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Characterisation of biomass resources in Nepal and assessment of potential for increased charcoal production

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1. Abstract

Characterisation of 27 types of biomass was performed together with an assessment of regional resource availability. Charcoal was produced under two conditions from all samples and their yields were compared. Sugarcane bagasse, sal and pine produced the best charcoal with a low volatile matter and high calorific value.

The amount of high quality charcoal which can be made within Nepal from the biomass types tested is equivalent to 8,073,000 tonnes of firewood a year or 51% of the yearly demand. The areas which would benefit the most from charcoal making facilities are the Mid-hills of the Western, Central and Eastern Development Regions, as well as the Terai in the Central and Eastern Development Regions. The main potential benefit is to convert agricultural residues which are underutilised because, in their original form, produce large amounts of smoke, to cleaner burning charcoal. The conversion of agricultural residues to charcoal is also a viable alternative to anaerobic digestion in the Mid-hills.

2. Introduction

Nepal is a country which is highly dependent on traditional biomass energy resources, contributing to 85% of the total energy consumption (Pokharel, 2007). Fossil fuels account for 14% and modern biomass (e.g. briquettes and biogas) and other renewables contribute a mere 1% of the total energy consumption (Water and Energy Commission Secretariat (W.E.C.S.), 2013). Between the years of 2000-09, the energy supply consumption by 20%, 13% and 125% from traditional, fossil fuel and renewable types respectively (W.E.C.S., 2010). The total energy consumption accounted for by traditional solid fuel types, fuelwood, animal dung and agricultural residue is 71.1%, 5.1% and 3.5% respectively (W.E.C.S. , 2014). Biomass is expected to remain the most important energy source for at least the next 30 years (W.E.C.S., 2013).

The residential sector accounts for 88% of the energy used, over half of which is for cooking (W.E.C.S., 2010). Approximately 64% of households primarily use firewood for heat and cooking and 10% use cow dung (National Planning Commission Secretariat (N.P.C.), 2012). The remaining households use clean burning fuels, most frequently L.P.G., but also biogas and kerosene (N.P.C. , 2012).

The use of traditional biomass combustion technologies, especially for cooking, is of serious concern in Nepal and other developing countries because the pollutants emitted by the burning of biomass in a confined space cause serious health problems, leading to the premature deaths of approximately 3.3 million people per year worldwide (World Health Organisation, 2014). Smoke from indoor biomass burning is associated with illnesses such as chronic obstructive pulmonary disease (Perez-Padilla et al., 2010). Switching to charcoal for heating and cooking is one option to reduce the amount of indoor smoke pollution (Obeng et al., 2017).

Conversion of biomass resources into charcoal is performed by a process called pyrolysis. Volatile matter, which is associated with smoke emissions, is converted to fixed carbon, which burns hotter and slower, therefore improving the safety and value of the material as a cooking fuel (Bautista et al., 2009; Protásio et al., 2017). The energy density is also improved making it easier to transport than the untreated biomass it is made from (Konwer et al., 2007; Somerville and Jahanshahi, 2015).

Agricultural residues are an underutilised source of energy with just 6% of the total used in Nepal (Webb and Dhakal, 2011). Residues have other uses which need to remain, as fodder for example, but it is still estimated that 75% of the total energy need for cooking could be met with this fuel type (K.C. et al., 2011). W.E.C.S. (2014) estimated higher, suggesting that the energy potential of agricultural residues is larger than the total yearly firewood consumption. One reason for the underutilisation is the increase in indoor air pollution when used compared to firewood (Das et al., 2017). Pyrolysis is one thermochemical route to converting residues to a clean fuel. It is, however, limited in that high moisture content materials are unsuitable as the evaporation of this water creates significant energy losses. Residues, such as straw and potato tops are therefore more suited to anaerobic digestion as a conversion method to clean biofuels (Mussoline et al., 2013; O'Toole et al., 2013; Parawira et al., 2008; Wu et al., 2012). The main crops by output in descending order are: rice (27.9%), sugarcane (18.3%), maize (12.6%), potato (11.8%) and wheat (10.4%) (Ministry of Agricultural Development (M.O.A.D.) , 2014).

Natural forests are the main source of household fuel but have historically been under pressure for conversion to agriculture and from overexploitation. A period of deforestation began shortly after the nationalisation of the nation's forests in 1957, replacing community forestry systems that had previously been successful (Pokharel, 2003). Reintroduction of community forestry policies in the 1990s significantly reduced the rate of deforestation (Shrestha et al., 2014). By putting forests into the control of local communities those using them have an interest in preserving the resource. Between the years of 2010-2015, the area of land covered by forest was unchanged (Food and Agricultural Organization (F.A.O.) , 2015). In 2013, there were over 17,810 community forest user groups (C.F.U.G.'s) controlling 1,665,419 ha (K.C. et al., 2015). An estimate from 2008/09 quantifies the amount of sustainable firewood available in reachable areas as 12.5 million tons per year- 80% from forests, 9% from cultivated land and the rest from shrubland, grassland and non-cultivated inclusion (land predominantly used for grazing) (W.E.C.S. 2010). The majority of the firewood from forests is produced on land controlled by C.F.U.G.'s, totalling 7.1 million tons per year (W.E.C.S. 2010).

Forests in Nepal are diverse owing to the range of climates occurring from the large variation in altitude. In the more tropical Terai along the south of the country, the dominant species is Shorea robusta, known locally as sal (Paudel and Sah, 2015). In the Mid-hills, which covers 58% of the nation, the forests are varied containing pine and broadleaf species such as Schima wallichii, Alnus nepalensis, Pinus roxburghii and Rhododendron spp. (Pandey et al., 2014). Forests in the Mountains region mostly consist of conifers, oak and Rhododendron spp. (Rana et al., 2016).

Charcoal making has been undertaken for thousands of years. The oldest methods involve the use of an earth pit kiln. These are made by digging a hole in the ground and filling it with wood. This is then topped with earth to create an air tight seal. An inlet and outlet are made in the side of the pit to allow a small amount of air to burn a small amount of wood to provide the necessary heat for pyrolysis (Chidumayo and Gumbo, 2013). The charcoal yields are generally low, and the quality and homogeneity of the produced fuel is varied (Vahrman, 1987). Emissions from this practice are high and can harm the health of operators and the environment (Vahrman, 1987).

The retort kiln is a more efficient and less polluting option for charcoal production (Sparrevik et al., 2015). There are many different designs however most consist of a brick kiln filled with wood. Hot inert gases circulate in and under the kiln causing the wood to pyrolyse. The emissions are reduced and efficiency increased by recirculating and combusting the gases produced during the process (Sparrevik et al., 2013).

There are many studies relating to the consumption of firewood in Nepal, but there are often marked differences in the results obtained. Frequently, this is a result of the methods employed to estimate use. Fox (1984) found that a survey asking respondents for an average of the quantity of firewood they burn on a hot and a cold day was a factor of two higher than a weight survey of wood collected. Other reasons for the large discrepancies in consumption estimates has been thought to be caused by the array of climates, forest accessibility, education and caste leading to a range of 200-2000 kg per person per year (kg/ppyr) of firewood consumed (Webb and Dhakal, 2011). A study by Rijal and Yoshida (2002) weighing the amount of collected firewood found the average firewood (including crop residues) consumption in a mountain region was 1,130 kg/ppyr but as little as 348 kg/ppyr in a Mid-hills region. However, the survey was brief with only a small number of households involved over few measurement days. Most studies estimate the average firewood consumption in the range of 450-700 kg/ppyr (Bhattarai, 2013; Fox, 1984; Kandel et al., 2016; Pokharel, 2003; Shrestha, 2007; Webb and Dhakal, 2011).

