillea prunings, improved stove with Grevillea prunings and 3-stone-fire with Grevillea prunings in that order on the Y-axis. The rank value is on the X-axis.

6 Discussion

6.1 The energy use efficiency

Charred biomass proved to have higher energy use efficiency than conventional charcoal, but charred Grevillea prunings was the only one with significantly higher energy use (see Table 7). Charred maize cobs were almost equal to the conventional charcoal so it is uncertain if charred maize cobs are more or less energy effective than conventional charcoal.

Charred Grevillea prunings used 31 % less energy to cook a standard meal and the answer to why lies in the energy density of the different types of charred biomass and charcoal. The Kenya ceramic Jiko stove was filled up the same way independent of fuel and the energy density differed quite clearly between the different types of charred biomass and the charcoal. A similar starting volume, but 60 % less energy for charred Grevillea prunings compared to conventional charcoal and the mean power being quite low as well (1.98 kW compared to 3.06 kW) results in less energy used during the cooking test.

The stove was hot enough to cook a meal with all alternatives, but charred Grevillea prunings were the most energy efficient. Since all fuel types provided enough heat to cook food, the other fuel types produced too much heat compared to what was needed. Thus the one with the lowest power gave the highest energy use efficiency.

Charred coconut husks have almost the same energy density as conventional charcoal (8 % less than conventional charcoal) and the mean power is closer to the level of conventional charcoal (2.48 kW compared to 3.06 kW). This makes charred coconut husks more energy efficient (≈ 12 % less energy used per meal) than conventional charcoal, but not as much as charred Grevillea prunings, since charred coconut husks is more similar to conventional charcoal. Charred coconut husks had three refills (out of five tests) compared to conventional charcoal that had none (Table 2). This might indicate that the conventional charcoal was close to run out before the cooking test was finished, but considering how much charcoal that was left in the stove after every cooking test, this was not the case (Figure 5). Even for charred coconut husks it was not close to being finished after a cooking test, if you compare with charred maize cobs or Grevillea prunings. It was up to the farmers to decide when and how much they wanted to refill with. Some of the farmers probably refilled the stove just to be on the safe side instead of trying to be energy efficient and risk running out of fuel.

Charred maize cobs proved to be almost equal to conventional charcoal in energy use efficiency (≈ 2% lower than conventional charcoal) and the reason for this is the combination of the energy density (too low) and the mean power (2.82 kW, almost as high as conventional charcoal with 3.06 kW). This combination meant that the charred maize cobs burned faster and had a lower energy density which led to many refills (Table 2) compared to the other types of charred biomass. Even with many refills, the amount of charred maize cobs left in the stove was low at the end of the cooking test (Figure 5). The different behavior in heat radiation is probably due to the structure of the charred biomass. Charred maize cobs were lighter and had a higher porosity compared to the other charred biomass, which might be a reason to why it burned faster than charred Grevillea prunings. Coconut husks and conventional charcoal had a higher density, which also would lead to a faster burning rate since more material can burn. Charred Grevillea prunings had a low density, but a more solid structure with less pore space and thus having lower air circulation. Less air circulation would give a slower burning rate.

The largest benefit with producing and using charred biomass is when its energy balance is evaluated. This way of using the gasifier to cook food and produce charred biomass and then using the charred biomass to cook food lowered the amount of energy used per cooked meal. Using Grevillea prunings as an energy source, the energy cost is 30.7 MJ per cooked meal when a traditional 3-stone-fire is used compared to 18.4 MJ (gross fuel) and 16.1 MJ (net fuel) per cooked meal when a gasifier stove and a Kenya ceramic Jiko is used. Compared to the improved cooking stove the combination of a gasifier stove and the Kenya ceramic Jiko had lower energy use per cooked meal compared with the improved cooking stove, which used 24.7 MJ per cooked meal. Cooking with the gasifier stove requires some effort, since the charred biomass has to be harvested during the cooking process.

