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Review, Assessment and Development of Search Engine for Residential Wood Combustion

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Finnish Environment Institute (SYKE) is developing integrated assessment models systems and assessing the emissions of residential wood combustion and its effects on the environment. The emissions from residential wood combustion have several negative impacts on human health and environment. Mainly the health effect from particulate matter is higher than PCDD/F, PAH and carbonaceous compounds etc. The particulate matter with diameter less than 2.5-micron cause harmful effects on health. Experimental data were obtained from different countries varying with the appliances, fuel quality, combustion conditions and their operational practices. The aim of the project was to assess the collected data and develop a search engine for future uses.

The data was obtained from thirty-seven scientific articles and reports on experimental results of small-scale residential wood combustion and their emission factors in different countries. For uniformity, all units were converted to mg/MJ. Finally, the emissions factors were analysed using R software and Microsoft Excel. An R function is also prepared to assess the database for future uses.

The result showed that emissions from primitive appliances were significantly higher than those from modern appliances. The replacement of the old appliances and good operational practices resulted in the reduction of emissions to some extent. The ranking of used appliances was done by using Tukey test and mean aggregate in R and ranking was done on the basis of the significance level of eight emission factors. The search engine of assessed database was prepared in R programming language. The result of every emission factors was obtained by using the R function. Nevertheless, the results are affected by the measurement methods used in the experiments, some conversion factors and the accuracy of results as few measurements were knowingly done in poor combustion. The results obtained can be implemented for analysing emission factors with different appliances and to find good combusting appliances according to the emission level.

Keywords	Residential wood combustion, assessment, appliances

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I would also like to thank my friends and colleagues for their constant encouragement of my endeavours and support to uplift my thesis to success.
I love my family. This is dedicated to them.

List of abbreviations

CO	carbon monoxide
GC-MS	Gas Chromatography-Mass Spectroscopy
MMD	mass median diameter
GMD	Geometric mean diameter
NO	nitrogen oxide
OGC	organic gaseous carbon
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
RWC	residential wood combustion
TOC	total organic compounds
VOC	volatile organic compounds
IEA	International Energy Agency
BLPI	Berner low pressure impactor
DLPI	Dekati low pressure impactor
ELPI	electrical low pressure impactor
TSP	total suspended particles
St	stoves
S_S	sauna stoves
MH	masonry heaters
LB	log boilers
PB	pellet boiler
P_S	pellet stoves
NRWC	non-residential wood combustion
O_t	others
FP	fireplaces
C_S	cook stoves

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1 Introduction

In recent years researchers have done many studies in residential wood combustion (RWC), its emission factors, its effects on human health and environment, and the ways of reducing the emissions. Different combustion appliances have different level of emissions depending on the operational practices such as moisture content, kindling effect and wood species. For example, the pellet boiler is the best wood combusting appliance when it is supplied with wood with lower moisture content (< 6 percent). Previous studies have identified the appliances and operational practices which inhibit incomplete combustion and yield higher emissions and have suggested replacing them with those appliances and operational practices which have complete combustion with lower levels of emissions.

The use of wood as fuel for residential heating and cooking purpose has been practiced from ancient ages. Since 1980s, the study of emissions from wood and possibility for reduction of emissions has been topical issue. Experimental observations suggested that the PM emissions from residential wood combustion appliances are significantly higher than expected.

A considerable amount of research has been done for experimental analysis of emission factors. The experimental results have been presented in scientific journals, but the existing on RWC database was limited to only a few articles. However, this thesis has gathered and summarized the data from forty RWC's articles, published in scientific journals in between 1990 to 2012. The RWC's articles also contain a few small scale industrial wood combustion appliances.
The purpose of this thesis was to prepare a database for the recently published experimental articles on RWC. The appliances used in RWC and in some small scale industrial wood combustion have rated power below 50 kW. Some industrially used appliances with rated power are studied during this thesis. This paper compares the appliances on the basis of their emissions and ranks them

according to their emission levels. It also includes an R script that sources the main database and analyzes the emissions factors.
By analyzing the data of the emission factors with appliances, it is found that older appliances have a higher level of emissions than modern appliances. The ranking of results show that the modern appliances with best operational practices have the least emissions. The ranking of appliances on the basis of eight most important emissions factors will make it easier to select a suitable for appliance for wood combustion for residential purposes.

This paper is divided into six chapters, introduction included. The first section gives the introduction; the second section gives the theoretical background of wood combustion. The third section explains methodology for appliances; the forth section describes the search engine and its development; fifth section interprets the results and comparisons. Finally, the sixth section gives conclusion and discussion.

2 Theoretical background

2.1 Residential wood combustion

Residential wood combustion in indoor practices produces various amounts of air pollutants. Wood smoke reduces the quality of air. One important emission from residential wood combustion is the emissions of particulate matter. Particulate matter emissions cause health effects and climatic effect. The emissions differ with the types of appliances. Modern appliances have lesser emissions than the traditional appliances. The emissions contain various compounds such as nitrogenous compounds, particulate matter, carbonaceous compounds and large amount of carbon dioxide. The classifications of the appliances are done according to the general basis in 10 categories.

In Nordic countries and in other parts of world the utilization of wood fuel can be a good alternative to reduce the greenhouse emissions. From the study, it is found that the conversion of logs into pellets reduce the emissions. In the year

2000 the total wood fuel use in Nordic countries was 24,127, 50 and 157 PJ in Denmark, Finland, Norway and Sweden respectively. [1]

Residential wood combustion emits about 20-90% of fine particles in winter time with stagnant weather conditions. Health effects due to inhaled aerosol particles from wood combustion are a burning issue. Small scale wood combustion contributes to asthmatic problems in human beings. In addition, the soot emission from combustion influences the climate by absorbing solar radiation which warms the atmosphere. [4]

The combustion condition for residential combustion plant is different from large scale plants. Factors like local temperature, dispersion, appliance types and operational practices play an important role in the level of emissions. Different factors such as origination of tree species, fuel seasoning, combustion parameters and kindling approaches are uncontrolled by law. The infeasibility of flue gas filtering system in local burning appliances and economic aspects lead to the use of high emitting appliances.

The fact that due to the particle and gaseous emissions of wood combustion have direct effects justifies further study of emission factors from residential wood combustion.

2.2 Effects of Residential wood combustion

2.2.1 Health effects due to PM and other emissions

Wood combustion produces a complex mixture which contains number of “non-threshold pollutants”. The harmfulness of the pollutants depends upon the level of emissions which may occur both indoors and outdoors. Outdoor exposure is affected by the factors such as poor combustion, poor wind dispersal and other atmospheric conditions. Meanwhile, indoor exposures are affected by the similar reasons as outdoor and also can be by the leakage from pipes or back drafting from chimneys. [2]

Studies have found that residential wood combustion is now recognised as a major particle source in many developed countries [2]. The negative effects from the wood smoke are increasing nowadays. Higher exposure to ambient particulate matter (PM) has become a greater risk to health. The major health effects associated with wood combustion are respiratory and cardiovascular effects. Exposure to wood smoke can developed into chronic pulmonary diseases in the future. A recent study by international agency for research on cancer (IARC) has classified indoor emissions from household combustion of biomass fuel as probable carcinogens to humans. Heavy burning of wood causes haze and odour problems. The smell of burnt wood may be noticeable both indoors and outdoors. The nuisance impacts degrade personal health and the quality of life. [2]

2.2.2 Effects on climate change

Wood burning produces a significant amount of black carbon or soot which is a part of group of substances known as short lived climate forces (SLCF). Particulate matter in general has a cooling effect. Although the SLCF substances remain in the atmosphere less time than CO_2 but it is responsible for the significant portion of current global warming. [2]

2.3 Characteristics of wood fuel

The composition of wood fuel depends upon the species and varieties of trees. It also depends upon the handling process. Typically, wood contains about 70% of cellulosic material, 25% of aromatic compounds (lignin that binds or glues the cellulose together), and 5% of extractives (terpenes, resin acids, fatty acids and phenols) and between 0.2 to 3% of ash. Wood as a fuel is found mostly in wood logs but sometimes also as wood chips, briquettes and pellets. About 99% of dry matter of wood is carbon, hydrogen and oxygen. Nitrogen content is about 0.5% and sulphur content is less which is about 0.05% [5].Table 1 show the elemental composition of typical wood and bark mix. [3]

Table 1: The elemental composition of typical wood and bark mix [3]

Element	Wood	Bark
Carbon	50.8%	52.8%
Hydrogen	5.9%	5.8%
Oxygen	41.2%	38.7%
Sulphur	0.05%	0.1%
Nitrogen	0.1%	0.1%
Chlorine	Varies	varies
Ash	<1%	2.5%

2.4 Wood combustion process

Wood combustion is defined as a reaction where fuel reacts with oxygen and heat is produced by this chemical process. According to fuel particles combustion is divided into several phases [4]:

a. Drying and heating of fuel

Drying and heating of fuel is the first stage where heat has to be delivered to the wood in order to evaporate the moisture content in wood. After the moisture content of the fuel is dropped sufficiently, the temperature of the fuel increases and vaporization of volatile organic compounds starts.

b. Pyrolysis

Pyrolysis contains many complex chemical reactions that are parallel and sequential. The fuel constituents begin to hydrolyze, oxidize and dehydrate, while the large structures such as cellulose, hemicellulose and lignin begin to degrade. During the process of pyrolysis several gaseous and liquid products are formed which are mainly H_2O, CO_2, H_2 and CO.

c. Firing

Firing stage is the de-volatilization of wood which starts at 200°C. The firing increases faster where most volatiles are vaporized at 400°C. The pyrolysis products burn around the fuel particle as a diffusion flame. This generates heat for other pyrolysis reactions. The increase in heat generation leads to the rise in fuel temperature.

d. Combustion

The combustion process is accelerated until pyrolysis gas production slows down. During pyrolysis, the proportional share of carbon compared to hydrogen increases and residual char combustion starts. In the last stage of the combustion, there is the flameless combustion of residual char.

