621.042
SED

T345

FUELWOOD CHARACTERISTICS OF SOME INDIGENOUS TREE SPECIES OF ARUNACHAL PRADESH

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

PITAMBAR SEDAI
Registration Number 021 of 2011

SCHOOL OF ENGINEERING
DEPARTMENT OF ENERGY
TEZPUR UNIVERSITY
JUNE, 2014

This Thesis is dedicated to my dearest grandmother

Late Basalla Devi

&

My parents

Their love and constant effort inspired me to complete this research work successfully.

Pitambar

DECLARATION

I do hereby declare that the thesis entitled ***"Fuelwood characteristics of some indigenous tree species of Arunachal Pradesh"***, being submitted to the Department of Energy, Tezpur University, is a record of original research work carried out by me. All sources of assistance have been assigned due acknowledgment. I also declare that neither this work as a whole nor a part of it has been submitted to any other University or Institute for any other degree, diploma or award.

Pitambar Sedai

Place : Tezpur University, Tezpur

(Pitambar Sedai)

Date :

TEZPUR UNIVERSITY

(A Central University established by an Act of Parliament)

NAPAAM, TEZPUR-784028, ASSAM

CERTIFICATE BY THE SUPERVISOR

This is to certify that the matter embodied in the thesis entitled ***"Fuelwood characteristics of some indigenous tree species of Arunachal Pradesh"*** submitted to the School of Engineering, Tezpur University in partial fulfillment for the award of the degree of Doctor of Philosophy in **Energy,** is a record of research work carried out by **Mr. Pitambar Sedai** under my supervision and guidance.

All help received by him from various sources have been duly acknowledged.

No part of this thesis has been submitted elsewhere for award of any other degree.

Supervisor: Prof. Dhanapati Deka

Designation: Professor

School: Engineering

Department: Energy

Date: 1/5/15

TEZPUR UNIVERSITY

(A Central University established by an Act of Parliament)
NAPAAM, TEZPUR-784028
DISTRICT : SONITPUR :: ASSAM :: INDIA
Ph: 03712-267004, 267005 Fax: 03712-267005, 267006

CERTIFICATE

This is to certify that the thesis entitled ***"Fuelwood characteristics of some indigenous tree species of Arunachal Pradesh"*** submitted to the Tezpur University in the Department of Energy under the School of Engineering; in partial fulfillment for the award of the Degree of Doctor of Philosophy in Science, has been examined by us on May 1, 2015 and found to be satisfactory.

The committee recommends for the award of the degree of Doctor of Philosophy.

Supervisor
Prof. D. Deka

Date: 1/5/15

External Examiner

Date: 01-05-2015

ACKNOWLEDGEMENT

In the endeavor of the journey towards my doctoral work, this thesis has been kept on track and seen through to completion with the support and encouragement of numerous people including my supervisor, well-wishers, friends, colleagues and different laboratories. It is a pleasant opportunity to express my wholehearted thanks to all those people who made this thesis possible and contributed in different ways.

I am greatly indebted to my venerable supervisor Prof Dhanapati Deka for his keen interest, constant guidance and encouragement, authoritative discussion during the entire course of my Ph. D. programme and innumerable constructive suggestions and help during the preparation of this manuscript.

I would also like to thank my doctoral committee members, Prof. D. C. Baruah and Dr. R. Kataki of department of Energy and Prof. T. K. Maji Department of chemical sciences for serving as my doctoral committee members and their valuable advice, helpful suggestions, comments and encouragement.

I convey my sincere gratitude and thanks to Prof. D. Deka, Head, Prof. S, K. Samdarshi and Prof. D. C. Baruah, former heads, Dept. of Energy for providing me the necessary facilities to carry out my research work. I would also like to thank Mr. S. Mahapatra, Mr. P. K. Choudhury and Dr. P. Kalita of Department of Energy for their support, encouragement and valuable advices.

I offer my special thanks to all my lab-mates Dr. Jutika Boro, Lakhya, Subrata, Plaban and Anuchaya for their help and inspiration.

It is my pleasure to offer gratitude and thanks to Biswajit Gogoi, Technical officer, Tapanjit Borah, Technical Assistant, T. Lahon, Lab assistant, Chittaranjan Gogoi, Office Assistant, Department of Energy, Tezpur University, for their co-operation and encouragement.

I received great help from my friends, Rahul, Mayur, Debashis and all my fellow researcher friends, department of Energy, during the entire period of my Ph.D. work.

I express my gratitude and thanks to Prof. B. N. Medhi, Prof. S. K. Duloi, Prof B. K. Danta, Dr. R. R. Hoque, Dr. Hironmoyee Borah Dr. Barnali Das and Dr. Seema Srakar for their help and encouragement.

I express my sincere thanks to Dr. J. Chetia, Dibrugarh University, Dr. Dipul Kalita and Dr. Prasenjit Saikia, NEIST, Jorhat for their support while facilitating the infrastructure for sample testing.

I am thankful to L.O.K.D. college authority for providing me time to carry out entire research work. I am also very much thankful to my colleagues for their inspiration and valuable suggestions.

Last but not least, I am grateful to my family members for their timely inspiration, love, care and support during the uncompromising time of my research work.

(Pitambar Sedai)

Abstract

ABSTRACT

At present, the greatest share of the world's energy need comes from conventional fossil fuels. Looking into the finite nature of the existent petro fuels reservoirs, the wide scale availability of biomass is much alluring as a source of energy. Biomass has been serving mankind from antiquity as a primary source of energy in the form of wood and charcoal for cooking and heating appliances. Biomass fuels are available almost everywhere on earth, virtually inexhaustible, and, when properly managed, renewable and environmentally friendly. Besides, greenhouse gas emissions can be effectively reduced through sustainable management of fuelwood.

Globally, fuelwood has long been recognized as an energy source for heating and cooking appliances. In India, about 70% of the energy requirement in rural areas is met by fuelwood collected from the forests. The North-Eastern region of India has been characterized with different topography, soil characteristics and climatic conditions as compared to other parts of the country. A majority of household in this region is dependent on fuelwood as a primary energy source. Commercial fuel is generally beyond the reach of rural people of this region, due to their socio-economic conditions, lack of transportation facilities etc.

Arunachal Pradesh is one of the states in N-E India having largest forest area (61.5% of the total geographical area) among the North-Eastern states of India. Heavy rainfall and favourable climatic conditions in the Arunachal Pradesh favour the abundant growth of numerous indigenous tree and shrub species. But as of now, there is paucity of scientific literature pertaining to fuelwood characterization of the available indigenous tree species of this region. In this regards, the present study is an endeavor to screen out potential fuelwood species available in Arunachal Pradesh, India through a systematic study.