Cooking one meal with the gasifier stove provided enough charred biomass to cook a meal except when maize cobs were used as a feedstock (Table 7 and Table 2) where only an average of 317 grams of charred maize cobs was produced and the average amount of charred maize cobs needed for a meal is 381 grams. The rate at which energy is released from the Kenya ceramic Jiko stove during these tests (1.98 kW- 3.06 kW) is reasonable compared to how a modern 2 kW single electric stove plate performs in terms of power (Komplett.se).

Although this new way of cooking food saves energy it might not be appreciated by the farmers since they use the excess heat as indoor heating and in some cases they burn fuel just to heat some water and the room. This comfort heat will not be as much as it would have been if a traditional way of cooking was used, since the heat from the stove is enough to cook the food, but maybe not enough to heat the space of the kitchen as well. The impact and need of this indoor heating has to be evaluated and assessed since the farmers might turn this way of cooking down just because of the lack of indoor heating.

6.2 Cooking time, bulk density and energy density

The mean cooking time for each fuel was quite similar to each other, 65-66 min for the different types of charred biomass and 62 for the conventional charcoal (Table 13). Considering that conventional charcoal radiates more heat than the different types of charred biomass and that it never required adding of fuel, this result is reasonable. Every time fuel was added to the stove the temperature dropped, but with conventional charcoal the stove was warmer and the heat level more constant, since it did not require refilling of fuel. This would explain why charred maize cobs took longer time to cook the food than conventional charcoal did. They were quite similar in terms of power (2.8 kW and 3.04 kW), but charred maize cobs needed at least two times of adding of fuel compared to conventional charcoal that did not need it at all.

Comparing the total cooking time of the different households to each other, the difference is quite clear between Household B having a mean cooking time of 53 minutes and Household E having a mean cooking time of 70 minutes (Table 14). This was however not significantly different and the reason might be too few data points (only 4 values for each household). The time being quite similar to each other when comparing the fuel types, but not the households indicates that the individual cooking style affected the cooking time more than the type of fuel used. When comparing the individual dishes against each other, the variation was greater when cooking Ugali than when cooking Sukuma Wiki. This is probably due to the households having a different approach to how Ugali should be cooked. Household A always aimed to cook the Ugali for 30 minutes, whilst Household B and Household C cooked their Ugali for 9-10 minutes on average (Table 16, Dish 1).

The bulk density was quite similar for charred coconut husks and conventional charcoal, indicating that they might be quite close in energy density as well, which they were when the calorific value from the lab test were used to calculate the energy density (Table 6). Charred Grevillea prunings and maize cobs, however, had quite low energy density with around one third the energy density of conventional charcoal. A lower bulk density would also mean that the transport cost for charred Grevillea and maize cobs would be higher since a truck filled with charred coconut husks would have a higher energy value compared to a truck filled with charred Grevillea prunings or maize cobs.

6.3 Emissions

The different households and the different fuel types were compared to each other. This meant that there were five observations for each fuel type and four observations for each household. This might have been too few observations to find significant differences between either the different fuel types or the different households. Even though it was hard to find any significant differences some indications were found. Household B had for example always the highest mean rank in each test and the emissions of charred maize cobs always had a little higher mean than the other fuel types. This was clear when the all the emission measurements were used for each test instead of the mean emission level for each test. The emission curve for each fuel type and household could then be evaluated and the test got more data points to work with so it was easier to find a significant differences.

Only the $PM_{2.5}$-emission levels and CO-emission levels were evaluated with Kruskal-Wallis, since the CO_2-emissions lacked data (missing 2 tests out of 20). CO_2-emission levels obtained in this study were instead compared to the considered dangerous levels of CO_2-emission to see if it was dangerous or not to cook with charred biomass. Out of these emission types, CO_2 is the least important to monitor since the concentration levels have to be abnormally high to be dangerous to human beings. The levels presented in Figure 7 are very low compared to what would be considered as toxic or unhealthy levels of exposure. The maximum level of concentration is around 900-1 000 ppm (Figure 7), which is completely safe since the guidelines are set to 10 000 ppm for 8 hours of exposure (Minnesota department of health, 2013). It would, however, have been interesting to monitor the CO_2-levels out of global warming perspective since it is a greenhouse gas.