For the complete combustion process, the following are the important parameters [4]:

I. High combustion temperature
II. Sufficient amount of combustion air supply
III. Adequate mixing of combustion air and fuel gas

2.4.1 Batch or continuous combustion

Combustion process in RWC appliances can be continuous or batch. Combustion phase is the period for the minimum oxygen concentration of 14%. In batch combustion fuel is loaded in separate batches and the combustion starts from the first phase for each batch. During the first batch the fuel quality, combustion and firing practices have the strongest effect on the emissions. The temperature of the firebox is low at the time of firing. In order to lower the emissions firing should be done on the top of the first batch. The first batch burns more slowly than the subsequent batches, and the firing phase is also longer than that of subsequent batches. When the firebox heats up, the combustion rate increases which leads to increase in the rate of pyrolysis. In batch combustion phases there is a distinct separation between combustion phases in position and time. [4]

During continuous combustion different combustion phases occur in the fuel layer and combustion is steady. The continuous combustion process is steady and can be better controlled than batch combustion. However, the process can be unstable especially during interference, cleaning, on-off use and low load combustion phases in continuous combustion appliances. [4]

2.5 Factors affecting emissions

There are various factors which are responsible for the higher and lower emissions despite the appliance types. Each factor is described in more detail in the following subsections.

2.5.1 Operational practices

Operational practices such as kindling effect and fuel particle size affect the emissions.

Table 2: Important practices which increases the emissions and their effects [5]

Factor	Characteristic affecting emissions	Effect
Fuel	- Moisture - Ash content - Amount of gasifying substances - Log size	- Lowers combustion temperature - Increases particulate emissions - Difficult to control pyrolysis - Firing and gasification rate
Appliance	- Firebox size, shape and materials - Flue gas outlet dimensions - Air supply	- Affects draft combustion and combustion temperature - Affects draft combustion - Affects mixing of combustion air
Smoke-stack	- stack height, size and shape	- Affect draft condition
Combustion condition	- Flue gas residence time - Combustion temperature	- Affects emission burnout - Affects emission burnout
Flue gas after treatment	- After-treatment appliances	- Affects flue gas and air missing
Operating conditions	- Combustion rate - Fuel loading rate - Control devices	- Affects gasification rate - Affects combustion rate - Affects fuel and air
Appliance user	- Operation habits , garbage burning	- Affects several combustion factors

2.5.2 Moisture content

The heating value of the fuel depends upon the moisture content in the fuel. The lower content of moisture results into the low heating value and vice versa. The amount of heat generation will be lower with the higher moisture content in the fuel. The lower heating value of absolutely dry wood is about 19 MJ/kg (19 MJ/kg of heat generated from the combustion of 1 kg of wood). However, for fresh wood with a humidity of 50% it will be about half of this value [6].

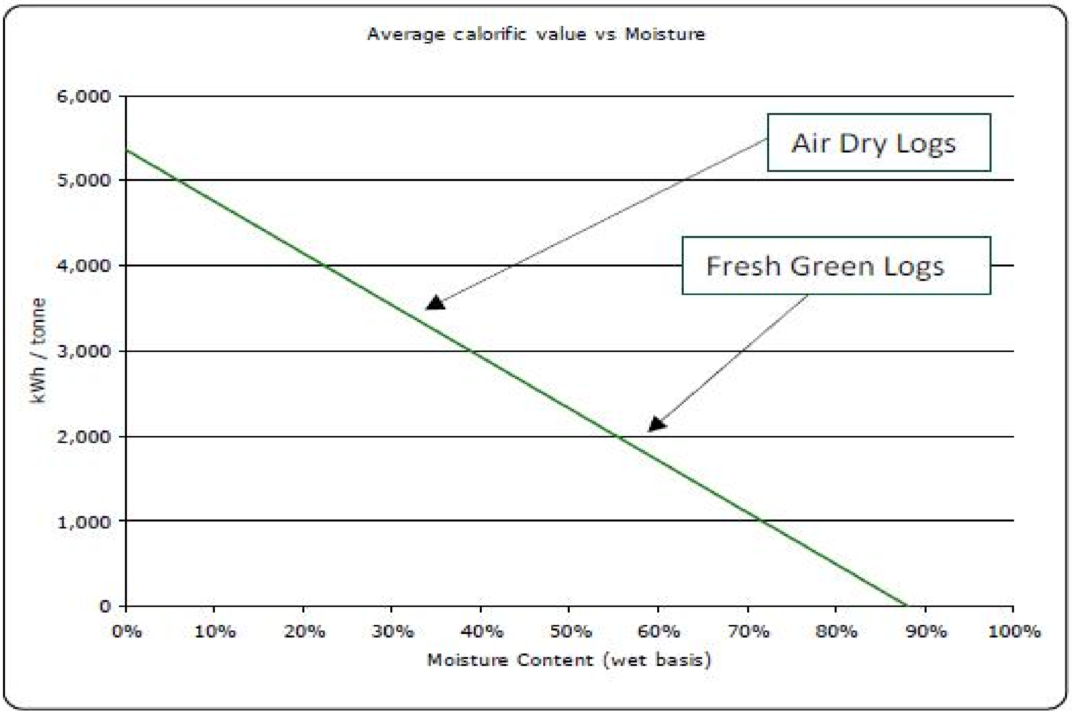

Figure 1: Moisture content of wood vs. calorific value of wood [7].

The moisture content of wood is a measure of the relative weight of water and weight of solid wood which are expressed on dry and wet basis. The table below shows the moisture content of wood according to the type of wood that are used for combustion purposes. [6]

Table 3: Moisture content of wood is summarized as follows [5]:

Wood type	Moisture content (%)
Fresh wood	40-60%
Wood logs(desired)	15-20%
Dry pellets	6%
Wood chips	upto 60%

2.5.3 Dispersion

The emitted particles and their concentration in the atmosphere depend upon various factors. Among these the topography of environment and weather conditions has a strong effect on local concentration levels. Other affecting factors are the source length, distance from the source, the atmospheric processes encountered during the transport, and mixing and interaction with gases and particles from other sources during transport. The speed of particle formation in the atmosphere quickly drops after the emissions due to rapid dispersion. The temperature of the exhaust gas quickly drops after it leaves the chimney into the atmosphere. This enhances the condensation of different compounds on the surface of the particles. [5]

2.6 Formation of emissions

During the complete combustion process only CO_2 and H_2O are produced. In wood combustion there are always unwanted products produced along with the main gas compounds which are N_2O, CO_2, H_2O and O_2. The first particle formed in wood is soot particles which are already formed in the flame from hydrocarbons. In addition to aerosol particles from wood combustion, it also includes liquid or tar like parts which are products from the gas-to-particle conversion of organic vapors in cooled flue gas. The formation of unwanted products can be divided into three main groups: formation of gaseous emissions and organic particles, formation of soot particles and formation of ash particles. [4]

Formation of gaseous emissions and organic particles

The combustion of wood fuels in small scale appliances is always partially incomplete. The reasons for the incomplete combustion are local incomplete combustion conditions around the flame, insufficient supply or poor mixing of combustion gases and air. These results to the formation of CO and volatile hydrocarbons emissions .Incomplete combustion produces hundreds of different organic compounds which can occur as both gaseous and solid particles. One important VOC from combustion is $CH_{4,}$ which is very strong greenhouse gas. PAHs are formed in the flame in the local fuel-rich areas when hydrocarbons polymerize instead of oxidizing. [5]

Formation of soot particles

Soot particles are formed mainly in the flame from hydrocarbons. The formation is a very complex mechanism. Due to insufficient mixing of combustion gases and air in RWC, the flame zone always contains fuel rich areas even in the presence of excess air. In the first step PAH compounds polymerize; in the next step PAH compounds increase and a high level of PAH are reached. Most of the soot burns in the oxygen rich zone in the flame, and only a small part of the soot agglomerates which is composed of about 30-50 nm solid carbon. [5]

Formation of ash particles

In good combustion conditions, fine particles emissions are formed mainly by vaporization of ash forming elements from wood fuel. The vaporization is dependent on the chemical composition of the wood and the reactions of inorganic species. [5]

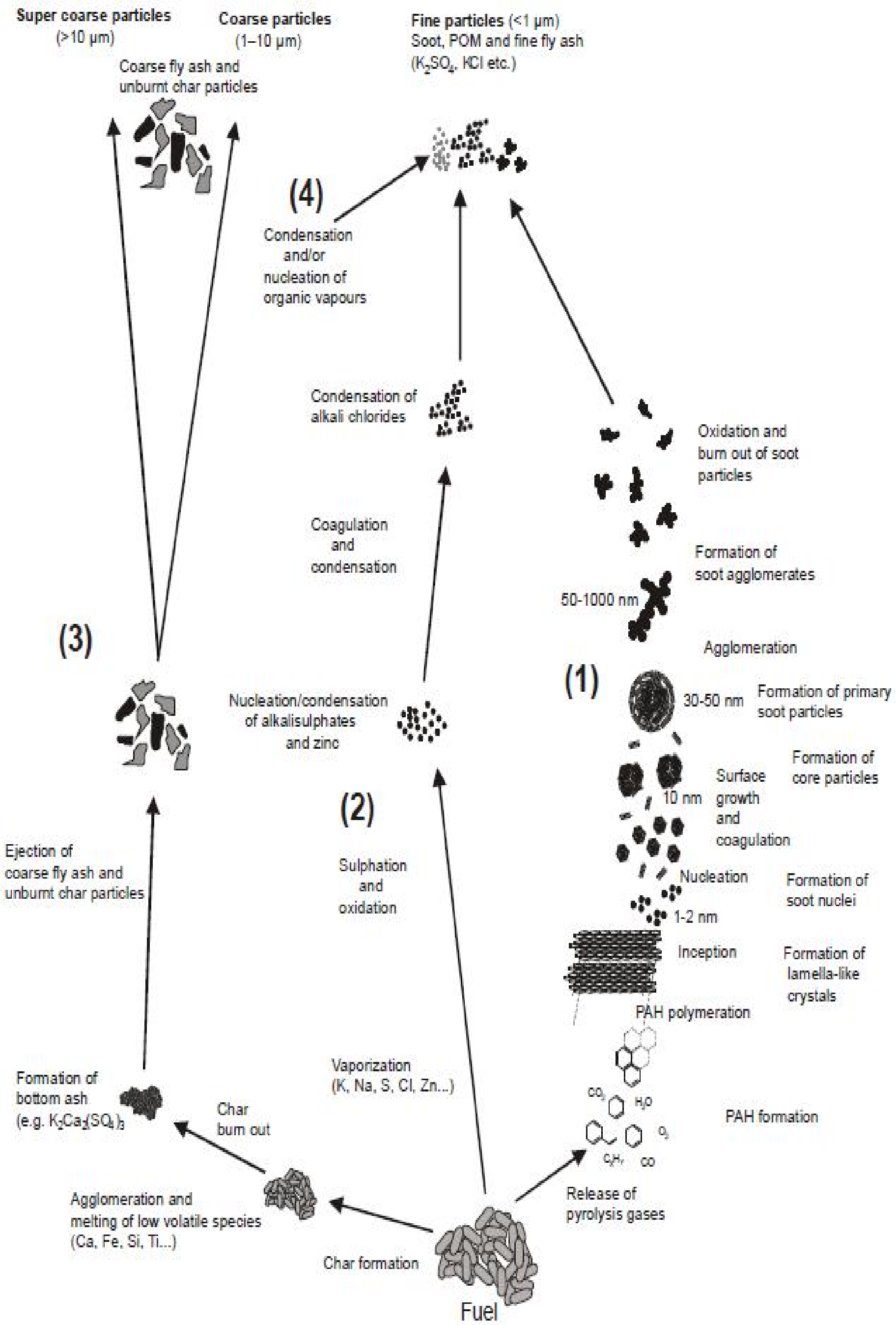

Figure 2: formation of emissions

(1) Soot, (2) fine ash, (3) coarse particles, and (4) particle organic matter (POM) in residential combustion [4].