The present investigation was undertaken with a view to identify some potential indigenous fuelwood species of Arunachal Pradesh based on local users knowledge. The tree species selected for the present investigation were *Castanopsis indica, Macaranga pustulata, Dysoxylum binectariferum, Bridelia retusa, Myrsine semiserrata, Celtis australis, Dysoxylum procerum, Terminalia myriocarpa, Syzygium cerasoides, Kydia calycina, Mallotus phillipensis, Albizia odoratissima, Litsea polyantha, Mimusops elengi, Bauhinia variegata, Premna integrifolia, Talauma hodgsonii, Pterospermum acerifolium, Vitex altissima, Schima wallichii, Alnus nepalensis, Qurcus lanata, Qurcus leucotrichophora, Rhododendron arboreum, Myrica esculenta* and *Ehretia acuminata.*

The present thesis mainly consists of five chapters viz., Introduction, Review of literature, Materials and methods, Results and discussion and Summary and conclusion.

The introduction chapter (1st Chapter) deals with present world energy scenario along with the importance of biomass as a source of renewable energy. In addition, importance of wood as a source of primary energy along with its demand and supply relevance to India is also highlighted. The chapter also includes the objectives defined for the current investigation.

In the literature review chapter (2nd Chapter), a brief description about wood and its properties, the study conducted on fuelwood species in abroad and India are presented. Different fuelwood characteristics such as calorific value, density, proximate and ultimate composition, biochemical composition along with their influence on heating value are also discussed. Besides, the studies on thermal degradation of wood/biomass with the help of thermogravimetric analysis (TGA) as reported by many researchers are also presented.

The third chapter deals with the materials used and methodology adopted for the present study. The detail methodology for sample collection and analysis as per standard methods are presented in this chapter.

The Chapter 4 presents the results obtained in the present investigation along with the discussion. The chapter is subdivided into seven parts.

In the first part, the important fuelwood quality criteria considered by the local users of Arunachal Pradesh for selection of suitable fuelwood species were identified with the help of key informers. A ranking matrix was drawn from the pair-wise comparison (PWC) of these fuelwood species using 10 quality criteria (fast drying, hot flame, ember production, flame not smoky, easily flammable, non-sparking, weight when dry, easiness of splitting, low moisture when fresh cut and insect/termite resistance). On the basis of PWC, the 10 best fuelwood species in descending order was found as follows:

Q. lanata ~ *D. procerum, V. altissima, L. polyantha, Q. leucotrichophora, R. arboreum, M. pustulata, E. acuminata, D. binectariferum* and *M. esculenta.*

The second part of this chapter deals with the ranking of fuelwood species on the basis of Fuel Value Index (FVI) and its comparison with pair-wise comparison (PWC) ranking. In this part different fuelwood characteristics such as moisture, density, ash, and calorific value were determined to calculate three different types of FVIs (FVI-I, FVI-II and FVI-III). FVI-I depends upon calorific value and density as positive character and moisture and ash contents as negative characters. Thus, FVI-II depends upon calorific value and density as positive character and ash contents as negative character whereas moisture content is considered only as negative character for FVI-III with calorific value and density as positive character.

FVI-I was highest for *Q. lanata* among all the species under investigation followed by *D. procerum, Q. leucotrichophora, R. arboreum, D. binectariferum, M. esculenta, M. pustulata* etc. and lowest for *B. variegata.*

FVI-II was highest for *Q. lanata* followed by *D. procerum, R. arboreum, M. pustulata, Q. leucotrichophora, M. esculenta, L. polyantha, D. binectariferum, E. acuminata, T. hodgsonii* etc. and lowest for *B. variegata.*

FVI-III was highest for *Q. leucotrichophora* followed by *M. elengi*, *Q. lanata*, *V. altissima*, *D. binectariferum*, *S. wallichii*, *A. odoratissima*, *M. semiserrata*, *C. indica*, *M. phillipensis* etc. and lowest for *A. nepalensis*.

The values of FVIs showed similarity between for FVI-I and FVI-II ranking. Similarly, the FVI-I & FVI-II ranking were also in close proximity with the PWC ranking. However, no similarity was observed for the aforesaid rankings with FVI-III ranking. FVI-II can be easier to resemble with PWC ranking, it considers only ash as negative character. On the other hand, moisture content is not an important characteristic for the common people during selection of preferred fuelwood species, they keep the tree species for sundry at least 6-8 weeks before use as firewood.

The third part deals with the drying behaviour of the fuelwood species and the effect of moisture content on heating value. The study revealed that the final moisture content retained in the fuelwood species after 8 weeks of sundry was independent with the green moisture content of the tree species. On the other hand, Gross calorific value (GCV), Net calorific value (NCV) and Usable heat content (UHC) [calculated at their green moisture] decreased with the increase in green moisture content of the fuelwood species. It signifies that tree species with low green moisture content are more desirable as firewood for getting effective and usable heat.

The fourth part of the study deals with the proximate, ultimate and biochemical composition analysis of the tree species. The statistical analysis to study the relationship of the various components such as GCV, carbon content (C), lignin content, ash content of the fuelwood species is also presented in this chapter. GCV of fuelwood species increased with increase in carbon, hydrogen, lignin and extractive content (extracted with ethanol-benzene) whereas, decreased with increase in ash content. Statistical analysis further revealed the same (in terms of positive correlation between GCV and carbon content; GCV and lignin content; and negative correlation between GCV and ash content).

The fifth Part of the investigation presents the analysis of ash of the fuelwood species. Ash analysis of the fuelwood species revealed the predominance of Ca and K over

other inorganic elements. The study showed that the concentration range of heavy metals such as Cu, Zn, Pb and Cd were well below the pollution concentration limit.

The ranking of fuelwood species on the basis of Combustion characteristic factor (CCF) is presented in sixth part of this chapter. Different combustion characteristics such as ignition temperature, burnout temperature, Maximum combustion rates, peak temperature etc. were determined with the help of TGA and CCF for individual tree species were calculated. The calculated CCF was highest in *Q. leucotrichophora* while lowest in *M. phillipensis*. On the basis of CCF the most suitable fuelwood species was *Q. leucotrichophora* followed by *M. esculenta, D. procerum, R. arboreum, Q. lanata, S. wallichii, L. polyantha, V. altissima, M. pustulata, D. binectariferum* etc.

The seventh part of this chapter presents the overall ranking (OR) of the fuelwood species on the basis of PWC, FVI and CCF.

In the present investigation on the basis of OR, the potential fuelwood species in descending order were: *D. procerum, Q. lanata, Q. leucotrichophora, R. arboreum, L. polyantha ~ M. esculenta, M. Pustulata, V. altissima, D. binectariferum, S. wallichii ~ E. acuminata, M. elengi, C. australis, T. hodgsonii, A. odoratissima ~ M. semiserrata, B. retusa, P. acerifolium, K. calcyna, A. nepalensis, S. cerasoids, T. myriocarpa, C. indica, M. phillipensis, P. integrifolia, B. variegata.*

In the last chapter of this thesis (Chapter 5: Summary and Conclusion), summary of all the results with some conclusions drawn from the study are presented. Finally, some recommendations for future work in relation to the present investigation are suggested.