6.3.1 PM-emissions

There was a significant difference between the different fuel types, but the post hoc was not able to detect which one. Looking at the variation of the different fuel types in Figure 10 it is likely that the significant difference was between charred maize cobs and conventional charcoal. This was probably because the post-hoc uses the median between the groups to find a significant difference, while Kruskal-Wallis uses the mean value between the groups. This indicates that charred maize cobs have a higher $PM_{2.5}$-emission level compared to the other fuel types. When looking at the top values of each fuel type, there were no significant differences, but this is probably due to too few data points. Figure 12 show that conventional charcoal had lower emission tops since its 0.5 mg/m^3 was its top value while charred Grevillea prunings reached levels of 5 mg/m^3.

When all the measurements were used for comparison between the different fuels, there were no significant difference between charred coconut and conventional charcoal (quite low levels). There are significant differences between charred maize cobs and all other fuel types (Figure 15). Charred Grevillea prunings had significantly higher emission than charred coconut and conventional charcoal and significantly lower emission than charred maize cobs. This is a clear indication that the emission curve of charred maize cobs reaches higher levels of $PM_{2.5}$-emission more often than for other fuel types. This is also graphically presented in Figure 13 where the oscillations for charred maize cobs are more frequent and reach higher levels more often than for the other types of fuel. Most of the particles were emitted during the beginning of the combustion and since charred maize cobs required adding of fuel more often it would emit more particles. The emission levels from charred Grevillea prunings shows a mean rank closer to conventional charcoal and charred coconut husks than to charred maize cobs.

The mean value of the $PM_{2.5}$-emission obtained during the cooking tests showed no significant differences between the households. This meant that no household accumulated more $PM_{2.5}$ in their kitchen than the others. Since the households only had 4 observations per household (compared to 5 observations for each fuel type) there might have been insufficient number of data points to find any significant differences. Household B and D reached higher values for the mean (Household B had almost 0.4 mg/m^3 compared to Household A that reached 0.05 mg/m^3), which indicates that there might be a significant difference, but there is not enough observations to confirm this.

When comparing the emission curves for each household to each other, a pattern can be found in the post-hoc and that is that Household B has a higher accumulation of $PM_{2.5}$ compared to the others. Household E had the lowest mean rank and was significantly different from Household C and D as well as Household B. Household A was not significantly different from any household except Household B. The emission levels in Household A were somewhere in between the other households emission levels except for Household B. This can be seen in Figure 16 as well, but not as clearly as the post-hoc shows it in Figure 17.

The mean emission level throughout the cooking time over all tests for $PM_{2.5}$ was 76.3 $\mu g/m^3$. The recommended guideline is 25 $\mu g/m^3$ per day and this will not be exceeded since it took about an hour to cook each meal (World Health Organization, 2005). This cannot be considered a danger to the farmer even if you would consider that they cook food 2 or 3 times a day. The concentrations of $PM_{2.5}$ went down to normal levels quite fast as one can see in Figure 14 and the background levels were low.

6.3.2 CO-emissions

Comparing the mean CO-emission for each test shows no significant difference between the different fuels. This was probably because of insufficient number of observations since charred maize cobs seems to have higher mean rank (Figure 19), which is the same result as for the $PM_{2.5}$–emissions. Investigating the top value, gives us a significant difference between charred maize cobs and the charred coconut husks. Charred coconut husks has the lowest mean rank for the top value and charred maize cobs has the highest mean for top value (Figure 23).

When all the measurements obtained during the cooking tests were compared the result shows that all the fuel types differed significantly from each other. Charred maize cobs had the highest emission level, while charred coconut husks and conventional charcoal (in that order) had lower emission levels. The emission level for charred Grevillea prunings were somewhere in between. This means that the CO-emission curves for charred maize cobs reached higher levels more frequently and emitted more CO-emission than the other types of fuel. This can be seen in Figure 25 with the green line being higher than the other lines most of the time.