2.7 Emission factors

2.7.1 Particulate matter

Particulate matter is the sum of air borne solid particles and droplets. PM is the complex mixture of airborne particles and liquid droplets composed of acids, water, ammonium, black and elemental carbon, organic chemicals metals and soil material.

“Fine particles” (or $PM_{2.5)}$ such as those found in smoke and haze have diameter less than 2.5 microns. $PM_{2.5}$ referred to as “primary” if it is directly emitted into the air as solid or liquid particles and is called “secondary” if it is formed by chemical reaction of gases in the atmosphere.” [10].

Anthropogenic primary PM originates predominately from combustion and other high temperature process, and from activities causing suspension of particles produced by the mechanical wear of solid particles, i.e. fugitive dust. High temperature process produces predominately fine PM below 2.5 µm, whereas fugitive dust emissions are mainly coarse particles. Primary PM emissions from combustion are mainly ash and carbonaceous particles. [11]

Combustion process is not well controlled in small scale domestic appliances. Domestic wood combustion usually has incomplete combustion which leads to high PM emissions. Some part of the volatile hydrocarbons of wood remain unburned and carry the flue gases, forming fine particles of soot and organic compounds condensed on the surfaces of the soot particles. [11]

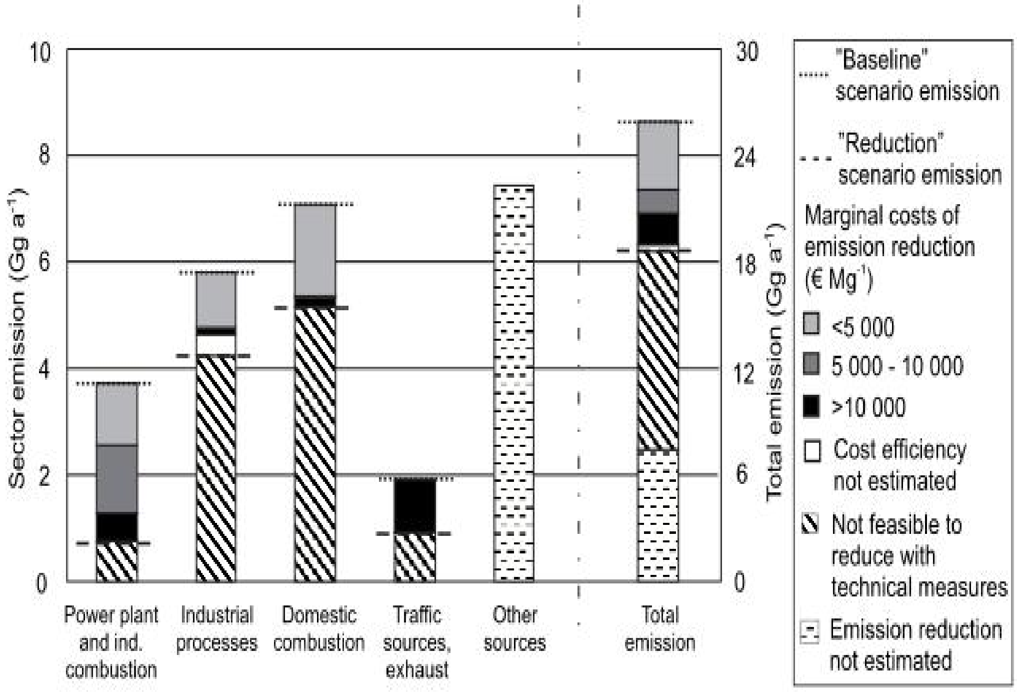

Figure 3: Primary $PM_{2.5}$ from main source sectors and total emissions in Finland in 2020 [11].

2.7.2 Carbonaceous compounds

The carbonaceous aerosols during the fuel combustion are classified as black carbon (BC), organic carbon (OC), elemental carbon (EC) and many others. There are different varying factors such as time, temperature, pressure and air flow which cause variation in transient cycles. Out of all combustion phases, the start-up phase contributes to 70% of the organic material emissions. The carbonaceous particles, i.e. soot, are formed due to the condensation of volatilized organic materials. Black carbon is usually known as soot, which is the light absorbing part of the particles and consists mostly of elemental carbon. Thus, carbonaceous compounds have the global warming properties due to their ability to absorb light over reflective surface. [3]

2.7.3 Carbon dioxide and carbon monoxide emissions

Carbon dioxide emissions depend upon the water content in the wood. The more water content in the fuel, the more CO_2 emissions. Furthermore, it takes

more energy to evaporate the water in the wood. The larger mass of wood is necessary to compensate for the losses from the vaporization of all water.
Carbon monoxide is formed mainly due to incomplete combustion of carbon atoms. The combustion of carbon compounds occurs in two stages. The first stage is to oxidize carbon to form carbon monoxide and later it is oxidized further to form CO_2. In the later step, most of the energy in carbon is released. Therefore, combustors are used to maximize the oxidation process from carbon monoxide to carbon dioxide. In spite of the combustor, there are different conditions that lead to incomplete combustion which includes lack of excess air, poor fuel-air contact and reduced temperature in the combustion zone. [3]

2.7.4 Other emission factors

Wood is a complex compound which is composed of cross-linked aromatics, primarily phenyl propane terpines, resin acids, fatty acids and phenols and cellulose. During the combustion process lignin and levoglucosan are incompletely oxidized, which are partially broken down into products of incomplete combustion such as PAHs. PAHs are usually two or three aromatic compounds. [3]

2.8 Emission reduction possibilities

There are numerous ways to reduce the emissions by qualitative and quantitative methods. The development of advanced technologies has reduced the emission factors to a countable level. There are still possibilities for the reduction of emissions dramatically. The most significant emissions to control from the wood combustion are particulate matter.

The most straightforward way to reduce emissions from wood combustion is to replace the traditional devices with the low emitting modern appliances. Emission reduction also depends upon the operational practices of the user. The emission reduction problem arises with the price of new devices and long life of older residential wood combustion. Use of dry wood and hot small fires can be a good practice to reduce the further emissions. [1]

In compared with older conventional fireplaces, wood stoves and other wood burning appliances produced today that burn the fuel more cleanly have dramatically lower emissions. The modern wood burning appliances include the following advanced wood heating technologies [5]:

a. Advanced combustion technologies:
   The non-catalytic wood combustion technology includes better insulation, preheating of pre-combustion air, air diversion and well-positioned baffles to retain heat.
b. Catalytic stoves
   Catalytic stoves have a replaceable honeycomb shaped device with a catalytic coating that lowers off gas ignition temperature. This allows exhaust gases to burn more quickly and efficiently.
c. Densified pellet stoves
   These types of wood burning appliances burn fuel made from ground wood and bio-mass cleanly and without any additives. The rate of fuel added is automated and controlled.
d. High efficiency fireplaces
   The advanced factory-built appliances have a tight fitting ceramic glass door and heat exchanger technology. They have duct kits to distribute warm air to other parts of the home.
e. Advanced wood stoves(EPA certified)
   These types of wood stoves utilize the advanced combustion systems which emit 70% less particle pollution and are approximately 50% more energy efficient than wood stoves which are manufactured before 1990.
f. Pellet stoves
   These stoves have a hopper on top of the device to hold wood or biomass pellets which are automatically fed into the stove to achieve a temperature controlled by a digital thermostat [12].

The use of accumulator tank with a log boiler or the promotion of pellet boiler installations can reduce emissions. Table 5 shows the reduction efficiency of different measures.

Table 3: Most important identified technical emission reduction measures [1].

Measure	Reduction efficiency	Description
Installation of accumulator tank	70%	Installations of boilers do not have an accumulator tank. Use of log boiler without accumulator results in high emissions
Fuel switch from logs to pellets	50-90%	Installation of pellet boiler. Pellet boiler typically has lower emissions and better heat production efficiency than log boilers.
Catalyst for wood burner	30%	Catalytic burners are equipped with a honey comb device coated with catalyst material that enhances the combustion of unburned compounds.
Secondary combustion chamber	30%	Flue gases with unburned hydrocarbons are directed into a secondary chamber where they are mixed with fresh preheated air and after burned.

3 Methodology

3.1 Database preparation of residential wood combustion

Based upon the thirty-seven official science journals on RWC, a database was prepared in MS-Excel. The database contained the emission factors from various appliances published in different journals after 1990 A.D.

The main purpose of the database is to summarize the information of the small scale wood combustion. The appliances are classified into 10 categories. The database includes measurement methods, wood species, and emissions and origin of the articles. The measurement methods used in experiments are also included in database. Most used measurement methods are MMD and GMD. The ELPI, DLPI, BLPI, GC-MS, etc. are experimental parameters required for finding the various emission factors.

The database includes the dilution ratio for calculation of emission factors, wood combustion conditions, temperature and operational practices depending upon the availability on the article. The moisture content of the fuel plays a major role for the data analysis of the emission factors. The higher the moisture content, the higher are emissions of greenhouse gases. Table 4 shows the detailed emission factors mentioned in the articles

Table 4: Classification of emission factors

PM	Carbonaceous compounds	Nitrous compounds	Carbon containing compounds	Others
PM_{10}	OC	NOx	CO	Levoglucosan
$PM_{2.5}$	EC	N_2O	CO_2	PAH
PM_1	OGC	NO_2	CH_4	PCDD/F
	BC		C_6H_6	TVOC
	TE		CxHy	TSP

The countries where the measurements had been performed are given in Figure 11 below.