Table of contents

Chapter 1: Introduction

Chapter 2: Review of literature

Chapter 3: Materials and methods

Chapter 4: Results and Discussion

Chapter 5: Summary and conclusions

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBRIVIATIONS

$(dw/dt)_{max}$	Maximum combustion rate
$(dw/dt)_{mean}$	Mean combustion rate
a	Ash content
ADF	Acid detergent fibre
ADL	Acid detergent lignin
AOAC	Association of Official Analytical Chemists
ASTM	American Standard Test Method
Btu	British thermal unit
CCF	Combustion Characteristic Factor
CV	Calorific value
d	Density
DP	Degree of polymerization
DTG	Differential thermogravimetric
dw	Dry weight
EDTA	Ethylenediaminetetraacetic acid
GJ	Gigajoule
ha	Hectare
FC	Fixed carbon
FSP	Fiber Saturation Point
FVI	Fuel Value Index
GHG	Greenhouse gas
HCV	Higher calorific value
HEC	Hot water extractive content
HHV	Higher heating value
IEO	International Energy Outlook
ISFR	India State of Forest Report
LCV	Lower calorific value
m	Green moisture

NDF	Neutral detergent fibre
N-E	North-East
NO_X	Oxides of nitrogen
OEC	Organic extractive content
PWC	Pair-wise comparison
SO_X	Oxides of sulphur
SPSS	Statistical Package for the Social Sciences
TAPPI	Technical Association of the Pulp and Paper Industry
T_{BO}	Burnout temperature
TEC	Total extractive content
TGA	Thermogravimetric analysis
T_i	Ignition temperature
TOF	Tree outside forest
UHC	Usable heat content
VM	Volatile matter
ORSI	Overall rank sum index

Chapter 1

Introduction

Chapter 1
Introduction

Energy is an essential input for industrial and economic development and for improving the quality of human life. Improvements in lifestyles have historically been associated with increases in energy consumption and the access to appropriate energy services [1]. Future economic growth will rely heavily on long term availability of energy from sources which are affordable, accessible, secure and sustainable [2]. Until the 18th Century, almost all energy used by man was supplied locally from traditional energy sources such as human and animal power, wood, dung, crop residues, charcoal, peat, coal and the utilization of wind, water power etc. Before man started using petroleum, coal was the major source of energy. It became the foundation upon which early industrial society was built [3]. At present, the greatest share of the world's energy need comes from conventional fossil fuels (Figure 1.1.)

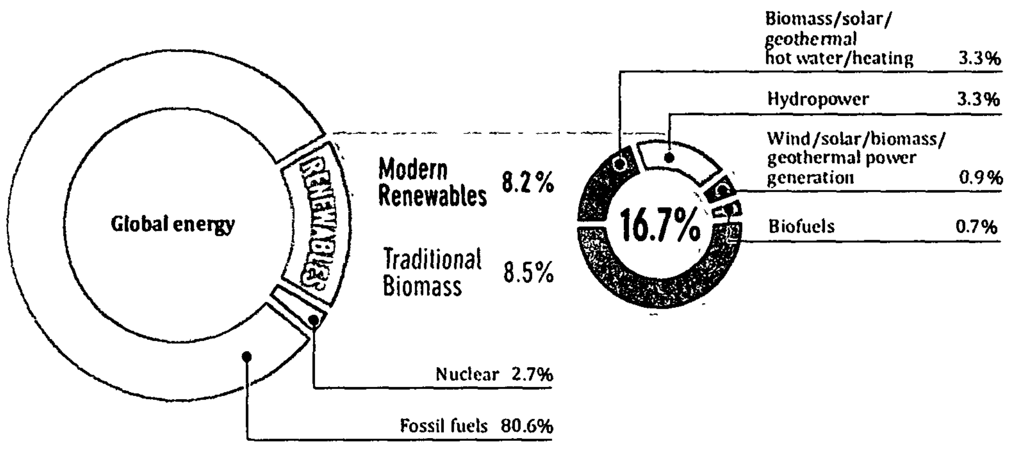


Figure 1.1: Global final energy consumption along with renewable energy share, 2010 [4]

The present century has witnessed exponential hike in global energy demand owing to population explosion and urbanization. According to the International Energy Outlook (IEO 2013) projections world energy consumption will increase by 56% between 2010 – 2040 where total world energy consumption is projected to be 630 quadrillion Btu in 2020 and 820 quadrillion Btu in 2040. Fossil fuel furnishes the major share of the global energy usage and liquid fuels mainly petroleum based remain the largest source of energy (Figure 1.2). The global use of petroleum and other liquid fuels from 87 million barrels per day in 2010 is projected to increase to 97 million barrels per day in 2020 to 115 million barrels per day in 2040 [5].

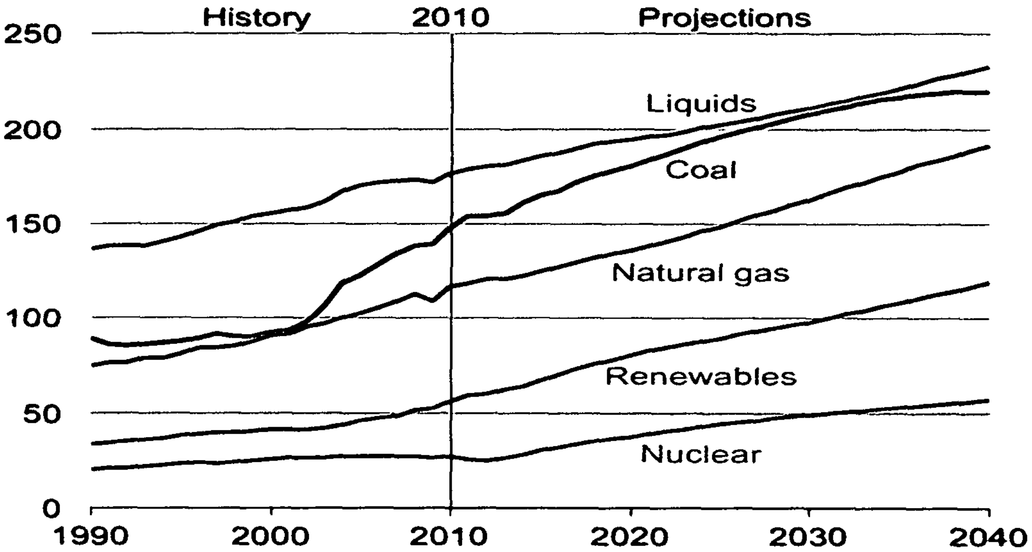


Figure 1.2: World energy consumption by fuel type, 1990-2040 (quadrillion Btu) [5]

Fossil fuel use is mainly responsible for the exponential hike in greenhouse gases (GHGs) which contributes to deleterious environmental consequences such as global warming, acid rain, ozone depletion climate change etc. thereby triggering key challenges for mitigation [6-8]. Given current policies and regulations limiting fossil fuel use, worldwide energy-related CO_2 consumption has risen to about 31 billion metric tons in 2010 and projected to be 45 billion metric tons in 2040 (46-percent increase) [5]. On the other hand, due to extensive usage, fossil fuels are at the brink of quick depletion. The global energy repertoire for conventional fuel has been reported as coal for 218 years, oil for 41 years and natural gas for 63 years under a business-as-usual scenario [9]. Declining fossil fuel reservoirs and increasing energy demands along with the problem of global warming resultant from extensive use of fossil fuels have highlighted the need for renewable or non-conventional energy sources like bio-energy, solar energy, geothermal energy, ocean energy, wind energy etc. In this regard one of the prospective facets for scientific realization of futuristic energy intensive scenarios may be well furnished by mankind's reliance on energy derived from biomass