The mean value of the measurements obtained during the cooking tests had no significant difference between the households. This is also probably because of insufficient amount of data points, since Household B probably has a higher level of CO-emission (Figure 19). When comparing the top values for the different households, no significant difference is detected. We can however see a slightly higher mean rank for the top value of Household B (Figure 22) compared to the other households which again indicates that this household accumulates more emissions, in this case CO.

When comparing all the measurements obtained during the cooking tests for each household, the result is that Household B shows significantly higher mean rank than the other households and Household A has the lowest mean rank (Figure 26). The other three households are more similar and have mean ranks between Household A and B. This pattern can also be seen in Figure 25 where the red line (Household B) is more often higher than the others and the blue line (Household A) is more often lower than the others.

The mean exposure to CO-emission when cooking with a gas stove is between 5 and 15 ppm and symptoms such as headaches, nausea etc. start to show above 70 ppm if the exposure is for longer than 3 hours (EPA, CO, 2013). Since the cooking is only done for about an hour this is not noticed even though charred maize cobs had levels above 100 ppm. In the beginning of the cooking the water is heated to boiling temperature for about 20 minutes and it is usually left to heat in an empty kitchen. The emissions are the highest in the beginning which can be seen in Figure 18 for the 5 random cooking tests. It is only charred maize cobs that show higher values throughout the test since it requires refilling. Even though the CO-concentration is not dangerous it is still harmful compared to an ordinary gas stove that has levels around 5 to 15 ppm.

6.3.3 Comparison of emission data from Trial 1 and Trial 2

The emission levels from the production of charred biomass (Trial 1) and the combustion of charred biomass (Trial 2) were compared against each other. The comparison was made so that the complete chain from production to use of charred biomass could be evaluated in terms of emission levels. When looking at the $PM_{2.5}$-emission levels we can see that Trial 2 has lower values. This means that fewer particles are emitted when combusting charred Grevillea prunings instead of the raw material. This is something we can be certain about, since the same equipment was used for Trial 1 and Trial 2. The reason to why fewer particles were emitted could be that the lighter particles that were more likely to spread did that during the first combustion process.

The CO-emission levels did not follow this pattern and Trial 2 had higher levels than Trial 1. The reason for this is the change of CO-monitor. The CO-monitor that was used during Trial 1 and in the beginning of Trial 2 had to be changed due to the monitor's expiration date. This was the guarantee date of the monitor and the measurement done after that date would not be scientifically valid. Both monitors were used during Trial 2 even though the first one was expired, to see if there was any impact of the change or not. The measurements for two cooking tests were compared and the differences in mean CO-concentrations between the monitors were 49 percent higher for one of the tests and 74% higher for the other test that was compared.

The new CO-monitor registered around 50-70 percent higher emission levels which might be a reason to why the CO-emission levels were higher for Trial 2. When the CO-emission levels from the new monitor were divided by 1.6 in order to make it comparable with the measurements by the old monitor and the significance test was performed again, the results showed no significant differences between the trials.

The mean CO-emission for the charred Grevillea prunings and conventional charcoal were lower, although not significantly, than the mean CO-emission for Grevillea prunings in the other stoves. When performing the significance test with all the measurements and not the mean values, the charred biomass and conventional charcoal still had significantly higher values, but not with as much distance.

It is difficult to say if the values are in fact higher for charred biomass and conventional charcoal or if the change of monitor is the reason for this effect. It could be that the levels were higher for Trial 1 and it would have been detected if a fresh monitor would have been used. Due to the change of CO-monitor and the fact that the monitors measured different values for the same cooking test, no conclusions can be drawn in the comparison of CO-emissions between the different trials.