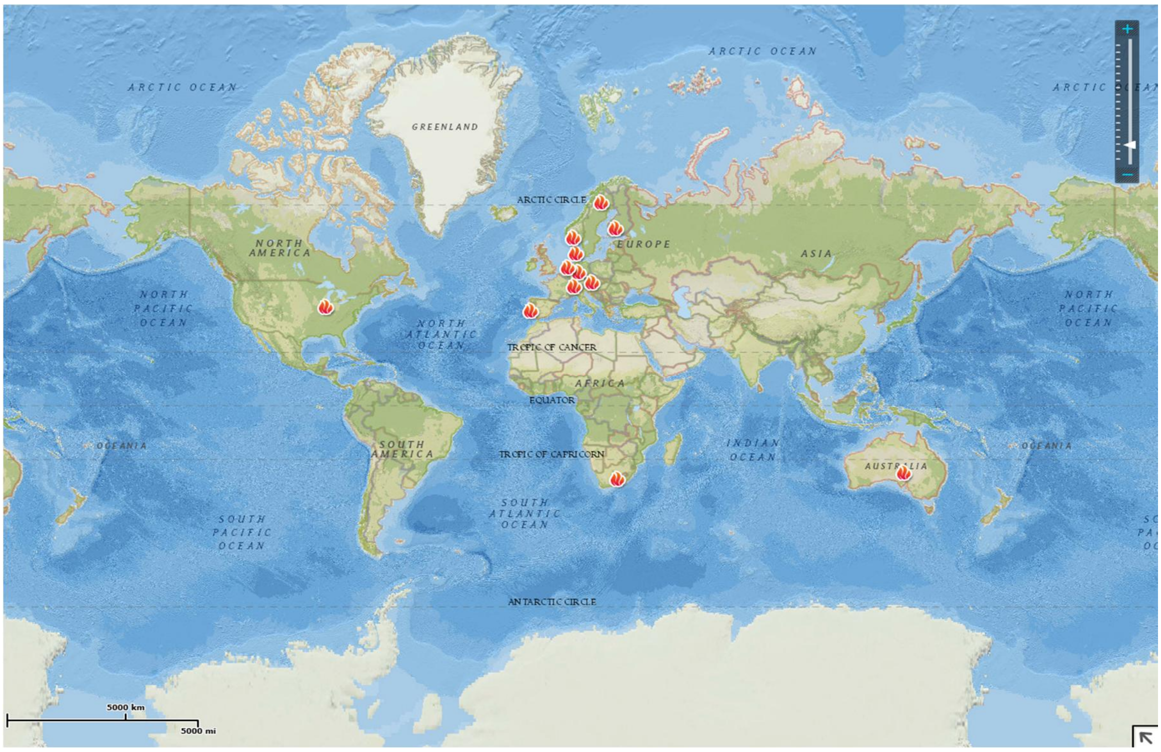

Figure 4: World map showing the countries used for experimental purpose

The countries involved are mostly Nordic countries (Finland, Norway, Sweden and Denmark), Austria, Germany, Portugal, Switzerland, The Netherlands, Portugal, The United States of America, Australia and The Republic of South Africa.

3.2 Residential wood appliance classification

Indoor and outdoor burning of the residential combustion appliances mainly includes masonry heater, stoves, pellet stoves, cook stoves, sauna stoves, fireplaces, log boilers and pellet boilers. In many developing countries, wood combustion is widely used as a major source of energy for indoor cooking and heating purpose.

3.2.1 Masonry heaters

Masonry heaters are mainly of high mass of about 3000 to 8000 kg. They are typically enclosed combustion appliances made up of basically masonry products and combination of ceramic materials. Some of them are covered with decorative tiles. Masonry heaters include modern or conventional masonry heaters and masonry ovens. These appliances are mainly used for warming the interior space by burning fuel and capturing the heat. They undergo batch combustion process where wood is combusted for a short period of time at high power by which the combustion rate and temperature are high. Typically these heaters are upright fireboxes with a glass door. Combustion efficiency is about 75-85%, where the energy released provides both primary and supplemental heating. The average rate of heat radiation is about 1-3 kW. Figure 3 below shows the air taken into the combustion chamber.

Figure 5: modern masonry heater. The arrows indicate the intake air [5].

3.2.2 Wood stoves

Wood stoves are usually free standing and they are used as the principal source of heat for home, for the cooking purpose or to supplement conventional heating systems. They have a mass of less than 800 kg and are usually made of steel, soapstone to increase heat storage in Figure 6. A typical wood stove has the loading capacity from 15 to 40 kg, which results in 4 to 12 hours of operation for continuous refueling [2].

In warmer countries, wood stoves are used for primary source of residential heating and for supplementary heating. They release heat to the surroundings by radiation and convention process. The users can control these types of stoves control combustion by restricting the amount of air that can lead to smouldering combustion conditions. In some countries like USA, they use the catalytic stove, which is equipped with ceramic or metal honeycomb device called a combustor. There are also some uncertified heaters which are recognized as stoves. [4]

Figure 6: typical wood stove [2]

3.2.3 Pellet stoves

Pellet stoves are a modified form of wood stoves, but they have active air flow systems, which burn compressed wood or biomass to create a source of heat for residential spaces in Figure 7 Sawdust or other waste biomass materials are usually compressed into small cylinders 8 mm in diameter and 10 to 30 mm long to produce pellets. [2]

Slow feed of fuel from a storage container into the burn pot area can increase the efficiency of these types of stoves. It also enables the stoves to create a constant flame that requires little physical adjustments. Pellet stoves are environmentally friendly stoves which are ignited automatically and cycle themselves by means of a thermostat. The efficiency of pellet stoves is the same as that of advanced combustion wood burning stoves. [2]

Figure 7: A typical pellet stove

3.2.4 Cook stoves

Cook stoves are usually old fashioned stoves that are used mainly as a source of energy for indoor cooking and heating in many developing countries. These types of appliances have simple designs usually simple tripods or three-stone stoves or portable metal or ceramic cook stoves in Figure 8. Cook stoves have a very low efficiency of about 8 to 30% and high emissions. The combustion process of the cooking stove is a batch process. Wood logs with a lower moisture content are used as a fuel. [4]

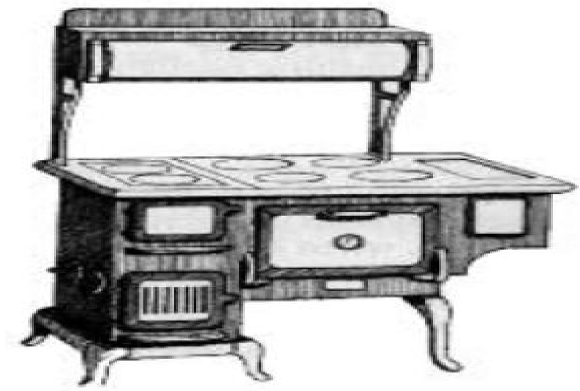

Figure 8: typical cook stove [2].

3.2.5 Sauna stoves

Sauna stoves are used for heating sauna rooms, and they are usually product is made of steel as in figure 9. This type of stove reserves the heat produced in stones. Due to undeveloped combustion process, only half of the released energy can be stored in the stones; consequently the exhaust gas temperature is high. Due to the small firebox and no secondary combustion, its efficiency is lower. The air supply to sauna stoves is insufficient in relation to high gasification rate which results to incomplete combustion. In order to reduce the emissions, the combustion technique should be developed or secondary removal techniques should be used [5].

Figure 9: Sauna stove [5]

3.2.6 Fireplaces

Fireplace is the traditional term which is used for burning wood logs in a wood-burning device in which fire can be seen during the burning phase. Nowadays, there are more effective and advanced fireplaces for effective fire viewing. Fireplaces have higher emissions than other burning appliances. There are some fireplace ovens which are used for cooking purpose. [8] Mainly fireplaces are divided into two broad categories:

a. Open fireplaces

   An open fireplace is designed to burn the wood logs in an open area where the ignition is visible. As the fireplace is open, a sufficient amount of oxygen is supplied during combustion. For complete combustion, a high enough temperature is needed. During incomplete combustion, the open fireplaces produce unburned gases which are released into the atmosphere contributing to pollution. The open fireplaces provide about 20% of heat on 80% fuel which results into low efficiency. [8]

b. Closed fireplaces

With the development of various modern appliances, the use of closed fireplace is not practiced much, but is not totally diminished. There are modern technologically advanced solutions for the fireplaces these days. As in Figure 8 a closed fireplace is about 80-85% more efficient than an open fireplace. However, closed fireplaces have about 80-90% of heat loss from the chimney. [8]

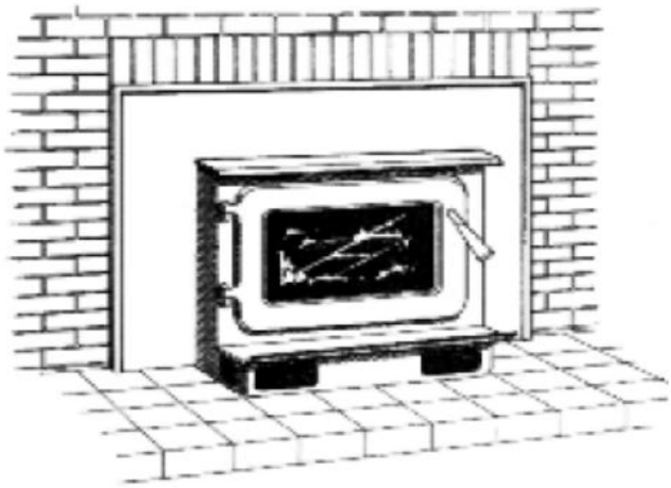

Figure 10: A fireplace inserts [2]

3.2.7 Log boilers

Log boilers are mainly wood log boilers used primarily as heating devices as in Figure 11. Log boilers are divided into three categories according to air flow designs in combustion: up draught, downdraught and cross draught boilers. Old aged up draught boilers operate in the same as wood stoves. Modern wood boilers are usually designed for downdraught and cross draught combustion with lower emissions. These modern devices often have a secondary combustion chamber which is normally insulated with ceramics and connected to the storage tank. In cross draught boilers, the flue gas flow resistance is quite high so advanced control devices such as O_2 sensors, air control sensors are used. [4]