1.1 Biomass as a source of energy

Looking into the finite nature of the existent petro fuels reservoirs the wide scale availability of biomass is much alluring as a source of energy. The use of biomass by men as an energy source dates back to the days of antiquity, when dry grasses, wood, and twigs were burnt for cooking and heating applications. Today, the biomass sources are once again regaining attention as researchers and policy makers are searching for carbon neutral renewable energy alternatives. Biomass has the potential to become one of the major global primary energy sources during coming days, and modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development in industrialized as well as in developed nations [10-14]. Biomass, with its energy-rich stores of fixed carbon and volatiles, is projected to have a global bioenergy potential ranging from nearly 10% to more than 60% of primary energy consumption [15, 16]. Biomass is a feasible alternative in offering potentially attractive solutions for addressing issues related to energy security, energy crisis and sustainable development

The term biomass (Greek *bios*, life + *maza* or mass) refers to non-fossilized, biodegradable organic material originating from plants, animals and microorganisms derived from biological sources. Biomass comprises of products, byproducts, residues and waste from agriculture, forestry and related industries as well as the non-fossilized biodegradable organic fractions of industrial and municipal solid wastes [17]. The major categories of biomass feedstocks are shown in Table 1.1

Table 1.1: Classifications of biomass adopted with due permission from [17] Springer

Sl. No.	Categories	Examples
1	Algae	Prokaryotic algae, eukaryotic algae, kelps
2	Bio- renewable wastes	Agricultural wastes, crop residues, mill wood wastes, urban wood wastes, urban organic wastes
3	Energy crops	Short-rotation woody crops, herbaceous woody crops, grasses, starch crops, sugar crops, forage crops, oilseed crops, switchgrass, miscanthus
4	Aquatic plants	Algae, Water weed, water hyacinth, reed and rushes
5	Food crops	Grains, oil crops
6	Sugar crops	Sugar cane, sugar beets, molasses, sorghum
7	Landfill	Hazardous waste, nonhazardous waste, inert waste, liquid waste
8	Organic wastes	Municipal solid waste, industrial organic wastes, municipal sewage and Sludges
9	Forest products	Wood; logging residues; trees, shrubs, and wood residues; sawdust, bark, etc.
10	Mosses	Bryophytes, polytrichales
11	Lichens	Crustose lichens, foliose lichens, fruticose lichen

The existent research trends have highlighted the importance of biomass in the energy sector besides indicating that it would continue to be a significant source of renewable energy for the foreseeable future. Biomass feedstocks on account of their wide range of geographical distribution can serve as an excellent source to meet both the present and future energy demands. In addition to the sustainable favorability of biomass, they are, in general, more evenly distributed over earth's surface than fossil fuels or uranium and may be exploited using less capital-intensive technologies [18]. Although numerous biomass feedstocks have been reported with regard to energy conversion, fuelwood as a source of biomass is of special importance and credible as one of the more environmentally benign alternatives.

1.2 Importance of wood as prominent bio-energy source.

Wood represents almost an inexhaustible repertoire of renewable biomass which when judiciously exploited can compassionate in mankind's quest for present and futuristic energy utilities. Even much before the dawn of civilization, mankind has relied heavily on wood as a primary energy source. Wood still serves as the primary source of fuel for cooking and heating appliances in many emerging economies besides contributing a share to the energy demands of developed nations. Woody biomass contributes approximately 10% to the global primary energy mix and is still one of the most sought after renewable energy source [19]. The importance of fuelwood is not only with regard to household consumption but also from the industrial standpoint. According to estimates about 3.4 billion m^3 of wood were used throughout the world in 2010 (over half for industrial use and the rest for firewood) [20]. The use of wood for heating and cooking appliances dominates end-use and its consumption is still increasing in most of the developing nations [21]. As of date, wood still accounts for 90% of the total energy consumption in many of the developing nations and are often a sought after tradable commodity due to unaffordable costs of other energy sources [22]. Wood fuels, which have an important role in both providing energy requirement for production units as well as heating appliances for household and healing energy deficit, disperse very less CO_2 than fossil fuels to the atmosphere [23]. The net amount of CO_2 emitted during the process of wood combustion is typically 90% less than that of fossil fuel combustion [24]. Consequently, wood may be considered as an eco-friendly energy source.

There are various possibilities for utilizing wood as a source of energy. Ordinary combustion has been used for millennia and is still common [25] .With the help of suitable conversion processes, fuelwood can be converted into potential biofuels such as bio-oil, bio-alcohols, charcoal, syngas etc., thereby partially compassionating in meeting the existent fuel demand. Renewable, recyclable, and compostable products sourced from trees have great potential as low ecological impact products and part of a new sustainable way of life. Conversion of woody biomass to biofuels is technically feasible, but these conversion processes are marginally economical with existent technologies [26].

In order to make fuelwood as an attractive and viable source of energy in the near future, the state of art technology requires improvement of short-rotation intensive culture techniques for plantations, selection of the suitable fuelwood species for further plantation and improvement of electrical power and ethanol production processes. These efforts can help to improve the comparative advantage of wood biomass feedstock relative to fossil-fuel feedstock [27].

1.3 Fuelwood demand and supply in India

Globally, fuelwood has long been recognized as an energy source for heating and cooking appliances. In India, about 70% of the energy requirement is met by fuelwood collected from the forests. According to a report by National Sample Survey Organization (NSSO) [28], in rural India more than three-quarters (76.3%) of households are dependent on firewood and chips as primary source of energy for cooking. In Chhattisgarh 94% of the household uses firewood and chips for cooking appliances. This is highest among all the Indian states followed by Rajasthan (92.5%) and Madhya Pradesh (90.5%). On the other hand in urban areas, about 18% households are dependent on firewood and chips as primary source of energy for cooking. According to India State of Forest Report (ISFR) [29], based on interpretation of satellite data (October 2008-March 2009), the annual production of wood from forest and tree outside forest (TOF) was estimated to be 3.175 million m^3 and 42.77 million m^3, respectively. Again the annual estimated production of fuelwood from forest and TOF was estimated to be 1.23 million tons and 19.25 million tons, respectively. The annual consumption of wood in household construction and furniture, industrial construction and furniture, and agricultural implements was estimated to be 48.00 million m^3 whereas; the annual consumption of fuelwood was estimated to be 216.42 million tons [29].

So, there has been a big gap between demand and availability of fuelwood in India. This imbalance statistics creating an additional pressure on the existing forest resources and are expected to rapidly beckon exhausted if the plantation programmes are not intensified. The availability of fuelwood from the forests is continuously declining at an ever-increasing rate due to indiscriminate deforestation and slow regeneration as well as afforestation. Therefore, a massive tree plantation is urgently required to alleviate the situation where the tree species should have high fuelwood quality. Fuelwood can be planted in the forests, degraded forests, strips or rows of trees along road sides, streams, railway lines, canals, crop land boundary and bunds (separating small plots), common land and homestead garden [30].