6.4 The execution of the project

The farmers were the ones to cook the food, so that the results obtained would represent how a typical farmer would cook the food. This is important since the aim is to make the results of the master thesis applicable to a realistic environment, so that the master thesis can be used as a guideline if these gasifiers are implemented in the future. This might not have been fully achieved since they were cooking in an unusual situation. They had to cook the same dishes for each test and they might not have wanted to cook those particular dishes that day. Some of the households started cooking food again after the test for their own use and this could have been for several reasons, such as the ones mentioned above.

The impact that these elements of uncertainty had on the result is difficult to assess, but if the purpose of the trial would be to compare the different fuel types against each other, then more repeatable results could have been obtained by having the ones performing the study to also cook the food at all the locations. Then the cooking style of one person would be used for all 20 tests and the use of fuel and time might had been more uniform.

The farmers were often the ones cooking the meal, but sometimes Ms. Njeri or the author had to step in and cook if they were not able to do it themselves. The reasons could be that they had to work that day and we could only borrow their kitchen for the day or that they had some matters to handle for the moment and needed us to help out with just a part of and not the whole cooking process. This made the cooking process less uniform for that particular household, since they would cook for the whole process during the next test. When this happened it was recorded in the field work sheet. This affected the cooking time since we might have cooked the food for longer or shorter than what the farmer would have done. Each household had their own way of cooking Ugali (Dish 1) and it was hard for us to imitate how each farmer would have cooked the food. This also affected the number of times fuel was added since this also is something that everyone does in their own way. Some might add a lot of fuel just to be safe (and there would be a lot left in the stove) and some might take a risk and believe that what they have in the stove will be enough to finish the cooking process. Some of the variation is natural since cooking is not a precise procedure and usually varies from time to time.

A good thing with cooking in different households and with different farmers cooking is that the variation that would occur due to variation between households if charred biomass was used widely is included in the study. This has its own value since it might be difficult to estimate how much it can differ between households and different kitchens. For the results to show this more clearly more households should have been included in these trials. This was not possible, due to the limited amount of time and resources.

A recommendation is the use of two different pots for cooking the dishes since Ugali needs a thicker pot so as not to burn. We had to change the pot after a few tests because otherwise the pot would have a hole in the bottom from all the scrubbing to get it clean. The change of pot did probably not affect the outcome of the results, but made the cleaning of the pots easier and we did not need to risk burning through the pot. This would also mimic the way the farmers cook better since they all told us that the first pot was too thin to cook Ugali.

When the farmers were chosen to participate in the project they were informed about the purpose of the study and the importance of the measurements done during the trials. It was important that the farmers included in the study were aware of the sensitivity of the equipment used and the importance of exact measurements. Another briefing of the farmers should have been done before the start of Trial 2, since the time between the end of Trial 1 and the start of Trial 2 was longer than expected. This might be a factor to why the initial information was not enough or was forgotten by the farmers.

6.5 Future projects and implementation of the gasifier

Future projects should investigate other types of feedstock like the eucalyptus tree or another fast growing tree. The use of rice husks or coffee husks are also of interest since they are common byproducts in Kenya like the coconut husks, which could become an important energy source instead of waste. The problem with rice husks and coffee husks is probably their size since it was preferable with larger pieces of charcoal than the small ones like maize cobs that fell through the stoves grate. If they are to be used then they should be produced as briquettes. I also recommend inquiring among the rural farmers if indoor heating is crucial and important for their choice of cook stove. If this is an important factor, then the gasifier and the charred biomass might not be considered worth the reduction in fuel consumption.

Another thing to evaluate would be what types of dishes or meals the different charred biomass are best suited for. Since charred maize cobs needs so much refilling to cook these two dishes, it might be better suited for cooking a fast breakfast or just boiling water for tea or coffee. They might also be better suited for other energy needs than cooking, for example heating or drying. This master thesis has assessed the properties of the different fuel types, but not the best way of utilizing them.