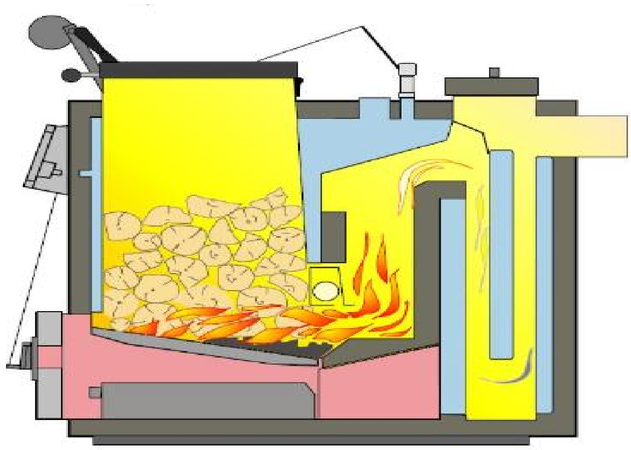

Figure 11: Wood log boilers [5]

3.2.8 Pellet boilers

Pellet boilers are described as wood pellet boilers in the thesis. As in Figure 12 wood boilers are suitable for hot water radiant systems and hydro-air systems. With the addition of a hydronic coil, wood pellet boilers function with fully automatic operation like oil boilers. For ignition, any ignition element can light pellets. Normally, pellet boilers do not have heat storage tanks and the boiler is set at thermostat control, which results in cyclic intermittent operation of pellet burner. The efficiency of pellet boilers is higher than of other appliances. [4]

Figure 12: Pellet boiler [5]

3.2.9 Non-RWC appliances

In addition to wood combusting appliances, some experiments have been performed with appliances which do not use wood as the fuel. These include biomass, industrial combustion plants, automatic combustion plants, fluidized bed combustion. These are classified as non-RWC appliances. These non-RWC appliances are used mainly for small scale industrial purpose.

3.2.10 Others

Others include open fire, cone calorimeter and incinerators. The use of open fire for recreational purposes is significant and contributes to pollution. There are some small scale cone calorimeters and incinerators whose emissions are experimented along with appliances which uses wood as a fuel.

3.3 Used program

The preparation of database, calculations and tables were created in Microsoft excel 2010. The calculations performed in the thesis were done with the freeware statistical program R, of version R×64bit version 2.15.3. For visualization of countries involved in the experiment, an interactive world map was used. For easy determination of the emission factors with different parameters in future, an idea of search engine was forwarded. Statistical program R was used as the tool for the development of the search engine. As a free software R, anyone interested in different emissions from wood combustion can view it easily.

3.4 Assumption and calculations

3.4.1.1 Unit calculation

The emission factors for the different experiments are given in different measurable units. To simplify the emission factors to measurable units, each emission factor unit is converted to mg/MJ.

The data is available in different units with various moisture contents according to wet and dry basis. The moisture content of the fuel is assumed to be 20% which is most probable for all the articles which had units other than mg/MJ. The detailed parameters assumed for the calculation of g/kg to mg/MJ are given in Appendix 2. The obtained value is used for the calculation for the emission factors.

The calculation of g/kg to mg/MJ was performed as follows:

$$\frac{mg}{MJ} = \frac{1000\ \frac{mg}{kg}}{14.7118\frac{MJ}{kg}}$$

The detailed parameters assumed for the calculation of mg/m^3 to mg/MJ are given in Appendix 3. The values obtained were used for the calculation of emission factors.

For the conversion of mg/m^3 to mg/MJ the following formula was used

$$\frac{mg}{MJ} = 0.696\frac{m^3}{MJ} \times \left(\frac{mg}{m^3}\ of\ compound\right)$$

For the conversion of ppm to mg/m^3 the following formula was used

$$\frac{mg}{m^3} of\ compound = \frac{(ppm\ value\ of\ compound) \times (molecular\ weight)}{24.45}$$

When analyzing the emission factors and appliance categories, the use of R program was found helpful. In the R program, there was a possibility to get box plots for every appliance and their emission value.

3.4.1.2 Rank calculation

For the process of ranking appliances according to the level of significance in their emission factors, all the emission factors and appliances were calculated in Microsoft Excel. The data was converted to data matrix form used in the R programming language for statistical computing and graphics. From the R program, the box plot was obtained and further used for analyzing appliances with their emission factors. The ANOVA test was also carried out for analyzing the variance within emission factors. Tukey range test was done for single step multiple comparisons to identify the difference between two means. The results from Tukey test were aggregated to get the results to compare the emission factors. These values of each emission factors were sorted according to the level of significance and the multiple comparisons of appliances from Tukey test were taken to find out the results for the appliances. On the basis of these results the ranking was given as a numeric letters, for example: 1, 2 and 3. Hence, the appliance with the least emissions was ranked as numeric letters 1 and the rest of the appliance followed accordingly. The results obtained from the summation of eight emission factors were also calculated. Finally, appliances having lower numbers were explained as good appliances and vice versa.

4 Development of search engine

4.1 Functions of the search engine

Figure 13 below gives the function for assessing the database in R. With the function below the database can be easily accessible.

```r
RWC.fun = function(DB,Variable) {
    if (class(DB) != "character") stop("The full file name must be given as a character string")
    if (class(Variable) != "character") stop("Variable name must be given as a character string")
    graphics.off()
    # It off all the graphics from the previous programme.
    data.RWC<- read.table(DB,header=TRUE)
    # data.RWC reads the datamatrix form of datamatrixform_RWC.txt where
    #it is database and header is true which reads header as it is.
    Var = data.RWC[,Variable]
    # The variable represents any emission factors from the database
    boxplot(Var~data.RWC$Appliance.category,xlab="Appliances",ylab="mg/MJ",main=Variable)
    # The purpose of the box plot is to plot the Var of the data.RWC from datamatrix
    # with appliance.category . The boxplot from the graph where xlab are the appliances ,
    #   ylab is the level of emisssion ; the unit for it is mg/MJ and main is the heading of any variable.
    Var_data.anova <- aov(Var~data.RWC$Appliance.category)
    # Var_data.anova gives the ANOVA of var with data.RWC and appliance.category.
    Anova = summary(Var_data.anova)
    # Anova gives the summary of ANOVA test for analysis of variance
    Tukey = TukeyHSD(Var_data.anova)
    # Tukey test gives the difference of means
    windows()
    # It opens the window when running the function
    plot(TukeyHSD(Var_data.anova))
    # It plot the tukey test of the function
    means = aggregate (Var~data.RWC$Appliance.category,data=data.RWC,FUN=mean)
    # It aggregates teh means of function
    stds = aggregate (Var~data.RWC$Appliance.category,data=data.RWC,FUN=sd)
    # It gives the standard deviation of function
    numbers = aggregate (Var~data.RWC$Appliance.category,data=data.RWC,FUN=length)
    # It gives the number of observation of appliance category.
    means = cbind(means,stds[,2],numbers[,2])
    # It binds the means, standard deviation and number of observation
    names(means) = c("Appliance category",Variable,'std','n')
    # It provides names of means
    out = list(Anova,Tukey,means)
    # It gives out the list of Anova, Tukey and means
    names(out) = c("ANOVA","Tukey_test","Appliance_means")
    # It combines the ANOVA, Tukey_test, Appliance_means
    return(out)
    # It returns out to the original function
}
```

Figure 13: Function used in R

To run the function of emission factors and their appliances from the data matrix prepared from database, the first step is to source the function in R. The data matrix of the database should be accessed in order to run the function of RWC. The data matrix can be accessed from the link below

http://woodcombustion.wordpress.com/documents/links/

The data matrix given in the link below is in Excel which should be converted into text file in the name datamatrixform_RWC.txt. The name of the function is RWC.fun.r

The function can be accessed from the link below

http://woodcombustion.wordpress.com/documents/search-engine/

The function is given in pdf format which should be converted in to RWC.fun.r to run this in R. After running the function in R, any name can be assigned a variable to view results from database.

a (name of assigned variable) = RWC.fun("datamatrixform_RWC.txt", "name variable from database" for example: "PM10")

The given script provides the tukey test graph and boxplot of appliances and the emission factor.

It also gives the ANOVA results, tukey test and appliance means by using the scripts given below:

a. Name assigned variable$ ANOVA
b. Name of assigned variable$ Tukey_test
c. Name of assigned variable$ Appliance_means

   For example: a$ANOVA

5 Results and comparisons

For formatting the database, first the units for every emission factor were converted to mg/MJ for uniformity of data. All the emission factors from each article were classified with their appliances. The whole process was done in Microsoft Excel 2010.All the excel files were converted to text files in order to read it in the R programming language, which does the box plot and Tukey test with the appliances used in the experiment for the specific emission factors. From the box plot it can be viewed the emission level of the experimented appliances can be viewed.

On the basis of the summary table obtained from Tukey test, the appliances were compared with each other according to the level of emissions. The aggregation of summary obtained from Tukey plot was done for 12 emission factors. The aggregation list was used to find out the combustion properties of appliances. The aggregation list was used in excel and sorted out according to the smallest to largest value. Finally, the appliances were compared each other according to the level of significance and were ranked according to it. The same procedure is followed all other emission factors.

The ranking of appliances was done with the summation of all ranks of emission factors. The result obtained from ranking provides the categories of appliances according their combustion. The combustion categories were classified as follows:

a. Poor combustion
   poor combustion refers to appliances that produce a higher amount of emissions during combustion.
b. Good combustion
   good combustion covers appliances whose combustion emissions are lower than those of the other appliances.

Appliances with lower sums of ranks were listed as good combusting appliances, whereas appliances with the higher sums of ranks were labeled as poor combusting appliances. In some cases, all the appliances were not used in the process. Thus, there was a certain amount of uncertainties for the appliances with missing values. Appliances whose values are missing were labeled as not available (NA).

5.1 Emission factors and their appliances used

From the database, the important emissions from the appliances were assessed, including particulate matter emissions. Along with EC, CO and NOx are also assessed with the use of R.