1.4 Selection of promising tree species for energy plantation

Almost all kind of trees and shrubs are used as fuelwood but its quality varies from species to species. Consequently, special attention is required for selection of tree species aimed at fuelwood plantation. In general, local farmers are the pioneers for selection of suitable fuelwood species, because they have ultimate knowledge about the site characteristics, local climate, and silvicultural characteristics of the tree species. On a priority basis for selection of fuelwood species, first preference should always be given to the native species because they are often better adapted to local environmental conditions, seeds may be readily available and farmers are usually familiar with them and their uses. Additionally, the plantation of indigenous trees helps in preserving genetic diversity and also serves as habitat for the local fauna [31]. The salient features of plant species towards fuelwood plantation are [32]:

- Fast growth
- Multiple uses
- Ability to produce high-calorific wood, which burns without sparks or toxic smoke, splits easily and dries quickly.
- Requires minimum time and effort for management.
- Tolerance to a wide range of environments, soil types, rainfall regimes, terrain etc.
- Wide adaptability to the site conditions.
- Ability to fix atmospheric nitrogen.
- Soil stability and maintenance of fertility.
- Disease and pest tolerance.
- Dense wood production for longer burning.

The North-Eastern region of India has been characterized with different topography, soil characteristics and climatic conditions as compared to other parts of the country. A majority household of this region is dependent on fuelwood as a primary energy source. Commercial fuel is generally beyond the reach of rural people of this region, due to their socio-economic conditions, lack of transportation facilities, price rise and limited supply [33]. Regular exploitation of the forest resources as a source of energy (mostly attributed to population explosion) in this regions is creating scarcity of fuelwood as well as massive deforestation. This has resulted in adverse effects on ecological balance. Therefore, a huge tree (fuelwood) plantation is urgently required to improve the situation. Due to heavy rainfall and favorable climatic conditions in the North-East (N-E) India favor the ubiquitous growth of numerous indigenous tree and shrub species which are yet to be identified with their fuelwood characteristics [34]. A few studies on fuelwood characterization from this region have been reported by Kataki & Konwer [34-35], Bhatt *et al.* [36 ~~38~~], Deka *et al.* [37-38], Chettri & Sharma [39].

Arunachal Pradesh is one of the states in N-E India which needs particular attention in this regard, as the state is abundant with a variety of tree species. The state comprises almost hilly region and about 80% household of this region still uses fuelwood as a main source for their daily energy requirements. Most of the tree species available in this region may not be available in other parts of the country. In addition, Arunachal Pradesh has the largest forest area (61.5% of the total geographical area) among the North-Eastern states of India [40]. Consequently, it is expected that there is a huge scope for energy plantation in this region. But as of now there is paucity of scientific literature pertaining to fuelwood characterization of the available indigenous tree species of this region. Therefore, a systematic and detailed study of the fuelwood characteristics of the existing indigenous tree species of Arunachal Pradesh is of paramount importance.

Objectives

The unique climatic and topographic profile of Arunachal Pradesh favors the growth of numerous fuelwood species. The present study deals with screening of the most promising fuelwood species of Arunachal Pradesh based on the preference of local peoples along with laboratory analytical tests on fuelwood characteristics for further energy plantation in the region. Such a study will identify the desirable indigenous tree species for inclusion in energy plantation and also for evaluation of their potential as a biomass energy source.

The present investigation was carried out with the following objectives:

I. To survey and screen the indigenous fuelwood species which are traditionally preferred for fuel by the rural people of Arunachal Pradesh.

II. To determine the physicochemical (e.g. moisture content, ash content, calorific value, density etc.), biochemical constituents (cellulose, hemicelluloses, lignin, extractive content etc.) and elemental analysis (carbon, hydrogen, oxygen, nitrogen etc.) of the selected tree species.

III. To study the effect of physicochemical characteristics, biochemical constituents and elemental compositions of the different tree species with their fuelwood quality.

IV. To study combustion performance of the selected tree species.

V. To evaluate the best fuelwood species for use in energy purpose based on the present study.

References

1. Pachauri, S. *An Energy Analysis of Household Consumption: Changing Patters of Direct and Indirect Use in India*, Springer, the Netherlands, 2007.
2. ICLEI Renewable Energy and Energy Efficiency Status in India, Report compiled by South Asia, May 2007, downloaded from http://localrenewables.iclei.org/fileadmin/template/projects/localrenewables/files/Local_Renewables/Publications/RE_EE_report_India_final_sm.pdf on 07/03/2014.
3. Environmental decision making, Science, and Technology, Carnegie Mellon University, 2003, downloaded from http://telstar.ote.cmu.edu/environ/m3/s3/11sources.shtml on 19/03/2014.
4. Renewables 2012 Global status report, REN21, downloaded from http://www.map.ren21.net/GSR/GSR2012.pdf on15/03/2014.
5. U.S. Energy Information Administration. International Energy Outlook 2013 with Projections to 2040, Washington, DC, July 2013.
6. Khan, M. M., *et al.* Impacts of Biodiesel on the Environment, *International Journal of Environmental Engineering and Management* **4** (4), 345-350, 2013.
7. International Energy Agency (IEA). CO_2 emission from fuel combustion-Highlights, 2012 edition.
8. Van Aardenne, J.A., *et al.* A 1°×1° resolution data set of historical anthropogenic trace gas emissions for the period 1890–1990, *Global Biogeochemical Cycles* **15** (4), 909-928, 2001.
9. Agarwal, A.K. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science* **33** (3), 233-271, 2007.
10. Hall, D. O. Biomass energy in industrialised countries—a view of the future, *Forest Ecology and Management* **91**, 17–45, 1997.
11. Hall, D.O., *et al.* Biomass energy: the global context now and in the future, *Aspects of Applied Biology* **49**, 1–10, 1997.

12. Hall, D. O., & Scrase, J. I. Will biomass energy be the environmentally friendly fuel of the future? *Biomass and Bioenergy* **15** (4–5), 357–67, 1998.
13. UNDP/WEC. *World energy assessment: energy and the challenges of sustainability*, United Nations development Programme: World Energy Council, United Nations Department of Economic and Social Affairs, New York, USA, 2001.
14. Berndes, G., *et al.* The contribution of biomass in the future global energy supply: a review of 17 studies, *Biomass and Bioenergy* **25**, 1–28, 2003.
15. Richard, T.L. Challenges in scaling up biofuels infrastructure, *Science* **329** (5993), 793–796, 2010.
16. Kenney, K. L., & Ovard, L. P. Advanced feedstocks for advanced biofuels: transforming biomass to feedstocks, *Biofuels* **4** (1), 1–3, 2013.
17. Demirbas, A. Fuels from biomass, in *Biohydrogen: For future engine fuel demands*, Springer-Verlag, London, 2009.
18. Satyanarayan, N., *et al.* Characterization of Canadian biomass for alternative renewable biofuel, *Renewable Energy* **35**, 1624–1631, 2010.
19. IEA BIOENERGY, Bioenergy- a sustainable and reliable energy source: A review of status and prospects, 2009, downloaded from http://www.ieabioenergy.com/wp-content/uploads/2013/10/MAIN-REPORT-Bioenergy-a-sustainable-and-reliable-energy-source.-A-review-of-status-and-prospects.pdf on 20/02/2013.
20. West, P. W. *Growing plantation forest*, 2nd ed., Springer, Switzerland, 2014.
21. Lamers, P., *et al. Global Woody Biomass Trade for Energy, in International Bioenergy Trade: History, status & outlook on securing sustainable bioenergy, demand and markets*, lecture notes in Energy, vol. 17, M. Junginer, et al., eds., Springer, The Netherlands, 42, 2014.
22. Munalula, F., & Meincken, M. An evaluation of South African fuelwood with regards to calorific value and environmental impact, *Biomass and Bioenergy* **33**, 415–420, 2009.