The use of maize cobs as a feedstock was inconvenient in many ways. It was the most difficult to light when using the gasifier and when the lighting failed, heavy smoke came from the gasifier, which was really unpleasant in comparison to when the other types of feedstock failed. The charred maize cobs where sometimes in so small pieces so that it fell through the grate of the Kenya ceramic Jiko stove, which led to a loss in fuel. Smaller holes would be a solution, but considering that the goal is to use a stove that is already on the market, then this is a problem that is not easily fixed.

A good instruction pamphlet is recommended when implementing the gasifier stove and the idea of harvesting the charcoal, which clearly states why it has to be put to cool in an oxygen free container. If there is a hole somewhere in the container then there is a risk that the combustion of the biomass will continue and it will not cool down. Explaining why addition of fuel should be kept to a minimum is also good information to pass on to the villagers. A lot of the emissions were emitted when cool fuel was added to the already hot fuel and thus lowered the temperature. Lowering the temperature would also result in a longer than necessary cooking time. Lighting of the stove should be done outdoors because of the high level of emissions connected to the beginning of the cooking tests. Otherwise the charred biomass itself should be handled like conventional charcoal and be stored in a dry place.

A recommended time of cooling of the charred biomass should be included in the pamphlet, since it could be dangerous to store charred biomass that has not cooled down enough with already cooled charred biomass. The whole amount of charred biomass could then catch fire and start the combustion process again. If mass production of charred biomass would be attempted then the cooling should be spread out, since too much charred biomass together might not cool even though a long time has passed. So the charred biomass should then be separated into several different cooling containers.

Since the household's emission curves differed from each other during this trial (Household B had higher levels) some work could be done in informing how a kitchen should be built and how the ventilation (just holes really) might be constructed so as to reduce the emission that these farmers are exposed to. The kitchen area differed between the households, which also could be a reason for the difference in emission between the households. The equipment measured concentration levels, which would be affected by the change in volume of the kitchen (larger space would lead to lower concentration). We could see that even though it was not proven with statistical significance that Household B had higher levels throughout the trial, it was always higher when compared to the other households in terms of both $PM_{2.5}$- and CO-emissions. This is under the assumption that the ventilation is the reason to these high levels in Household B. A reason could be that different cooking techniques would affect the emission levels, but Household B had a lower cooking time (Figure 11) and still had higher emission levels.

7 Conclusion

The overall conclusion is that the different types of charred biomass performed well or equally well compared to the more energy dense conventional charcoal as a fuel. Using Grevillea prunings in combination with the gasifier stove and the Kenya ceramic Jiko stove will save up to 40 % energy compared to using the 3-stone-fire, which is a huge improvement in terms of energy efficiency. Since the cooking process for the studied fuels does not require the fuel quality that conventional charcoal offers, the different types of charred biomass give an overall more energy efficient fuel without any significant difference in emissions. This is confirmed by the cooking time being almost the same for all fuel types, but the power being lower for the different types of charred biomass. This will result in less use of energy and higher energy use efficiency, but a loss in indoor heating for the user.

The charred biomass have proven to be energy dense enough for cooking a whole meal, although charred maize cobs requires a couple of refills more than the others and cooking one meal with a gasifier and maize cobs will not yield enough charred maize cobs to cook a second meal. This makes it a less valuable fuel considering overall preferences. It had higher emissions (although not significantly for most cases) especially the CO-emission levels which was 10 times higher than the average for homes with gas stoves. This makes charred maize cobs the least attractive of the different types of charred biomass to use as a fuel, but still worth using if available. Charred coconut husks had the lowest emission levels of all fuel types. Conventional charcoal had higher emission levels than charred coconut husks and lower emission levels than charred Grevillea prunings. This is the case for all fuel types and the CO-emission. There was no significant difference between conventional charcoal and charred coconut husks in $PM_{2.5}$-emission.

Comparison of the emission levels of Trial 1 to the emission levels of Trial 2 can only be done in terms of $PM_{2.5}$-emission. We can conclude that less particles are emitted when the charred Grevillea prunings are used instead of the raw material. It is not possible to make any conclusions on the CO-emissions since different monitors were used in Trial 1 and Trial 2 (although they were of the same type and brand). The results show that charred biomass from these feedstocks are useable to cook by the farmers in rural Kenya and that they are competitive to conventional charcoal when used as a fuel in terms of energy efficiency.