Nepal et al. (2010) used a survey containing a nationally representative sample of 3912 households to investigate how the type of cookstove and main fuel use affects firewood consumption. It was found that the type of biomass cookstove had little impact on the amount of firewood used. Households reporting to predominantly use kerosene/gas cookstoves used less firewood, yet still a significant amount was consumed for other activities.

The aim of the paper is to identify biomass available in Nepal which are suitable for charcoal making. The geographical distribution of suitable resources is also assessed and compared to where demand for biomass fuels exist to determine which locations could benefit most from charcoal making.

3. Materials and methods

3.1 Estimation of firewood consumption throughout Nepal

With insufficient data on the affect between climates in Nepal as well as local cultural and educational differences, data on firewood use by stove used in households from Nepal et al. (2010) and census data on households were used to make an estimate of the regional biomass demand (N.P.C. , 2012). From the data, it was estimated that households on average used 2.62 tonnes of biomass per year if woodstoves were used and 1.50 tonnes if kerosene/gas stoves were used. The census data was then used to calculate the regional consumption of firewood by multiplying the two cookstove factors by the amount of households reporting each cookstove type.

3.2 Sample collection

The field sites for collection of biomass samples represent the typical Mid-hills physiography in Central Nepal (Figure 1). The sites lie within the three adjoining districts viz. Kathmandu (the capital city of Nepal, coordinates: 27^{0}33'48.9”- 27^{0}58'38” N and 84^{0}48'49.5” - 85^{0}15'22.5” E), Makawanpur (coordinates: 27^{0}33'49.8” - 27^{0}36'22.5” N and 83^{0}12'18” - 85^{0}13'07.1” E) and Dhading (coordinates: 27^{0}56'40” - 28^{0}02'30.4” N and 84^{0}48'51.1” - 84^{0}51'23” E) districts within the elevation ranges from 500m to 1870 m above sea level (A.S.L.). Agricultural residues were collected from the market and/or households in Kathmandu and Arughat.

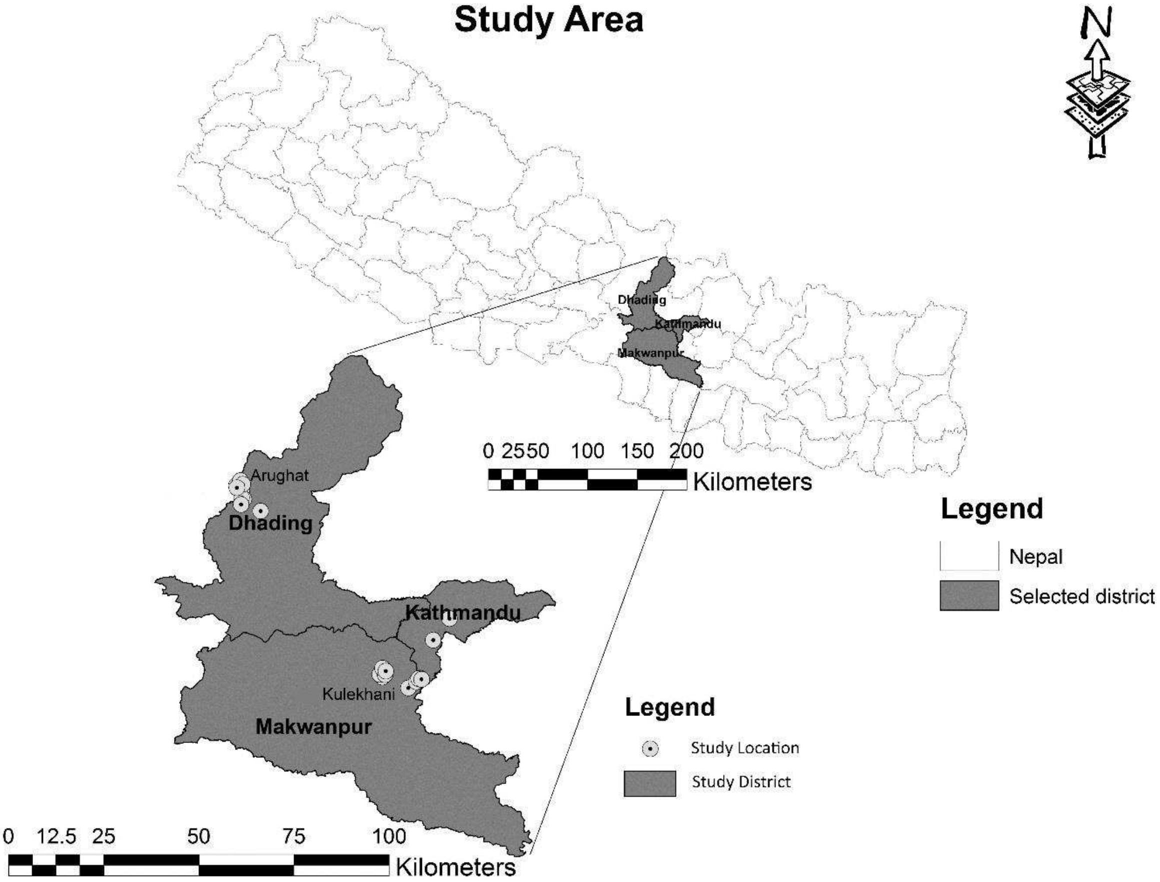

Figure 1 Sampling locations in Nepal.

A total of 27 different types of biomass were chosen, 12 tree species, 4 shrubs, 4 herbaceous plants and 7 agricultural residues. The selection was based on the total quantity throughout Nepal. After analysis of the raw material and charcoal produced from them, the samples were narrowed further, focusing on the most relevant types for charcoal production. Additional information regarding location of collection sites is contained in Appendix 1. The tree species selected were: Alnus nepalensis (Nepalese alder), Castanopsis inidica (chinkapin), Choerospondias axillaris (Nepali hog plum), Ficus semicordata (drooping fig), Lagestroemia parviflora (Crepe myrtle), Melia azedarach (chinaberry), Myrica esculenta (box myrtle), Pinus roxburghii (pine), Quercus semecarpifolia (oak), Rhododendron arboreum (rhododendron) and Schima wallichii (schima) and Shorea robusta (sal). All were collected from Nepal and exported for analysis, except for Shorea robusta which is forbidden from exportation. An alternative non-living sample was sourced from the Royal Botanic Gardens, Kew, originally collected from Darjeeling, India. The shrubs were: Gaultheria fragrantissima (fragrant wintergreen), the invasive Lantana camara (wild sage), Lyonia ovalifolia (angeri), Woodfordia fructicosa (fire flame bush) and Zanthoxylum armatum (winged prickly ash). The herbaceous plants were: Artemisia indica (oriental mugwort), the invasive Eupatorium adenophorum (crofton weed), and Thysanolaena maxima (Nepalese broom grass). The agricultural residues were: Brassica campestris (rapeseed mustard), Eleusine coracana (finger millet straw), Oryza sativa (rice husk), Saccharum officinarum (sugarcane bagasse) and Zea mays (maize cob, stover and shell).

Samples from each of the forestry plants were obtained from the primary branch of mature specimens. The circumference of the primary branch of specimens sampled was less than 25cm. The reason is branches with larger circumferences are often used instead for timber.

3.3 Sample preparation

During collection, the biomass samples were cut into approximately 30cm long pieces unless the size was already less, for example, maize cob . The initial weights of the samples were recorded and then air dried for 3-5 days. The larger sized samples were chipped and passed through a 10mm sieve in a Retsch Cutting Mill SM 100. All the samples were then further micronized and homogenised using a grinder.