5.1.1 Assessment of PM_{10} emission with their appliances

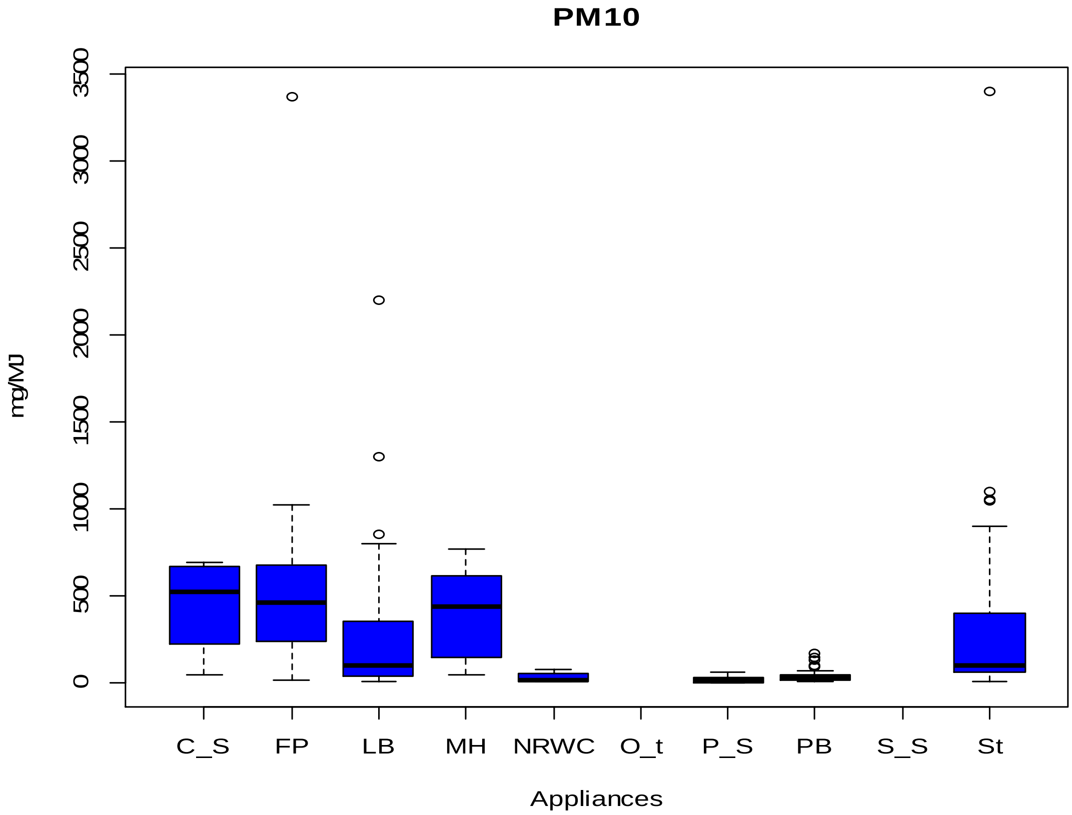

Figure 14: Boxplot of PM_{10} emissions and appliances [Appendix 1]

Box plot in Figure 14 shows that PM_{10} emissions of sauna stoves (S_S) and other appliances (O_t) have not been experimented. The spread of PM_{10} emission is narrower in non-residential wood combustion appliances (NRWC), pellet stoves(P_S) and pellet boilers(PB) than the spread in masonry heater (MH), fire places(FP), log boilers(LB), ordinary stoves(St) and cook stoves(C_S). There are also outliers in fireplace, log boiler and ordinary stove.

ANOVA was performed to test whether there were significant differences between mean PM_{10} emissions of different appliances. Null hypothesis was that the means of PM_{10} emission of all the appliances are equal; whereas the alternative hypothesis was that the means of PM_{10} emission of all the appliances are not equal. Results are presented in Figure 15 below.

```
                              Df   Sum Sq Mean Sq F value    Pr(>F)    
data.RWC$Appliance.category    7  6712724  958961   6.139 1.33e-06 ***
Residuals                    235 36709979  156213                      
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
349 observations deleted due to missingness
```

Figure 15: ANOVA Result of PM_{10}

```
  Appliance category      PM10       std  n
1                C_S 446.00000 293.69712  4
2                 FP 503.70522 456.06045 62
3                 LB 293.37838 441.19556 37
4                 MH 408.97225 274.15335  6
5               NRWC  28.75000  31.98307  4
6                P_S  17.87969  18.86330 15
7                 PB  39.90657  38.28660 37
8                 St 296.75026 460.37249 78
```

Figure 16: Result of emission mean, their standard deviation and the number of observations of PM_{10}

Result interpretation

Figure 15 shows that the p value is very low (<< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the PM_{10} of the appliances is not equal. Figure 16 shows the test has 592 observations, out of which 243 observations have the PM_{10} emission while 349 observations lack it. Mean value was estimated from the 243 observations (N) so the total degree of freedom is 242 (N-1). PM_{10} emission from eight different appliances was recorded. So, the df for appliances category is 7 (8-1) and the residual's df is 235 (N-7).

5.1.2 Assessment of $PM_{2.5}$ emission with their appliances

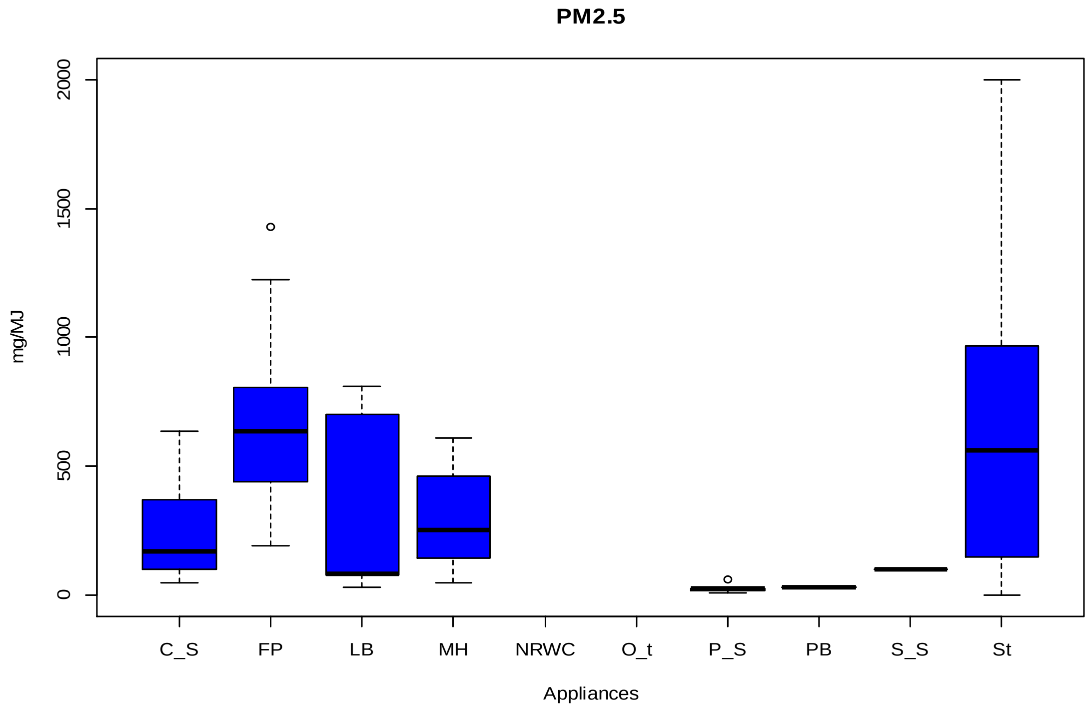

Figure 17: Boxplot of $PM_{2.5}$ emissions and appliances [Appendix 1]

The box plot in Figure 17 shows that a $PM_{2.5}$ emission of Non-residential wood appliances (NRWC) and other appliances (O_t) of has not been studied. The spread of $PM_{2.5}$ emission is much narrower in sauna stoves (S_S), pellet stoves (P_S) and pellet boilers (P_B) whereas the spread is wider in masonry heater, fire places, log boilers, ordinary stoves and cook stoves.

ANOVA was performed to test whether there were significant differences between the mean $PM_{2.5}$ emissions of different appliances. The null hypothesis was that the means of $PM_{2.5}$ emission of all the appliances are equal; whereas the alternative hypothesis was that the means of $PM_{2.5}$ emission of all the appliances are not equal.

```
                              Df   Sum Sq Mean Sq F value   Pr(>F)
data.RWC$Appliance.category    7  5061485  723069   4.208 0.000407 ***
Residuals                    103 17697704  171822
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
481 observations deleted due to missingness
```

Figure 18: ANOVA Result of $PM_{2.5}$

	Appliance category	PM2.5	std	n
1	C_S	249.5000	223.62267	6
2	FP	650.4885	303.98489	31
3	LB	339.6667	339.30607	12
4	MH	321.1693	199.53778	15
5	P_S	29.8000	19.12328	5
6	PB	30.5000	1.00000	4
7	S_S	100.0000	NA	1
8	St	668.2819	597.45221	37

Figure 19: Result of $PM_{2.5}$ emission mean, their standard deviation and the number of observations.

Result interpretation

ANOVA results in Figure 18 shows that p value is very low (<< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the $PM_{2.5}$ of the appliances is not equal. Figure 19 shows that test has 592 observations, out of which 111 observations have the $PM_{2.5}$ emission and 481 observations do not have. Mean value was estimated from the 111 observations (N) so the total degree of freedom is 110 (N-1). PM_{10} emission from eight different appliances was recorded. So, the df for appliances category is 7 (8-1) and the residual's df is 103 (N-7).

5.1.3 Assessment of PM_1 emission with their appliances

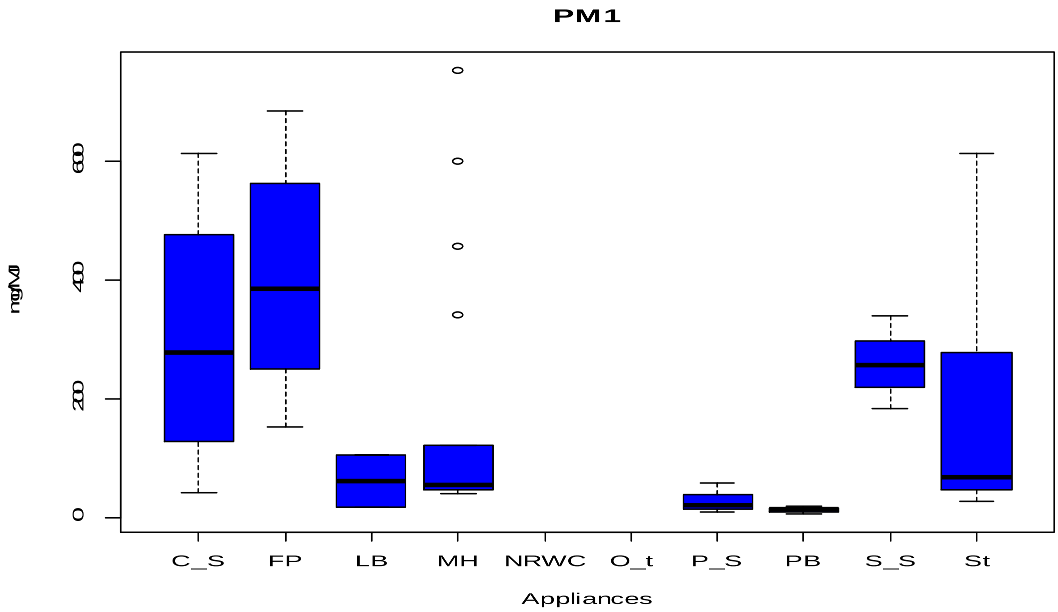

Figure 20: Boxplot of PM_1 emission and appliances [Appendix 1].