23. Akyuz, K. C., & Balaban, Y. Wood fuel trade in European Union, *Biomass and Bioenergy* **35**, 1588-1599, 2011.
24. Chen, H. Qualitative and quantitative analysis of wood samples by Fourier transform infrared spectroscopy and multivariate analysis, *Carbohydrate Polymers* **82**, 772–778, 2010.
25. Sedjo, R. A. Wood as a Major Feedstock for Biofuel Production in the United States: Impacts on Forests and International Trade, *Journal of Sustainable Forestry* **32**, 195–211, 2013.
26. Cai, Z., *et al.* New products and product categories in the global forest sector, in *The Global Forest Sector-changes, practices, and prospects*, Hanen, E. *et al*, eds., CRC press, Boca Ratan, 2014, pp. 143.
27. Ghose, M. K. Production of fuels from wood sources , in *The Biofuels Handbook*, J. G. Speight, eds., Royal society of chemistry, Cambridge, U.K., 2011.
28. NSSO 2009-10, NSS 66th Round. Energy Sources of Indian Households for Cooking and Lighting. Ministry of Statistics and Programme Implementation, Government of India, 2012.
29. ISFR 2011. Forest survey Of India. Ministry of Environment & Forests, Government of India, Dehra Dun.
30. Ravindranath, N. H., & Hall D. O. Sources of fuelwood in India, in *Biomass, Energy and Environment-a developing country perspective from India*, Oxford University Press, 1995, pp. 37.
31. Montagnini, F. Selecting Tree Species for Plantation, downloaded from http://www.bf.unilj.si/fileadmin/groups/2716/downloads/%C4%8Clanki_vaje/Mansurian_forest_restoration_38_tree_species_plantation.pdf on 24/03/2014.
32. Selecting multipurpose trees, The Birchley Hall Press, 2013, downloaded from http://www.treesforlife.info/gmptsf/selectingmpt.htm on 24/03/2014.
33. Kumar, M., & Sharma, C. M. Fuelwood consumption pattern at different altitudes in rural areas of Garhwal Himalaya, *Biomass and Bioenergy* **33**, 1413 – 1418, 2009.

34. Kataki, R. K., & Konwer, D. Fuelwood characteristics of indigenous tree species of north-east India, *Biomass and Bioenergy* **22**, 433 – 437, 2002.
35. Kataki, R. K., & Konwer, D. Fuelwood characteristics of some indigenous woody species of north-east India, *Biomass and Bioenergy* **20**, 17-23, 2001.
36. Bhatt, B. P., & Tomar, J. M. S. *et al.* Characteristics of some firewood trees and shrubs of the North Eastern Himalayan region, India. *Renewable Energy* **29**, 1401–5, 2004.
37. Deka, D., *et al.* Ranking of Fuelwood Species by Fuel Value Index, *Energy Sources* **29**, 1499–1506, 2007.
38. Deka, D. *et al.* Investigating Woods and Barks of Some Indigenous Tree Species in North-East India for Fuel Value Analysis, *Energy Sources* **36**, 1913–1920, 2014.
39. Chettri, N., & Sharma, E. A scientific assessment of traditional knowledge on firewood and fodder values in Sikkim, India, *Forest Ecology and Management* **257**, 2073–2078, 2009.
40. Sinha, G. N. Forest and Forestry in Arunachal Pradesh, SFRI information Bulletin No.27, Issued by Director, State Forest Research Institute & Mission Director, State Bamboo Mission, Arunachal Pradesh, India, 2008.

Chapter 2

Review of Literature

Chapter 2
Review of Literature

Wood one of the oldest source of energy has been used by men for over 500000 years [1]. Even much before the dawn of human civilization mankind relied on wood as the primary source of energy. However, with the advent of petroleum and modernization of human society a rapid decline in fuelwood usage was evident. This long-term decline in the diminishing importance of biomass energy was reversed following the 1973 OPEC oil embargo. With rapid decline in petro fuel reservoirs and frequent fluctuations in petroleum prices the importance of fuelwood is increasing dramatically. Biomass electrical power generation and cogeneration plants in Maine, New Hampshire, Vermont, Michigan, Wisconsin, and California have become significant new users of wood boiler fuel [2]. In developing nations, biomass in its traditional solid form (fuelwood and agricultural residues) represents a considerable and often insufficiently recognized proportion of the total energy supply. Fuelwood collected from forests, either by lopping branches, fallen wood or cutting down of dry and diseased trees, is the most common source of domestic energy in the rural areas [3]. In India, rural households depend primarily on locally available biomass sources collected from forests and nearby sites to meet their domestic energy needs [4]. Bhatt and Sachan [5] reported that fuelwood is the main source of energy in rural India. About 80% of the Indian population lives in villages where wood is the main source of primary energy. But however owing to the depletion of wood the rural poor are forced to use other forms of energy such as crop residues and dung [6].

Felling of trees for firewood accounts for the largest share of wood usage in developing nations, however this may lead to rapid deforestation [7]. In order to avert this situation, the prime requirement is large-scale energy plantations on unused and degraded lands. Although all kinds of trees and shrubs can be used as fuelwood for energy plantation, a systematic approach is necessary to identify locally available indigenous tree species, which can thrive best in the local climate. Local user's knowledge is crucial for selecting proper fuelwood species as they have an intimate knowledge of the local environment [8]. Deka [9] emphasized the need for studying the fuelwood characteristics of different tree and shrubs species of a locality along with their combustion performance, growth and biomass productivity in different agro climatic conditions as vital criteria to select fuelwood species for energy plantation. Time and again various researchers have identified plant constituents that correlate with the fuelwood quality. The Technology Innovation Board on Science and Technology for International Development Commission on International Relations, National Academy of Sciences, Washington, has listed a large number of promising firewood species of Humid Tropics, Arid and Semiarid Region and Tropical Highlands [10].

Before utilizing wood as a source of energy a brief description about wood and its properties have been presented below.

2.1 Wood and properties of wood

In general wood refers to the hard and fibrous structural tissues found in stems and roots of trees [11]. Botanically, wood is defined as a hard and fibrous material formed by the accumulation of secondary xylem, which is the principal strengthening tissue, produced by the vascular cambium and found in the stems and roots of trees and shrubs [12].