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8.4 Information obtained over e-mail

Jonas Bertilsson, salesman, Pentronic AB, jonas.bertilsson@pentronic.se, email conversation.

Appendix A1

Template for fieldbased cooking test

Test number:

Date:

Name and number of household:

Data of fieldbased performance test			Data of food cooked		
PARAMETERS	**Units**	**Test 1**	**Dish 1 Weight of pot (g):**		
Start weight of fuel (not gas..)	g		**Ingredient**		**Amount (g)**
Start time lighting	time		1	Maize Flour SOKO	
Start time of cooking (T1)	time		2	Water+ pot	
Boiling time	time				**Amount (milli)**
Time to boil (boiling time-T1)	min			Water used	
Finish time (F1)(cooking)	time		Dish 1 start time (cooking)		
Time Taken to cook (F1-T1)	min		Dish 1 finish time(cooking)		
Weight of fuel left unused	g		Total cooking time Dish 1 (min)		
Weight of fuel left in stove	g		Weight of dish 1 + pot (g)		
Moisture content:			Weight of Dish 1 minus cooking pot (g)		
Times of adding of fuel (time)			**Dish 2 Weight of pot (g):**		
			Ingredient		**Amount (g)**
			1	Kale	
			2	Tomatoes	
Temperature of flames (time)		**C°**	3	Onion	
			4	Salt	
			5	Fat	
			6		
			Dish 2 Start time (cooking)		
			Dish 2 finish time (cooking)		
Average temperature			Total cooking time Dish 2 (min)		
			Weight of Dish 2 + pot (g)		
			Weight of Dish 2 minus cooking pot (g)		
Summary					
Time taken to light the stove	min				
Total time taken to cook Dish1 and Dish2	min				
Total fuel used including what is left in the stove	g				
Total fuel used minus what is left in the stove	g				

Comments about cooking test

Appendix A2

The final list after all the wishes of the farmers was met.

1.	3 July	MARY MUTHONI	Grevillea
2.	4 July	JACINTA WAWIRA	Grevillea
3.	5 July	CECELIA GIKUU	Charcoal
5.	8 July	CECELIA GIKUU	Maize
7.	10 July	JACINTA WAWIRA	Coconut
8.	14 July	JACINTA WAWIRA	Maize
9.	15 July	CECELIA GIKUU	Grevillea
10.	16 July	JACINTA WAWIRA	Charcoal
11.	17 July	MARY MUTHONI	Coconut
13.	18 July	Edward	Maize
12.	19 July	MARY MUTHONI	Charcoal
14.	21 July	Mrs KARIUKI	Maize
15.	23 July	Mrs KARIUKI	Charcoal
6.	24 July	Mrs KARIUKI	Grevillea
4.	25 July	Mrs KARIUKI	Coconut
16.	26 July	MARY MUTHONI	Maize
14.	28 July	CECELIA GIKUU	Coconut

Appendix B1

Methodology of the laboratory where the samples were tested for calorific value, Moisture content, ash content, fixed carbon content and volatile matter. The experiment was done and compiled by Moses Elima Lukibisi at Kenya Forestry Research Institute Karura.

1.0 Introduction

Trees are an essential part of human existence. They provide numerous products and services, including: Fuelwood, timber, poles, human food, livestock fodder, medicine, soil conservation, live fences and fertility improvement. Kenyan farmers and pastoralists have long recognized the useful role of trees. E.g. Acacia, coconut, neem, prosopis and mangrove are some of the trees that are commonly used in the Coast Province.