3.4 Proximate and ultimate analysis

The proximate values (moisture, volatile matter, fixed carbon and ash) of each of the untreated and charcoal samples were determined using a Mettler Toledo TGA/DSC 1 Thermo-Gravitmetric Analyser (T.G.A.). Approximately 10mg of sample was first heated to 105°C in an inert atmosphere. The associated weight loss during this step represented the percent moisture content. The sample was then heated to 900°C- the mass loss during this section determined the volatile content. The gas flowing through the analyser was switched from nitrogen to air to burn the remaining fixed carbon. The ash content was measured as the remaining material after the test. Ultimate analysis was determined using a Thermo EA112 Flash Analyser. Oxygen was calculated by difference from the sum of carbon, hydrogen, nitrogen and ash on a dry basis. Calorific value is approximated using Dulong’s formula (Wanignon Ferdinand et al., 2012). The energy recovery (E.R.) is determined by:

$$\text{E.R. (\%)} = \frac{\text{mass yield x charcoal gross calorific value}}{\text{raw sample gross calorific value}} \qquad (1)$$

Energy recovery quantifies how much of the original energy from the sample is retained in the charcoal made. Proximate and ultimate analysis for all species sampled can be found in Appendix 2.

3.5 Inorganic analysis

To a quartz tube, 10ml of 69% nitric acid and 0.2g of biomass sample was added before sealing. The sample was digested using an Anton Parr Multiwave 3000 microwave. The digested sample was then diluted to 50ml with deionised water and filtered to remove any remaining solid material. This was performed on all the collected samples.

The digested samples were analysed using ICP-OES to determine trace element composition of Ca, K, Na, Mg, Cr, Cu, Fe, Li, Mn, Ni, Sr, Zn, Mo, V, Ba, Sn and S. Phosphorus was determined by colorimetry using ammonium molybdovanadate as the chromogen. Absorbance was measured at a wavelength of 430nm.

X-ray Fluorescence (XRF) was also used to determine elements less soluble after nitric acid digestion such as aluminium and silicon. The samples were prepared by calcining the samples at 550°C for two hours and then a further two hours at 900°C. The ash was collected, mixed with lithium borate flux and fused at 1050°C using a Katanax K1 Prime.

3.6 Preparation of charcoal from different samples

A pyrolysis reactor (Figure 2) was used to produce charcoal from each of the biomass samples. It consisted of a sealed tube furnace above a condenser set to 4°C which cooled the hot gases from the furnace. The tars were then collected in a catchpot below the condenser. Nitrogen was fed through the top of the furnace at a rate of 10 ml min^{-1} to remove volatile compounds and create an inert atmosphere. The exhaust gases passed through two impingers- the first contained water and the second, quartz wool to remove any further liquid or solid residue in the exhaust stream. Approximately 3g of sample was added to 25ml nickel crucibles, 18 of which were inserted into the tube furnace section of the pyrolysis reactor each time. The heating rate of the furnace was between 4.5 and 7.2 °C/min. The reactor was maintained at the pyrolysis temperature for 1 hour under a constant flow of nitrogen. After this period, the heater was switched off and the furnace cooled at a rate of 0.4-1.4°C/min. The produced charcoal samples were then removed from the furnace and weighed to determine the mass yield of charcoal on a percentage basis. Each sample underwent pyrolysis at two temperatures, 400 and 600°C. At each temperature the test was performed three times per sample, and the mass yield, averaged.

The total potential for high quality charcoal was normalised to make a comparison against the current consumption of traditional biomass in Nepal. The firewood equivalent (tonnes) takes into account the superior thermal efficiency of cooking on charcoal and the increased calorific value using the equation:

$$\text{Firewood equivalent} = \text{m}_{\text{charcoal}}\,\eta \times \frac{\text{CV}_{\text{charcoal}}}{\text{CV}_{\text{wood}}} \qquad (2)$$

Where $\text{m}_{\text{charcoal}}$ is the total mass of charcoal that can be produced, η is the increased thermal efficiency factor taken as 1.5 of firewood (Wiskerke et al., 2010), $\text{CV}_{\text{charcoal}}$ (MJ/kg) is the estimated upper calorific value by Dulong’s formula and CV_{wood} is the calorific value of wood which is approximated as 16.8 MJ/kg.

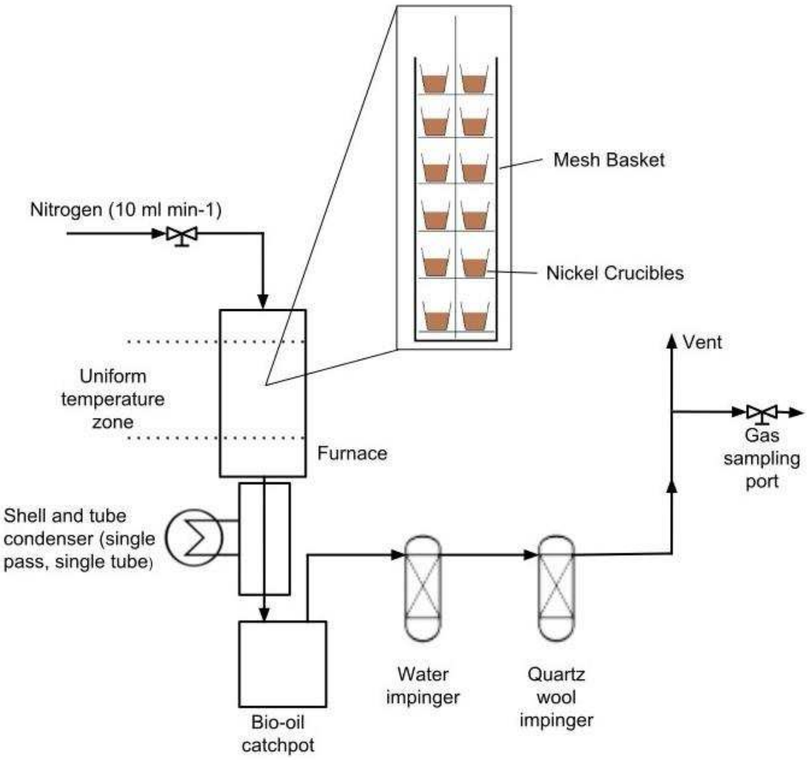

Figure 2 Pyrolysis reactor and basket assembly for producing charcoal.