Wood, a natural, cellular, composite material of botanical origin possesses unique structure and chemical characteristics that renders desirability for numerous end uses [13-14]. An understanding of the anatomical and physico-chemical properties of wood is a prerequisite for end applications. Anatomical properties identify the macroscopic structures of soft and hardwood. Physical properties deal with the relationship between specific gravity and moisture content. Chemical properties refer to carbohydrate and lignin structures and their contents as related to fuel reactivity and heating value [15].

2.1.1 Softwood and Hardwood structures

Generally wood is divided into two broad classes: hardwood and softwood. Botanically, hardwood is angiosperm and softwood is gymnosperm. Angiosperms are characterized by production of seeds, enclosed in the ovary of the flower whereas gymnosperms produce seeds that are naked [16-17]. This classification cannot be used universally to refer to the actual physical hardness of woods because some softwoods are quite hard (e.g. Dougla-fir and Southern yellow pines) and some hardwood are soft (e.g. Cotton wood.). Hardwoods are typically broadleaf, deciduous trees whereas softwoods are generally needle-leaved evergreen trees [18-19].

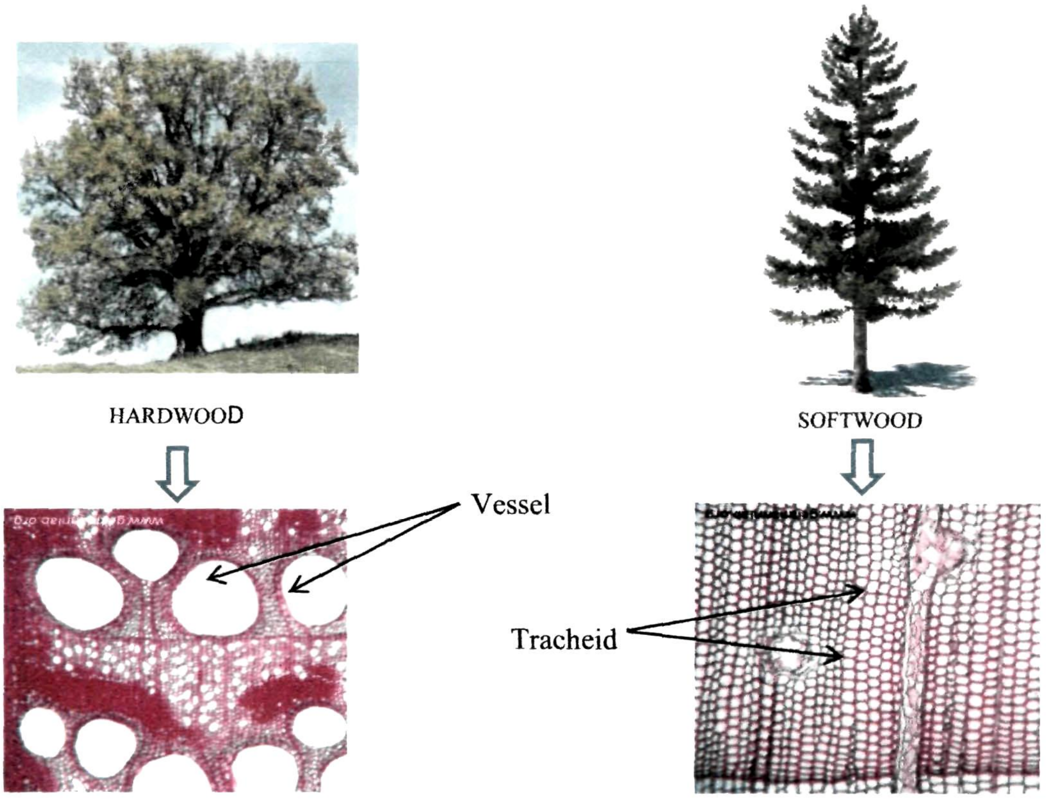


Figure 2.1: Cross section of hardwood and softwood structure showing pores of vessel element of hardwood and tracheid of softwood, compiled from [20-23]

Softwood and hardwood are quite different in terms of their cell components. Hardwood contain vessels, a structure composed of vessel elements which are joined end-wise to tubes or vessels along the stem, branch or root and are seen as pores on the wood cross section. They serve as pathway for fluid conduction in hardwood. This type of cells are absent in softwood. On the other hand, long cells known as longitudinal tracheid comprise 90 – 95 percent of the volume of softwood and provide both conductive and mechanical functions to softwood [17-20]. The cross section of softwood and hardwood structure showing pores of vessel elements of hardwood and tracheid of softwood are presented in Figure 2.1. As physico-chemical composition of soft and hardwood are different, their chemical nature and resultant reactivity at the cellular level potentially influence their use for various end applications.

2.1.2 Physical properties of wood

2.1.2.1 Moisture content

Wood is a hygroscopic material because of the hydrophilic nature of the cell wall constituent polymers viz., hemicelluloses, cellulose, and to a lesser extent lignin. The hygroscopic character of wood is attributed primarily to the presence of hydroxyl (-OH) groups in the polymer constituents comprising the cell wall. Carbohydrate fraction (hemicelluloses and cellulose) of the cell wall is mainly responsible for wood's hygroscopicity. Moreover, it is mainly the hemicelluloses that dictate hygroscopicity, due to their short, branched, open structures, and their location on the surface of microfibrils, which results in availability for water sorption. Cellulose, though abundant in -OH group, is less hygroscopic due to intra- and inter- molecular bonding within cellulose microfibrils. With changes in the chemical composition or chemical structure of these cell wall polymers, the water sorption capacity of wood changes and consequently the moisture content [24-25].

Water in wood is present in two forms: bound water which is held within the cell wall by intermolecular hydrogen bonding to the cell wall polymer constituents and free water which is located in the cell lumens. As the wood begins to dry, when exposed to ambient air, free water first leaves the wood from lumens while bound water content remains unaffected. The moisture content level corresponds to the lumens containing no free water (only water vapour) , while no bound water desorbed from cell wall material, is known as fiber saturation point (FSP). The fiber saturation point differs between tree species and is usually in the range of 20- 25% (wet basis) [26-27]. FSP is important in drying of wood. More energy is required to drive off a given amount of water below the FSP because the bound water is being removed and therefore, the attractive forces between the wood and water must be overcomed. The total amount of water, that wood can hold is dependent upon the actual amount of cell wall substance and the amount of void space (cell cavities) in a given volume of wood [28].

Moisture content is an important determinant of fuelwood preference as it affects the weight of wood on transportation, fire temperatures and ignition times [29]. It is also an important characteristic which is responsible for the ease of combustion of a fuelwood, the amount of smoke it emits, and its usable heat content [30]. As reported [31] moisture content does not contribute to the heating value but reduces the heat available from the fuel by lowering the initial gross calorific value of wood. The moisture content varies from species to species and also from one tree part to another. It is often lowest in the stem and increases towards the roots and the crown. Seasons are also known to effect moisture content [32]. Moisture content of wood is generally expressed in percentage of green moisture content, air dry and/or oven dry moisture content [33].