2.0 Methodology

2.1 Determination Of Calorific Values

The wood samples were grounded in a grinder. One gram of the samples were weighed in duplicate and wrapped with a weighed tissue paper of a known calorific value then tied with an ignition wire (Platinum) of known calorific value. Both ends of the wire were connected to the bomb calorimeter electrodes (+,-) and placed in a bomb and firmly closed. 30kg of oxygen was led into the bomb and the bomb immersed into the cylinder filled with distilled water upto 2,100g. The bomb calorimeter was calibrated with Benzoic acid tablet of a known calorific value.

The following formula was used to calculate the calorific value of the samples:-

$$CV\ (Cal/g) = \frac{\text{Water equivalent (g)} + \text{Water quantity of inner Cylinder (g)} \times \text{Rise in temperature (°C)} - \text{Calorie Correction}}{\text{Quantity of Sample (g)}}$$

2.2 Determination Of Moisture Content, Volatile Matter, Ash Content And Fixed Carbon

The crucibles were reconditioned by putting them into a muffle furnace at $900 \pm 25^{o}C$ for 2 minutes. Then the crucibles were removed from the muffle furnace and then cooled in a desicator for 10 – 15 minutes and weighed to the nearest 0.1mg.

2.2.1 Determination of Moisture Content

1.000g of the samples was weighed into the crucible in duplicate and put into the oven for atleast more than 12 hours for determination of moisture content at $100 \pm 3\ ^{o}C$.

$$\text{Moisture Content} = \frac{\text{Initial weight (g)} - \text{Oven dry weight}}{\text{Oven dry weight}} \times \%$$

2.2.2 Determination of Volatile Matter

Then using the muffle furnace tongues, the crucibles were transferred into the muffle furnace, ensuring that the maximum clearance between 0.5mm and 1.00mm. The furnace door was then closed. After exactly seven minutes (from the time of inserting the crucibles into the muffle furnace) remove the crucibles, and they were put into the desicator to cool for about 15 minutes and re-weigh. Then the volatile matter were calculated using the formular below:-

Appendix B2

The P-value for the different Kruskal-Wallis tests performed in Section 5 to determine significant differences in emission levels.

The P-values for the tests that had significant differences in Section 5.

Emission type	Type of test	Fuel or Household(HH) that differ	P-value
$PM_{2.5}$	**Mean value**	**Not found**	**0.034**
$PM_{2.5}$	**All measurements**	**All except coconut husks and charcoal**	**1.13e-87**
$PM_{2.5}$	**All measurements**	**HH B from all other HH** **HH E from all except HH A**	**2.22e-17**
CO	**Top Value**	**Coconut husks and maize cobs**	**0.0213**
CO	**All measurements**	**All differ from each other**	**0**
CO	**All measurements**	**All differ from all except HH C & HH E**	**0**

The P-values for the tests that did not have significant differences in Section 5.

Emission type	Type of test	Fuel based or Household based test	P-value
$PM_{2.5}$	**Mean value**	**Household based**	**0.3815**
$PM_{2.5}$	**Top value**	**Fuel based**	**0.1164**
$PM_{2.5}$	**Top value**	**Household based**	**0.2888**
CO	**Mean value**	**Fuel based**	**0.0677**
CO	**Mean value**	**Household Based**	**0.1452**
CO	**Top value**	**Household**	**0.4002**

Appendix C1

The raw data for how much charred biomass and charcoal was used during the trial.

Type	Grevillea [g]	Coconut [g]	Maize [g]	Charcoal [g]
Household A	309	379	354	373
Household B	287	207	403	349
Household C	279	300	348	311
Household D	300	339	449	391
Household E	272	326	351	294

Appendix C2

Rawdata for bulk density test. The different fuel types were weighted in the filled container with known volume.

Type of charred biomass	Coconut [g] ± 1g	Grevillea prunings [g] ± 1g	Maize cobs [g] ± 1g	Charcoal [g] ± 1g
Test 1:	1193	624	436	1 216
Test 2:	1224	594	454	1 189
Test 3:	1143	587	434	1 285
Test 4:	1170	627	442	1 233
Test 5:	1210	612	439	1 252
Mean:	1188	609	441	1 235
Standard deviation:	28.82	15.92	7.04	32.47

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