4. Results and discussion

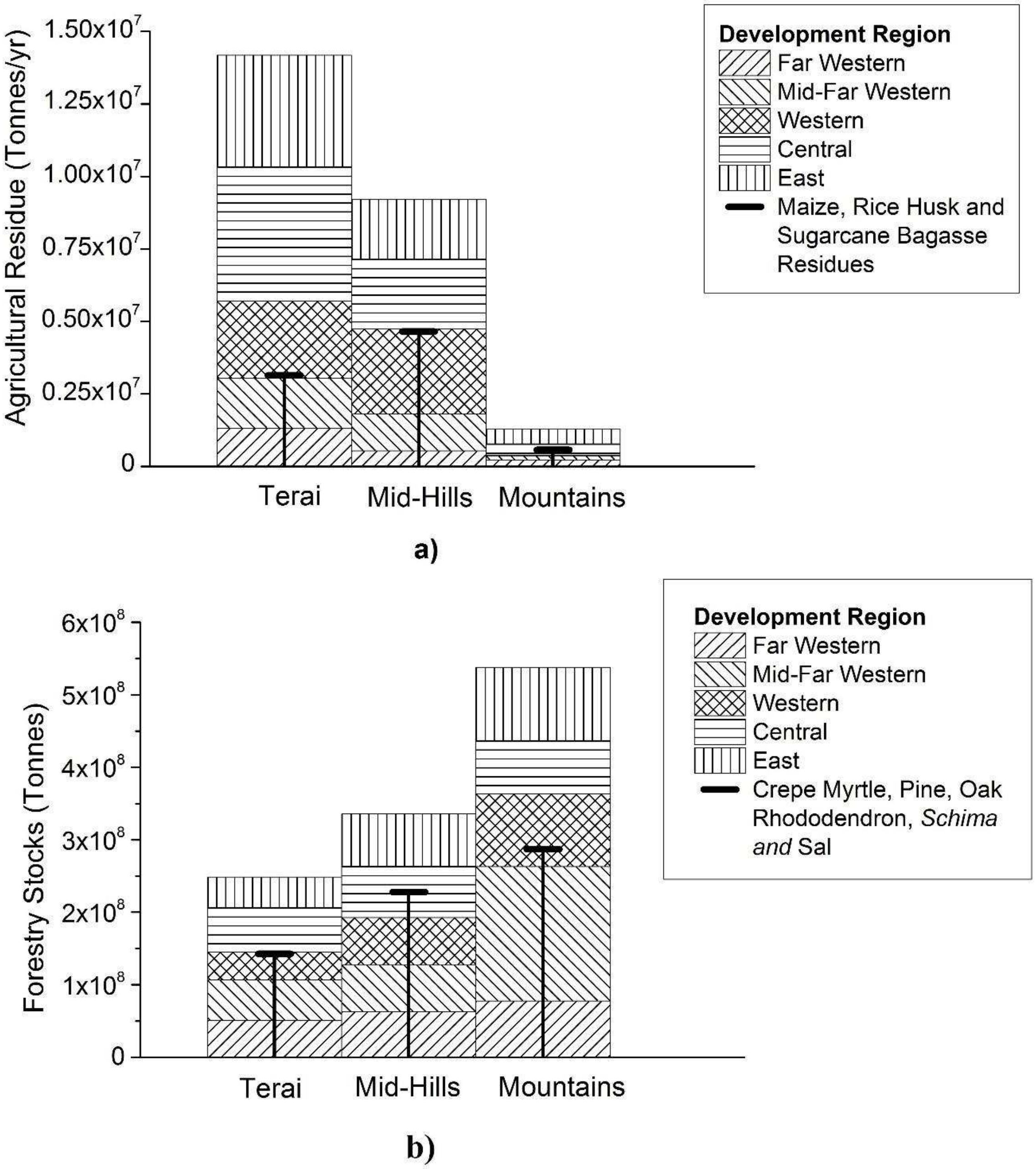

Figure 3a) Regional yearly production of agricultural residues from cereal and cash crops, and 3b) Regional distribution of forestry resource outside protected regions. The line represents the proportion of the total resource of several key species which were analysed (Department for Forest Research and Survey (D.F.R.S.), 2015; Koopmans and Koppejan, 1997; M.O.A.D. 2014). **(Black and White**)

Figure 3a) shows the distribution of agricultural residues across Nepal is primarily located in the low lying Terai regions, and the least in the colder and less populated mountain regions. Figure 3b) shows the distribution of above-ground forestry growing stock across Nepal in governmental and C.F.U.G. controlled forests. The six key tree species represent slightly over half the total growing stock of the nation's forests. Forestry stock is the highest in the Mountains and, in particular, the Mid-far Western region, the largest area. There is less in the Terai because much of the land has been cleared for growing a number of cash crops. Of the agricultural residues present but not analysed in this article, rice straw is the largest contributor in the Terai but is omitted as anaerobic digestion is more suitable because of the high moisture content. In this region, sugarcane bagasse, rice husk and maize residue are found in similar quantities and account for roughly a quarter of the total resource. In the Mid-hills, there is a large amount of rice residue but almost half of the agricultural residues come from maize cropping. Within the Mountains region, there is little agricultural residue as it is so sparsely populated.

Ministry of Forest and Soil Conservation (2009) predicted that 2.1 tonnes of firewood can be sustainably harvested from a hectare of forest every year in Nepal, which is 1.1% of the total mass of forestry growing stocks and approximately 10.4 million tonnes a year. The yearly energy potential from all agricultural residues in Nepal is more than double this figure. To be able to utilise agricultural residues by charcoal making, anaerobic digestion or other modern renewable technologies, would therefore have great benefit to the prevention of deforestation for energy.

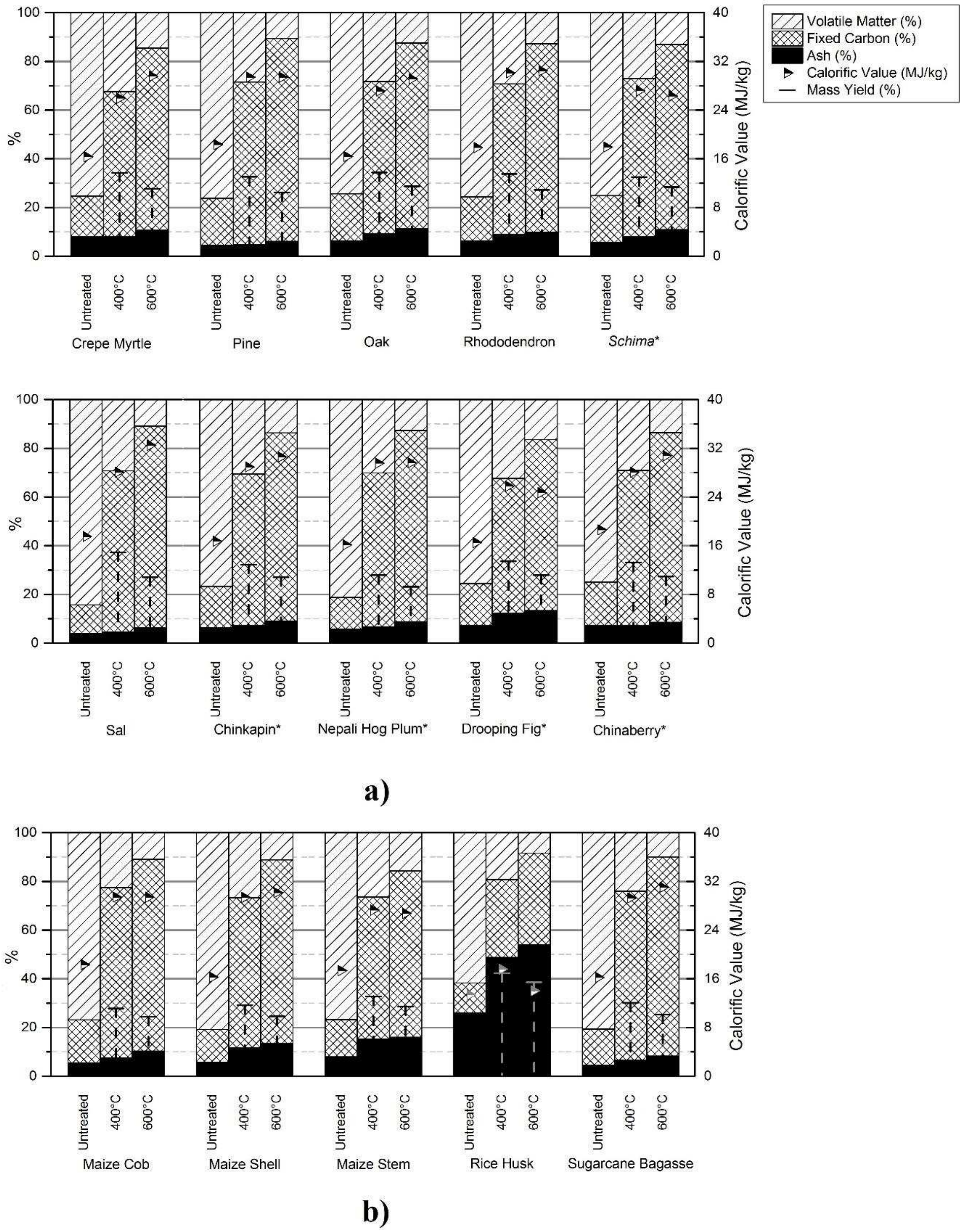

Figure 4 Proximate analysis (dry basis) and mass yields from different biomass and their associated charcoals. a) Ten common tree species, with five common cultivated for agroforestry highlighted with an asterisk, and b) Five agricultural residues.