Box plot in Figure 20 shows that PM_1 emissions of Non-residential wood combustion appliances (NRWC) and others (O_t) of PM_1 have not been experimented. The spread of PM_1 emission is narrower in sauna stoves (S_S), pellet stoves (P_S) and pellet boilers (PB) than the spread is less narrow in masonry heaters (MH), and log boilers (LB). Meanwhile, there are wider spread in cook stoves (C_S), fireplaces (F_P) and ordinary stoves (St). There are outliers in masonry heaters (MH).

ANOVA was performed to test whether there were significant differences between the means of PM_1 emissions of different appliances. The null hypothesis was that the PM_1 emissions of all the appliances are equal; whereas the alternative hypothesis was that the means PM_1 of all the appliances are not equal. Results are presented in Figure 21 below.

```
                            Df  Sum Sq Mean Sq F value  Pr(>F)
data.RWC$Appliance.category  7  818028  116861   3.143 0.00865 **
Residuals                   45 1673392   37186
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
539 observations deleted due to missingness
```

Figure 21: ANOVA Result of PM_1

```
  Appliance category       PM1        std  n
1                C_S 303.25000 240.354426  4
2                 FP 405.00000 188.073487 12
3                 LB  62.00000  62.225397  2
4                 MH 174.97563 222.811788 17
5                P_S  27.25000  21.266170  4
6                 PB  13.23333   6.882102  3
7                S_S 260.12980  78.215524  3
8                 St 178.39692 206.713304  8
```

Figure 22: Result of PM_1 emission mean, their standard deviation and the number of observations

Result interpretation

ANOVA results in figure 21 shows that p value is very low (< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the PM_1 of the appliances is not equal. Figure 22 shows that test has 592 observations, out of which 53 observations have the PM_1 emission while 539 observations lack it. Mean value was estimated from the 53 observations (N) so the total degree of freedom is 52 (N-1). PM_{10} emission from eight different appliances was recorded. So, the df for appliances category is 7 (8-1) and the residual's df is 45 (N-7).

5.1.4 Assessment of CO emissions with their appliances

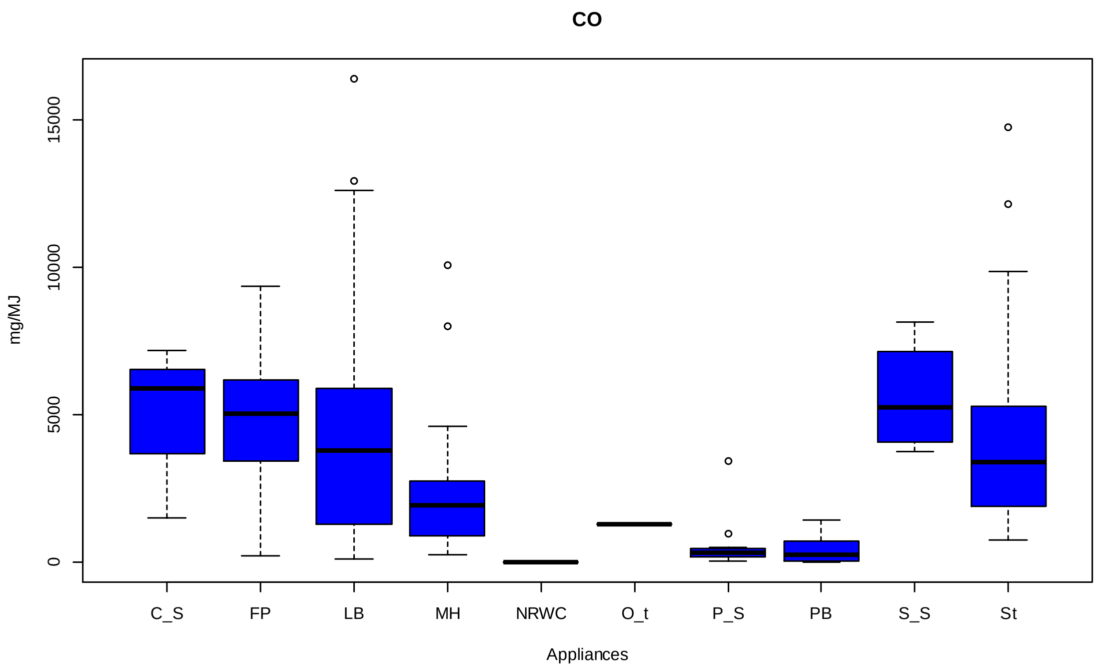

Figure 23: Boxplot of CO emission and appliances [Appendix 1].

The box plot in figure 22 shows that spread of CO emission is narrower in Non-residential wood combustion appliances(NRWC),pellet stoves(P_S), pellet boilers(PB),non-residential wood combustion appliances(NRWC) and other appliances(O_t) whereas the spread is wider in masonry heaters(MH), fire places(FP), log boilers(LB), ordinary stoves(St) and cook stoves(C_S). There are also outliers in masonry heaters, pellet stoves and ordinary stoves.

ANOVA was performed to test whether there were significant differences between the means of CO emissions of different appliances. The null hypothesis was that the means of CO emissions of all appliances are equal; whereas the alternative hypothesis was that the means of CO emissions of all the appliances are not equal. Results are presented in Figure 24 below.

```
                              Df    Sum Sq  Mean Sq F value Pr(>F)    
data.RWC$Appliance.category   9 8.072e+08 89686365    13.1 <2e-16 ***
Residuals                   275 1.883e+09  6846740                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
307 observations deleted due to missingness
```

Figure 24: ANOVA Result of CO

```
   Appliance category        CO         std  n
1                 C_S 4853.6667 2965.044069  3
2                  FP 4623.7561 2400.616911 67
3                  LB 4809.0929 4292.495466 33
4                  MH 2481.6633 2498.638583 20
5                NRWC    5.5000    4.949747  2
6                 O_t 1291.4803    0.000000  4
7                 P_S  486.4068  747.776347 19
8                  PB  415.8380  434.962373 39
9                 S_S 5598.8033 1974.166354  4
10                 St 4125.0658 2835.511028 94
```

Figure 25: Result of CO emission mean, their standard deviation and the number of observations.

Result interpretation

ANOVA results in Figure 24 shows that p value is very low (<< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the CO of the appliances is not equal. Figure 25 shows that test has 592 observations, out of which 285 observations have the CO emission and 301 observations do not have. Mean value was estimated from the 285 observations (N) so the total degree of freedom is 244 (N-1). CO emission from 10 different appliances was recorded. So, the df for appliances category is 9(10-1) and the residual's df is 275 (N-7).

5.1.5 Assessment of EC emissions with their appliances

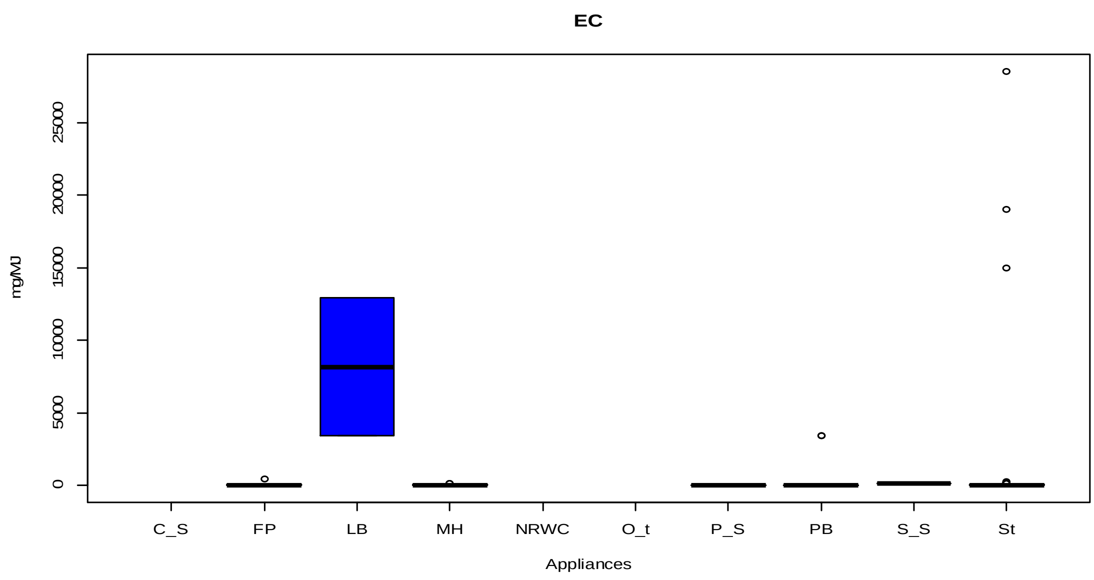

Figure 26: Boxplot of EC emission and appliances [Appendix 1]

Box plot in Figure 26 shows that EC emissions of cook stoves (C_S), non-residential wood combustion appliances (NRWC) and other appliances (O_t) have not been experimented. The spread of EC emission is narrower in all appliances than spread in log boilers. There are outliers in pellet boilers and ordinary stoves.

ANOVA was performed to test whether there were significant differences between the means of EC emissions of different appliances. The null hypothesis was that the means of EC emissions of all appliances are equal whereas the alternative hypothesis was that the means of EC emissions of all appliances are not equal. Results are presented in Figure 27 below.

```
                               Df    Sum Sq  Mean Sq F value Pr(>F)  
data.RWC$Appliance.category     6 1.487e+08 24789547   2.004  0.071 .
Residuals                     112 1.386e+09 12370622                 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
473 observations deleted due to missingness
```

Figure 27: ANOVA result of EC

	Appliance category	EC	std	n
1	FP	46.294106	81.2069811	27
2	LB	8156.717735	6728.9488258	2
3	MH	41.589793	42.0232482	18
4	P_S	1.012735	0.5118719	3
5	PB	460.271305	1193.0017763	15
6	S_S	123.796340	8.7732996	2
7	St	1248.049756	5087.6703020	52

Figure 28: Result of EC emission mean, their standard deviation and the number of observations.