Figure 4a) shows the ten tree species produce charcoal with similar characteristics but some minor differences. The calorific value is similar and ranges from 25 to 28 MJ/kg at 400°C, and 26 to 32.5 at 600°C. Pine and sal produce the best charcoal because they contain the lowest volatile matter, lowest ash and have a high calorific value at both temperatures. Crepe myrtle charcoal is poor as it is high in volatile matter, particularly at the lower pyrolysis temperature, and has a low calorific value.

In Nepal, agroforestry is also an important part of agricultural systems with many species cultivated for shade, fruit, firewood and timber. Schima is common to natural forests and farmland where it is cultivated as a shade tree. Charcoal from drooping fig and Schima branches are poorer than other species but are still usable as the volatile matter is low.

Figure 4b) shows the mass yield, proximate and calorific values of the agricultural residues tested and their associated chars. The sugarcane bagasse charcoal produced at 600°C has the highest calorific value and lowest amount of volatile matter. However, the highly fibrous structure of the material makes it harder to handle and so likely requires briquetting (compaction by mechanical means to improve density). Maize cob is a very suitable candidate for pyrolysis if a lower temperature of 400°C is used because the proportion of volatile matter is already much reduced. Of the maize residues, the stem is the worst part for charcoal production because there is more volatile matter remaining. Rice husk is a poor choice for producing charcoal because the calorific value is low, which results in poor combustion.

There are some differences in energy recovery. Pine and Schima both retain less energy than other forestry species. Sugarcane bagasse, sal, crepe myrtle, chinkapin and oak have very high energy recoveries meaning that they are more efficiently converted to charcoal.

The composition of the ash in the charcoal also influences the burning characteristics. The build-up of deposits, fouling, on cookstoves can occur in the presence of large amounts of alkali elements because they melt at lower temperatures (Saddawi et al., 2012). Table 1 shows this is a potential issue for agricultural residues from maize cob and sugarcane bagasse. Liu et al. (2013) and Gómez et al. (2016) found that removing alkali metals from biomass by leaching increases the temperature at which devolatilisation occurs and therefore reduces smoke. As the temperature at which fuels with less alkali metals burns is higher, the heat transfer coefficient will also be higher. Woody species sampled that were found to contain low levels of alkali metals include rhododendron, pine, sal, nepali hog plum and chinaberry. The presence of high alkali metal content in agricultural residues raises questions about the potential to create smoke which needs further investigation.

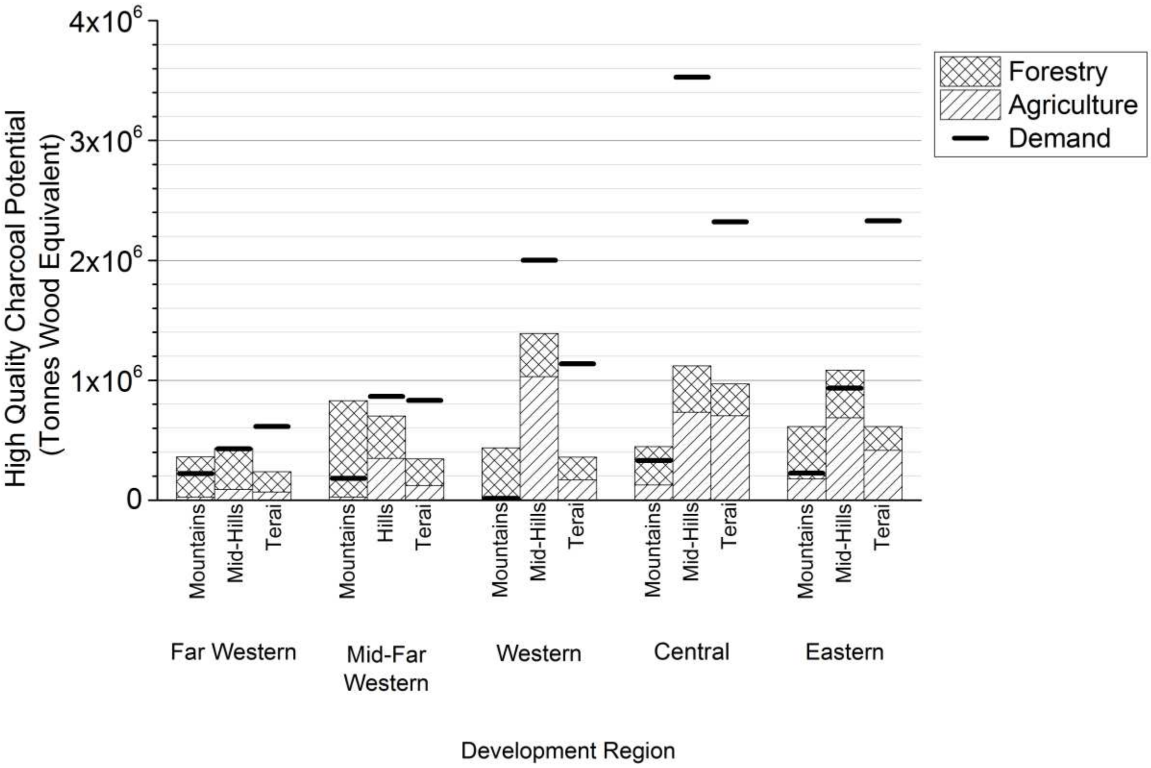

Figure 5 Comparison of regional demand against potential supply of high quality charcoal.

Figure 5 shows the regional supply and demand for high quality charcoal produced at 600°C. It was predicted that the total biomass demand in Nepal is 15,964,000 tonnes per year. The biomass demand is concentrated within the Mid-hills and Terai of the Western, Central and Eastern Development Regions. All of the forestry species and agricultural residues, excluding rice husk, can be converted to high quality charcoal at this temperature. The theoretical maximum high quality charcoal that can be produced is 9,945,000 tonnes of firewood equivalent each year. Whilst the Mountains regions contain some of the largest resource they contain the lowest demand. The areas with the most potential are the Mid-hills in the Eastern, Central and Western Development Regions and the central Terai which has a very large output of sugarcane. In the sparsely populated Mountains regions, the demand is much less than the theoretical source, hence the estimate is reduced by this difference (1,872,000 tonnes of firewood equivalent) to account for the infeasibility of collection, production of charcoal and transport to lower lying regions where demand is higher.

The estimated potential for high quality charcoal production from forestry and crop residues in the most populated regions in the east of the country is still well below reported demand for biomass fuels. The total potential for high quality charcoal is 9,945,000 tonnes of firewood equivalent per year with some surplus in the mountain areas. Taking into account accessibility and proximity of demand, the amount of charcoal is estimated to be approximately 8,073,000 tonnes of firewood equivalent. Compared to the current total use of biomass of 15,964,000, charcoal could provide 51% of the total energy need.

Of the total firewood collected in Nepal, between 60-70% is thought to be collected from state and community managed forests, the rest from private land (Bhattarai, 2013; Shrestha, 2007). The private land source hence equates to roughly 4,300,000 tonnes of firewood a year. Agroforestry, a traditional yet growing practice is one of the key sources of firewood from private land (Dhakal et al., 2015). The main drivers for the uptake include lack of access to public forest stocks, higher levels of education, larger farm size and a large labour force (Regmi and Garforth, 2010). Drooping fig trees planted in a field of maize and millet can produce 5.3 t/ha/yr without significantly affecting yields (Dhakal et al., 2015; Pandit and Paudel, 2013). An intercrop of alder and cardamom was estimated to produce a 3.2 t/ha/yr in thinnings (Zomer and Menke, 1993). The current supply of firewood from private land is already large and could potentially increase. By extrapolating from the area of agricultural land, the amount of charcoal which could be made from this is approximately 8,000,000 tonnes of firewood equivalent. Therefore, a large proportion of the total energy need can be achieved from the promotion of agroforestry. Producing more firewood in agricultural areas would also take stress of forests to provide the resource.

Removal and utilisation of invasive species is another potential source of biomass for charcoal production. Eupatorium adenophorum and Lantana camara, are invasive species, and were analysed and deemed capable of producing good charcoal (Appendix 2). There is, however, insufficient data as to the quantity of these resources available.

The agricultural residues, with the exception of rice husk, tested produced good charcoal, despite the poor starting material, which had a high volatile matter content when compared to the wood samples analysed. Figure 5 also shows that in areas where the demand for energy is the highest, agricultural residues have the potential to create the largest amount of good quality charcoal. As it is currently underutilised as a resource, producing charcoal with residues would be more sustainable than using forestry biomass. Throughout Nepal, the total amount of charcoal from the agricultural residues tested and found to be suitable that could be produced is 4,725,500 tonnes of firewood equivalent, providing 30% of the biomass energy need. With the potential to further increase the amount of fuel in agricultural areas through agroforestry, charcoal making in areas with large farming communities, such as the Central and Eastern Terai and Mid-hills, could be the most beneficial. The sum of charcoal that could be made in these areas from agricultural residues is 2,542,500 tonnes of firewood equivalent, 43% of the regional demand. For this situation, portable charcoal kilns could be suitable because they can be moved from farm to farm rather than transporting residues to a central location.

Recent policies for promoting anaerobic digestion have been moderately successful in Nepal and a similar framework could be used for charcoal technology (Rupf et al., 2015). Charcoal making systems could potentially be an alternative in farming regions in the Mid-hills and mountain regions where the low temperature makes anaerobic digestion with conventional systems unfeasible (Rupf et al., 2015).

Implementation of charcoal manufacturing systems would perhaps be simpler for the conversion of forestry firewood, compared to agricultural residues, because successful organisational structures already exist in C.F.U.G.’s. Historically, the groups have reduced deforestation showing that they can create products from the forests in a sustainable manner (Pokharel et al., 2015). Some C.F.U.G.’s manufacture advanced biofuels in the form of briquettes from forestry products and rice husk (W.E.C.S., 2013). Charcoal making could be integrated with the current briquetting activity using material from the forest or nearby farms. The energy densification (in terms of both weight and volume) that occurs during the process means that charcoal is easier to transport by foot from the forests to households than the equivalent in energy of wood- a useful advantage in a country where households usually spend several hours each day on the activity (St. Clair, 2016).

5. Conclusions

From the species tested approximately 9,945,000 tonnes of firewood equivalent of high quality charcoal could be produced. Once the infeasibility of transporting charcoal from the mountains to areas where demand is higher is considered, this reduces the value to approximately 8,073,000 tonnes of firewood equivalent per year.

The biggest advantage of introducing charcoal making systems is to increase the utilisation of agricultural residues. In the most agriculturally intense area of Nepal, the Western, Central and Eastern Mid-hills, and Central and Eastern Terai, 47% of the regional demand could be met by good charcoal produced from the materials analysed. By doing so, pressure would be reduced on forests to provide the biomass. Furthermore, charcoal fuels provide an alternative to biogas in the Mid-hills where the climate makes anaerobic digestion difficult.

The supply of firewood could be significantly increased by the adoption of agroforestry methods. Doing so could theoretically yield another 8,000,000 tonnes of firewood equivalent. To make this happen, farmer education is needed to ensure effective agroforestry practice. If this were achieved, then the majority of the biomass energy demand for the country could be met with charcoal produced from agricultural resources. In this situation, portable kilns could be a suitable technology, meaning a single piece of equipment could be used by several farmers.

There are two potential implementation strategies discussed. The first is to provide kilns to C.F.U.G’s which could produce and distribute charcoal made from forestry and nearby agricultural residues as is done with briquetting by some groups. The second is to use similar frameworks that have been used to promote biogas production in rural areas.

6. Acknowledgments

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Main text table

Sample	Na (ppm as recieved)	Mg (ppm A.R.)	K (ppm A.R.)	Ca (ppm A.R.)	P (ppm A.R.)	Si (ppm A.R.)	Al (ppm A.R.)
Forestry residues							
Lagerstroemia parviflora (Crepe myrtle)	485	1311	2976	11575	923	1776	1463
Pinus roxburghii (Pine)	470	217	550	1223	N.D.	2644	1714
Quercus semecarpifolia (Oak)	461	845	4526	6187	1123	1677	830
Rhododendron arboreum (Rhododendron)	476	545	2348	4181	563	9656	4689
Schima wallichii (Schima)	487	325	5980	5301	1019	840	N.D.
Shorea robusta (Sal)	78	500	52	2439	503	603	345
Agroforestry Species							
Castanopsis Inidica (Chinkapin)	537	783	5132	3807	1288	1552	N.D.
Choerospondias axillaris (Nepali hog plum)	435	1042	1702	5677	218	1141	515
Ficus semicordata (Drooping fig)	542	899	4411	11555	1289	3270	110
Melia azedarach (Chinaberry)	416	319	1488	5096	773	7944	3602
Agricultural residues							
Maize cob	451	262	4792	680	N.D.	17071	522
Maize stem	547	2002	8268	2232	2834	11926	247
Maize cover	509	1209	7244	1474	931	14490	2387
Rice husk	583	1148	6303	2638	2787	97509	43
Sugarcane bagasse	456	275	3984	577	1342	4630	N.D.

Table 1: Trace element analysis (parts per million (ppm)) of forestry resources, agricultural wastes, grasses and shrubs. All performed by ICP-OES except phosphorus (colorimetry) and silicon and aluminium (XRF). N.D denotes not detected.