Result interpretation

ANOVA results in Figure 27 shows that p value is very low (< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the EC of the appliances is not equal. Figure 28 shows that test has 592 observations, out of which 119 observations have the EC emission while 473 observations lack it. Mean value was estimated from the119 observations (N) so the total degree of freedom is 118 (N-1). EC emission from seven different appliances was recorded. So, the df for appliances category is 6 (7-1) and the residual's df is 112 (N-6).

5.1.6 Assessment of BC emissions with their appliances

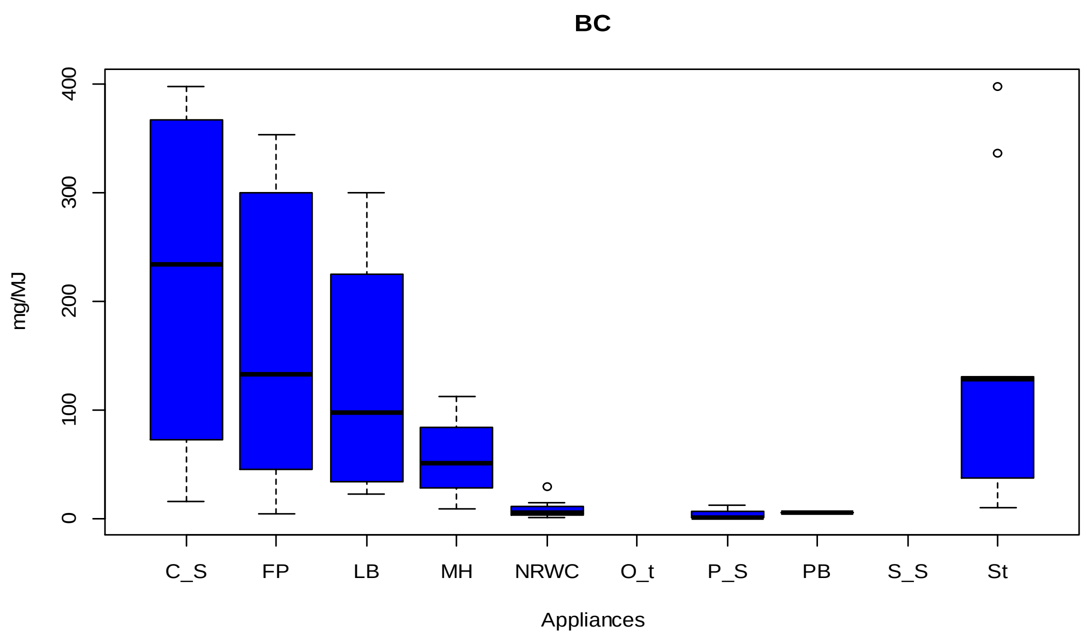

Figure 29: Boxplot of BC emission and appliances [Appendix 1].

Box plot in Figure 29 shows that a BC emission of sauna stoves (S_S) and other appliances (O_t) has not been experimented. The spread of BC emission is narrower in non-residential wood combustion appliances (NRWC), pellet stoves (P_S) and pellet boilers (PB) than the spread in cook stoves (C_S),log boilers (LB), ordinary stoves(St), masonry heaters(MH) and fireplaces(FP). There are also outliers in non-residential wood combustion appliances and ordinary stoves.

ANOVA was performed to test whether there were significant differences between the means of BC emission of different appliances. The null hypothesis was that the means of BC emissions of all appliances are equal whreas the alternative hypothesis was that the means of BC emissions of all the appliances are not equal. Results are presented in Figure 30 below.

```
                            Df Sum Sq Mean Sq F value Pr(>F)
data.RWC$Appliance.category  7 274285   39184   3.007 0.0124 *
Residuals                   40 521255   13031
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
544 observations deleted due to missingness
```

Figure 30: ANOVA result of BC

```
  Appliance category       BC       std  n
1                C_S 219.5000 177.86605  4
2                 FP 178.4643 131.00183 14
3                 LB 129.3750 126.59606  4
4                 MH  55.5000  42.89911  4
5               NRWC   8.3250   9.32826  8
6                P_S   3.7500   5.50000  4
7                 PB   5.2500        NA  1
8                 St 142.2222 136.44896  9
```

Figure 31: Result of BC emission mean, their standard deviation and the number of observations.

Result interpretation

ANOVA results of Figure 30 shows that p value is very low (< 0.05) and also the F value is large. So, the alternative hypothesis is accepted, which indicates that the mean value of the BC of the appliances is not equal. Figure 31 shows that test has 592 observations, out of which 48 observations have the BC emission and 544 observations do not have. Mean value was estimated from the 48 observations (N) so the total degree of freedom is 47 (N-1). BC emission from eight different appliances was recorded. So, the df for appliances category is 7 (8-1) and the residual's df is 41 (N-7).

5.2 Ranking of appliances

The ranking of the appliances was done on the basis of the results obtained from the aggregation of Tukey test based upon the multiple comparisons of appliances with their emission factors. Table 5 shows the ranking results.

Table 5: Ranking and summation of appliances with their emission factors

Appliance	PM_{10}	$PM_{2.5}$	PM_1	CH_4	CO	PAH	BC	EC	Sum of ranking	Combustion result
Cook stove (C_S)	3	2	3	NA	3	NA	3	NA	14	Poor
Fireplace (FP)	3	3	3	2	3	1	3	1	19	Poor
Log boiler (LB)	2	3	1	2	3	2	2	3	18	Poor
Masonry heater (MH)	2	2	2	3	2	2	2	1	16	Poor
Others (O_t)	NA	NA	NA	NA	1	NA	NA	NA	1	Not classified
Non-residential wood combustion(NRWC)	1	NA	NA	1	2	1	1	NA	6	Not classified
Pellet stove (P_S)	1	1	1	1	1	NA	1	1	7	Good
Pellet boiler (PB)	1	1	1	1	1	1	1	1	8	Good
Sauna stove (S_S)	NA	1	2	2	3	3	NA	1	12	Poor
Stove (St)	2	3	2	3	3	1	2	2	18	Poor

Some appliances do not have all the emission factors. According to the summation of ranking, pellet stoves and pellet boilers are good combusting appliances. Other appliances and non-residential wood combustion appliances had more missing values so the results obtained from these appliances are not taken into consideration. According to table 5, ordinary stoves, cook stoves, masonry heaters log boilers and fireplaces are poor combusting appliances.

Table 6: Ranking and summation of other emission factors with appliances

Appliance	TE	NOx	PCDD/F	C_6H_6
Cook stove (C_S)	NA	NA	NA	NA
Fireplace (FP)	NA	NA	1	NA
Log boiler (LB)	NA	2	1	1
Masonry heater (MH)	3	2	1	2
Others (O_t)	NA	NA	3	NA
Non-residential wood combustion (NRWC)	NA	1	NA	NA
Pellet stove (P_S)	1	2	NA	1
Pellet boiler (PB)	2	2	1	1
Sauna stove (S_S)	NA	3	NA	2
Stove (St)	1	2	2	2

Table 6 indicates that the missing values of the other least important emission factors are higher. Thus, the ranking of the appliances was not considered from these emission factors.

6 Discussion and conclusion

The aim of the project was to make a database from most of the available scientific experimental journals on residential wood combustion. The project was started by studying the journals, sorting the available data and making a database in MS Excel. The thesis was mainly focused on the appliance types and their available emission factors. The principle findings of the thesis project are assessment of emission factors from various appliances development and implementation of search engine for assessing the data. For example, the particulate matter (PM) emission of different appliances was analyzed by interpreting its emissions. The analysis was carried out by making the emission units' uniform, categorizing the used appliances, preparing the data matrix and extracting each emission factor with the corresponding appliances.

A search engine was prepared in R programming language for statistical computing and graphics of the emission factors and appliances. It was found that the primitively used appliances produce higher emissions than the modern appliances. Previous studies had also analysed emissions, but each study was limited to only a few emission factors. This thesis, in contrast, includes analyses of most of the previous measurements on 592 appliances and their twenty-six emission factors, at the same time. However, the ranking was done on only eight emission factors which have higher significance level. The obtained results were found to be similar to the expected results.

The major limitations which may have affected the results are mainly the measurement methods used in the previous experiments and the conversion formulae used for the emission factors having units other than mg/MJ. In addition, the accuracy of results might suffer some minor errors due to a few measurements that were knowingly done in poor combustion conditions.

The understanding gained from this research has provided to build a search engine which would be helpful for the further data analysis. The search engine can be used in analyzing any one of the twenty-four emission factors with their different appliances as per readers' interest. This data matrix can be updated in future and further investigation can be done. When further researches are done in RWC, existing data of emission factors can be updated in the data matrix text file and more analyses are possible by updating the text file of the search engine and running the function in R program.

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Appendix 2: Fuel composition for the conversion of g/kg to MJ/kg

Fuel Composition		
Effective heating values	**14.7118 MJ/kg**	
	weight -%	*kg/kmol*
C	40.0 %	*12.01*
H_2	5.0 %	*2.016*
O_2	32.0 %	*32.00*
H_2O	20.0 %	*18.015*
S	0.03 %	*32.06*
N_2	0.50 %	*28.01*
ash	0.5 %	
Sum	**98.0 %**	

Appendix 3: The air coefficient for the conversion of mg/m^3 to m^3/MJ.

Air coefficient			Air coefficient				
Effective heating	14.7118 MJ/kg		2.7				
			air		Flue gas		
Composition	weight %	kg/kmol	kmol/kgpa		kmol/kgpa		
C	40.0%	12.01		CO_2	0.03331	7 %	
H_2	5.0%	2.016		H_2O	0.0359	7 %	
O_2	32.0%	32	0.0964	O_2	0.06072	12 %	
H_2O	20.0	18.015					
							mg/MJ
S	0.03%	32.06		SO_2	0.000009	0 %	40.7
N_2	0.50%	28.01	0.3628	N_2	0.3629	74 %	
ash	0.5%						
Sum	98 %		0.4592		kmol/kgpa	m^3/kgpa	m^3/MJ
				dry smoke	0.457	10.24	**0.696**
				wet smoke	0.493	11.04	0.75