Appendix 1- Species list and sampling location

Family	Scientific Name	Local Name	Parts collected	Weight (gm)	Locality	Altitude (m)	Coordinates	
Verbenaceae	Lantana camara L.	Ban Fanda	Stem	255.38	CDB, TU	1330		
Moraceae	Ficus semicordata Buch.-Ham. ex Sm.	Khanaayo	Stem	256.55	Above Arughat Bazar, Dhading	520	280230.4	844851.5
Theaceae	Schima wallichii (DC.) Korth.	Chilaune	Stem	256.68	Above Arughat Bazar, Dhading	533	280230.2	844853.8
Poaceae	Zea mays L.	Makai	Cob	255.43	Arughat, Dhading	500		
Poaceae	Eleusine coracana (L.) Gaertn.	Kodo	Husk	265.04	Arughat, Dhading	500		
Poaceae	Oryza sativa L.	Dhaan	Husk	264.07	Arughat, Dhading	500		
Lythraceae	Woodfordia fructicosa (L.) Kurz	Dhayaro	Stem	256.64	Above Arughat Bazar, Dhading	518	280229.6	844851.1
Lythraceae	Lagestroemia parviflora Roxb.	Bot dhairo	Stem	255.62	Deorali, after Dakshinkali	1734	273401.5	851359
Ericaceae	Lyonia ovalifolia (Wall.) Drude	Angeri	Stem	254.76	Near Dakshinkali	1610	273502.6	851522.5
Ericaceae	Rhododendron arboreum Sm.	Lali Gurans	Stem	257.34	Kalanki, Kulekhani dam area	1600	273601.3	850955.5
Betulaceae	Alnus nepalensis D. Don	Uttis	Stem	255.89	Near Kakani, Kulekhani	1234	273349.8	831218
Anacardiaceae	Choerospondias axillaris (Roxb.) B. L. Burtt & A. W. Hill	Lapsi	Stem	255.89	Sim, Kirtipur	1330		
Pinaceae	Pinus roxburghii Sarg.	Salla	Stem	256.53	Nigalpani, Dhading	1180	275640	845123
Fagaceae	Quercus semecarpifolia Smith.	Khasru	Stem	256.74	Near Kulekhani Dam	1870	273556.8	851307.1
Fagaceae	Castanopsis indica (Roxb.) Miq.	Katus	Stem	257.53	Kume Jyamrung, Dhading	890	275838	845013
Myricaceae	Myrica esculenta Buch.-Ham. ex D. Don	Kafal	Stem	256.8	Near Kulekhani Dam	1620	273617	851132.4
Ericaceae	Gaultheria fragrantissima Wall.	Dhasingare	Stem	256.54	Deorali, after Dakshinkali	1734	273401.5	851359
Rutaceae	Zanthoxylum armatum DC.	Timur	Stem	255.17	Near Kulekhani Dam	1645	273622.5	851144.4
Asteraceae	Ageratina adenophora (Spreng.) R.M. King & H. Rob. (Syn. Eupatorium adenophorum Spreng.)	Banmaara	Stem	255.77	Near Dakshinkali	1610		
Poaceae	Zea mays L.	Makai	Stem	255.68	Arughat, Dhading	500		
Asteraceae	Artemisia indica Willd.	Titepaati	Stem	255.59	Near Dakshinkali	1610	273502.6	851522.5
Poaceae	Thysanolaena maxima (Roxb.) O. Kuntze	Amrisho	Stem, Flower	283.71	Sisneri, above Dakshinkali	1212	273348.9	851215.1
Meliaceae	Melia azederach L.	Bakaaino	Stem	256.36	Above Arughat Bazar, Dhading	509	280229.3	844849.5
Poaceae	Zea mays L.	Makai	Fruit cover	255.53	Arughat, Dhading	500		
Poaceae	Saccharum officinarum L.	Ukhu	Husk	255	Local market, Kathmandu			
Poaceae	Brassica campestris L.	Tori	Residue	260				

Appendix 2- Table of proximate and ultimate analyses performed on collected samples

Sample	Moisture (% As received (% AR))	Volatile matter (% Dry basis (%DB))	Fixed carbon (% DB)	Ash (% DB)	Carbon (% DB)^b	Hydrogen (% DB)^b	Nitrogen (% DB)^b	Sulphur (% DB)^b	Oxygen (% DB)^c	Higher Calorific value (MJ/kg) DB^d
Alnus nepalensis	3.55	80.37	14.43	5.19	47.82	5.89	0.38	N.D.	40.71	17.35
Castanopsis indica	3.77	76.65	16.95	6.40	46.67	5.75	0.34	N.D.	40.84	16.74
Choerospondias axillaris	3.39	81.28	12.96	5.76	46.07	5.66	0.29	N.D.	42.22	16.15
Ficus semicordata	5.20	75.59	17.21	7.20	46.60	5.55	0.31	N.D.	40.34	16.51
Lagerstroemia parviflora Roxb	4.51	75.31	16.64	8.05	46.07	5.51	0.41	N.D.	39.97	16.34
Lyonia ovalifolia	4.19	76.79	18.72	4.49	48.92	6.68	0.40	N.D.	39.50	19.09
Melia azedarach	4.53	74.92	17.88	7.20	48.03	6.37	0.50	N.D.	37.90	18.62
Myrica esculenta	4.97	74.60	18.74	6.67	47.47	5.44	0.51	0.06	39.86	16.72
Quercus semecarpifolia	5.49	74.32	19.51	6.17	47.45	5.30	0.39	N.D.	40.70	16.37
Pinus roxburghii	4.41	76.17	19.31	4.52	49.72	5.86	0.15	N.D.	39.76	18.12
Rhododendron arboreum	3.90	75.59	18.10	6.31	48.49	5.87	0.25	N.D.	39.08	17.84
Schima wallichii	3.90	75.08	19.30	5.62	47/89	6.20	0.27	N.D.	40.01	17.94
Shorea robusta	4.83	84.33	11.72	3.94	50.55	5.26	0.39	N.D.	39.85	17.52
Zanthoxylum armatum	3.50	77.80	15.35	6.85	46.79	5.84	0.49	0.02	40.02	17.04
Artemisa indica	4.30	75.16	18.40	6.44	47.19	5.83	0.72	N.D.	39.82	17.20
Eupatorium adenophorum	4.54	80.76	13.12	6.12	45.81	6.00	0.32	N.D.	41.74	16.65
Gaultheria fragrantissima	3.49	78.70	15.35	6.85	47.52	5.71	0.17	N.D.	41.26	16.89
Lantana camara	3.38	76.51	17.09	6.40	45.65	6.02	0.54	0.04	41.36	16.68
Woodfordia fructicosa	4.92	74.53	18.97	6.49	47.33	6.06	0.41	N.D.	39.70	17.61
Brassica campestris	5.12	70.98	12.99	16.02	41.51	5.26	1.76	0.05	35.40	15.25
Saccharum officinarum	2.79	80.68	14.77	4.56	45.81	5.94	0.12	0.11	43.47	16.23
Thysanolaena maxima	4.03	73.60	18.53	7.87	45.34	5.56	0.34	N.D.	40.89	16.00
Finger millet	5.26	69.73	13.88	16.39	40.61	5.66	1.50	N.D.	35.84	15.46
Maize cob	4.44	76.92	17/61	5/47	46.27	5.96	0.34	N.D.	41.96	16.69
Maize stem	3.51	76.81	15.29	7.90	47.27	5.75	0.31	0.14	38.62	17.33
Maize cover	4.81	80.68	14.77	4.56	45.42	5.94	0.42	N.D.	42.56	16.27
Rice husk	4.42	61.69	12.37	25.94	36.23	4.77	0.95	N.D.	32.11	13.37

Table of proximate and ultimate analyses performed on all produced charcoals

Sample and pyrolysis temperature (°C)	Char Yield (%)	Moisture (% As received (% AR))	Volatile matter (% Dry basis (%DB))	Fixed carbon (% DB)	Ash (% DB)	Carbon (% DB)^b	Hydrogen (% DB)^b	Nitrogen (% DB)^b	Sulphur (% DB)^b	Oxygen (% DB)^c	Higher Calorific value (MJ/kg) DB^d	Energy recovery (%)
Alnus nepalensis 400°C	30.3	3.08	28.05	63.21	8.74	69.85	3.42	0.76	N.D.	15.23	26.24	45.78
Castanopsis indica 400°C	33.1	4.49	30.46	62.40	7.14	74.47	3.49	0.71	N.D.	11.02	28.93	57.22
Choerospondias axillaris 400°C	27.9	3.89	30.09	63.29	6.62	75.52	3.73	0.28	N.D.	11.08	29.55	51.02
Ficus semicordata 400°C	33.6	4.01	32.36	55.40	12.24	67.42	3.43	0.42	N.D.	13.98	25.75	52.38
Lagerstroemia parviflora Roxb 400°C	34.2	3.84	32.4	59.61	8.00	69.83	3.23	0.70	N.D.	15.74	25.96	54.34
Lyonia ovalifolia 400°C	32.1	3.36	26.67	66.47	6.85	74.44	3.54	0.52	N.D.	12.31	28.59	48.03
Melia azedarach 400°C	32.2	3.71	29.00	63.88	7.12	72.90	3.61	0.72	N.D.	13.11	28.06	48.57
Myrica esculenta 400°C	33.3	3.93	28.87	63.07	8.05	73.27	3.29	0.81	N.D.	11.87	27.97	55.73
Quercus semecarpifolia 400°C	34.4	3.93	29.52	61.64	8.84	71.22	3.40	0.66	N.D.	13.07	27.14	57.00
Pinus roxburghii 400°C	32.6	3.28	28.60	67.53	3.88	76.31	3.80	0.20	N.D.	13.48	29.41	52.21
Rhododendron arboreum 400°C	33.8	3.35	29.21	61.96	8.83	76.25	3.66	0.51	N.D.	8.36	30.12	57.08
Schima wallichii 400°C	32.5	3.32	26.97	65.11	7.92	72.07	3.37	0.28	N.D.	14.15	27.16	49.19
Shorea robusta 400°C	37.3	1.26	29.28	66.23	4.49	76.13	3.53	0.37	N.D.	15.48	28.08	59.77
Zanthoxylum armatum 400°C	29.4	3.84	29.43	60.39	10.18	72.94	3.49	0.73	N.D.	10.04	28.46	49.15
Artemisa indica 400°C	30.5	4.45	28.22	62.25	9.53	74.40	3.61	1.06	N.D.	8.23	29.59	52.49
Eupatorium adenophorum 400°C	28.0	3.24	27.34	66.39	6.26	76.97	3.67	0.62	N.D.	10.13	30.04	50.47
Gaultheria fragrantissima 400°C	28.9	3.48	26.83	67.40	5.78	76.08	3.58	0.37	N.D.	11.72	29.34	50.24
Lantana camara 400°C	29.5	3.80	23.91	65.83	10.26	68.38	3.04	0.77	N.D.	15.15	25.26	44.73
Woodfordia fructicosa 400°C	33.9	4.05	30.19	61.52	8.29	69.29	3.26	0.41	N.D.	16.15	25.77	49.61
Brassica campestris 400°C	36.9	6.58	38.19	40.82	21.00	52.05	2.78	1.93	0.10	18.95	18.59	44.99
Saccharum officinarum 400°C	30.1	2.28	24.05	69.46	6.49	76.21	3.65	0.20	N.D.	11.84	29.29	54.38
Thysanolaena maxima 400°C	32.4	3.95	24.24	60.46	15.30	70.02	3.43	0.28	0.04	8.38	27.66	56.07
Finger millet 400°C	36.6	5.52	28.64	43.70	27.66	53.93	3.08	1.69	0.04	10.82	21.14	50.06
Maize cob 400°C	27.8	2.88	22.46	69.98	7.56	75.89	3.68	0.44	N.D.	10.39	29.58	49.30
Maize stem 400°C	32.8	4.27	26.35	58.35	15.29	69.25	3.40	0.35	N.D.	8.96	27.29	51.63
Maize cover 400°C	29.1	3.79	26.71	61.74	11.55	73.78	3.66	0.35	N.D.	8.05	29.37	52.61
Rice husk 400°C	42.3	3.69	19.20	32.08	48.72	42.96	2.46	1.22	N.D.	3.29	17.58	55.65

Table continued

Sample and pyrolysis temperature (°C)	Char Yield (%)	Moisture (% AR)	Volatile matter (% DB)	Fixed carbon (% DB)	Ash (% DB)	Carbon (% DB)[b]	Hydrogen (% DB)[b]	Nitrogen (% DB)[b]	Sulphur (% DB)[b]	Oxygen (% DB)[c]	HHV (MJ/kg) DB[d]	Energy recovery (%)
Alnus nepalensis 600°C	25.2	1.37	12.75	75.98	11.27	78.29	2.08	1.29	N.D.	7.08	28.23	40.95
Castanopsis inidica 600°C	27.3	2.60	13.68	77.42	8.90	83.34	2.20	0.97	N.D.	4.59	30.57	49.92
Choerospondias axillaris 600°C	23.1	1.57	12.71	78.66	8.63	81.28	2.29	1.11	N.D.	6.70	29.61	42.40
Ficus semicordata 600°C	27.9	2.38	16.46	70.17	13.37	72.79	1.52	0.45	N.D.	11.87	24.70	41.72
Lagerstroemia parviflora Roxb 600°C	27.7	1.78	14.58	74.66	10.75	81.93	1.86	0.73	N.D.	4.72	29.58	50.21
Lyonia ovalifolia 600°C	27.2	2.02	10.87	80.49	8.64	79.40	1.55	0.55	N.D.	9.86	27.35	38.96
Melia azedarach 600°C	27.1	1.97	13.61	77.89	8.50	83.28	2.41	0.82	N.D.	5.00	30.77	44.71
Myrica esculenta 600°C	28.1	1.95	13.34	77.21	9.45	80.52	2.10	1.41	N.D.	6.52	29.12	48.91
Quercus semecarpifolia 600°C	28.7	2.06	12.38	76.38	11.24	80.11	2.11	0.74	N.D.	5.80	29.13	51.05
Pinus roxburghii 600°C	26.1	1.09	10.50	83.52	5.98	83.06	1.97	0.27	N.D.	8.72	29.39	41.88
Rhododendron arboreum 600°C	27.2	1.72	12.69	77.41	9.90	82.56	2.28	0.95	N.D.	4.31	30.46	46.44
Schima wallichii 600°C	28.4	2.56	13.02	76.13	10.85	77.16	1.41	0.36	N.D.	10.23	26.31	41.70
Shorea robusta 600°C	27.0	0.39	10.82	82.86	6.32	87.36	2.44	0.39	N.D.	3.48	32.48	50.04
Zanthoxylum armatum 600°C	24.9	2.24	13.74	75.73	10.54	82.73	2.10	1.84	N.D.	2.80	30.54	44.60
Artemisa indica 600°C	27.3	3.44	13.03	75.64	11.32	80.39	1.90	2.74	N.D.	3.65	29.31	46.51
Eupatorium adenophorum 600°C	23.9	3.57	15.60	68.44	15.96	79.35	1.67	0.59	N.D.	9.50	27.56	39.50
Gaultheria fragrantissima 600°C	24.7	1.69	11.30	80.54	8.16	81.61	2.08	0.88	N.D.	7.27	29.33	42.90
Lantana camara 600°C	26.2	4.10	16.78	70.85	12.37	78.53	1.71	1.29	N.D.	6.10	27.96	43.92
Woodfordia fructicosa 600°C	27.9	1.91	14.30	74.69	11.01	80.43	2.17	0.45	N.D.	5.93	29.30	46.39
Brassica campestris 600°C	32.8	3.92	21.31	53.42	25.27	59.44	0.97	1.45	0.48	12.39	19.25	41.39
Saccharum officinarum 600°C	25.3	1.57	9.93	81.83	8.24	84.57	2.21	0.40	N.D.	4.57	31.01	48.36
Thysanolaena maxima 600°C	28.4	3.33	12.24	67.82	19.94	70.14	1.15	0.41	N.D.	8.36	23.90	42.45
Finger millet 600°C	32.5	4.97	19.69	48.77	31.54	57.47	1.56	1.39	N.D.	8.04	20.27	42.55
Maize cob 600°C	24.4	2.51	10.91	78.75	10.34	80.35	2.04	1.09	N.D.	6.17	29.04	42.50
Maize stem 600°C	28.6	3.57	15.60	68.44	15.96	74.56	1.82	1.32	N.D.	6.33	26.74	44.13
Maize cover 600°C	24.6	2.56	11.08	75.39	13.53	81.14	2.09	1.34	N.D.	1.89	30.15	45.58
Rice husk 600°C	38.5	1.85	8.42	37.59	54.00	39.72	0.94	1.05	N.D.	4.29	14.03	40.45