2.1.2.2 Density and Specific gravity

Density (D) is the mass or weight per unit volume of a material and is usually expressed in kilograms per cubic meter (kg m^{-3}) or grams per cubic centimeter (gcm^{-3}). On the other hand specific gravity (SG) is the ratio of the density of a material to the density of water. Both the term bears the same characteristic and they are different only in the fundamental sense that specific gravity is a pure number and density is not.

Wood density provides a simple measure of the total amount of solid-wood substance in a piece of wood. For this reason, wood density provides an excellent means of predicting end-use characteristics of wood such as strength, stiffness, hardness, heating value, machinability, pulp yield and paper making quality [34]. Density depends on the chemical nature and/or anatomical structure of wood, and these characteristics differ among species and environments [35-36]. Density or specific gravity of a wood species is greatly influenced by the moisture content. Weight of wood species varies with the moisture content and its volume changes with change in moisture content below the Fiber Saturation Point (FSP). Therefore, it is essential to specify the moisture condition during the determination of wood density or specific gravity [37]. When the weight of the wood is considered as oven dried weight (moisture free) and volume is taken at or above FSP (green volume), the density of wood is known as basic density [38].

2.1.3 Chemical properties of wood

The basic elements responsible for the formation of wood components are carbon, hydrogen, oxygen and nitrogen. A negligible amount of sulfur is also present in it along with ash forming inorganic minerals [37]. In chemical term, wood is defined as a three-dimensional biopolymer composite composed of an interconnected network of cellulose, hemicelluloses and lignin with minor amount of extractive and ash. The major chemical component of a living tree is water, but on a dry weight basis, all wood cell walls consist mainly of sugar-based polymers (carbohydrates) that are combined with lignin [39]. The Chemical composition of wood varies within the tree parts (root, stem, or branch), type of wood, geographic location, climate and soil conditions [40]. The chemical components present in wood is depicted in the general scheme shown in Figure 2.2

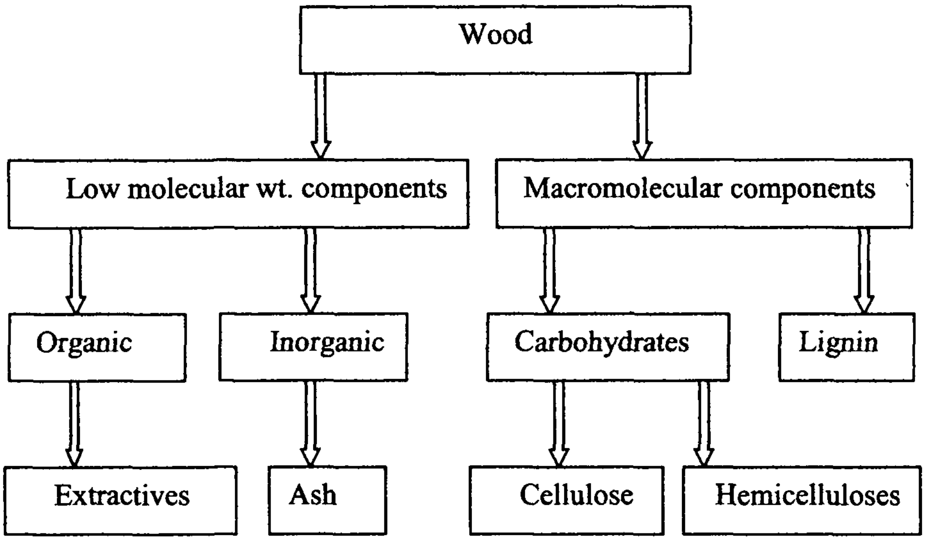


Figure 2.2: General Scheme of the wood chemical components [41]

2.1.3.1 Carbohydrates

The major carbohydrate portion of wood is composed of cellulose and hemicellulose polymers with minor amounts of other sugar polymers such as starch and pectin. The combination of cellulose and the hemicellulose is called holocellulose and usually accounts for 65–70 percent of the wood dry weight. These polymers are made up of simple sugars [39].

2.1.3.1.1 Cellulose

Cellulose is the most abundant constituent of the cell wall and constitutes 40–50% of dry weight of wood. Cellulose is a linear polysaccharide composed of β-D glucopyranose units linked together by (1→4) glucosidic bonds. The linear long chain polysaccharide, cellulose can be represented as $(C_6H_{10}O_5)_n$, where n is the degree of polymerization (DP) [42]. Goring and Timell [43] reported that the degree of polymerization (DP) is normally from 9000 to 10000, but possibly as high as 15000. Cellulose molecules are completely linear and have a strong tendency to form intra and intermolecular hydrogen bonds. Bundles of cellulose molecules are thus aggregated together in the form of microfibrils, in which highly ordered (crystalline) regions alternate with less ordered (amorphous) regions. Microfibrils build up fibrils and finally cellulose fibers. As a consequence of its fibrous structure and strong hydrogen bonding, cellulose has a high tensile strength [17, 39, 42]. Figure 2.3 shows a partial molecular structure of cellulose.

2.1.3.1.2 Hemicelluloses

Hemicelluloses are abundant components of the plant cell wall and constitute 20-35% of dry weight of wood. They are found in the matrix between cellulose fibrils in the cell wall. The main monomers of wood hemicelluloses are hexoses (D-glucose, D-mannose and D-galactose); pentoses (D-xylose and L-arabinose); uronic acids (4-O-methyl-D-glucoronic acid, D-galacturonic acid and D-glucuronic acid) and deoxyhexoses (L-rhamnose and L-fucose) in small quantity [44]. There are various types of wood hemicelluloses depending upon the types of monomers which undergo polymerization. Most of the hemicelluloses have a degree of polymerization of only 200 [17]. Generally, hemicelluloses are of much lower molecular weight than cellulose, having side groups and being branched in some cases [40]. Hardwood and softwood differ in structure and composition of hemicelluloses (Table2.1). The representative structural formula of major hemicelluloses found in hardwood and softwood are represented in Figure 2.4 (a, b, c, d).

Table 2.1: Prime hemicelluloses found in softwood and hardwood [44]

Wood	Hemicellulose type	Amount (% dry basis)	Units linkage	Molar ratio (App. values)	Linkage
Softwood	Glactoglucomannan	5-8	β-D-Manp	3-4	1→4
			β-D-Glcp	1	1→4
			α-D-Galp	1	1→6
			O-Acetyl	1	
Softwood	Glucomannan	10-15	β-D-Manp	3-4	1→4
			β-D-Glcp	1	1→4
			α -D-Galp	0.1	1→6
			O-Acetyl	1	
Softwood	Arabinoglucuronoxylan	7-15	β-D-Xylp	10	1→4
			4-O-Me-α-D- GlupA	2	1→2
			α-L-Araf	1.3	1→3
Larch wood	Arabinogalactan	3-35	β-D-Galp	6	1→3, 1→6
			L-Araf	2/3	1→6
			β-D-Arap	1/3	1→3
Hardwood	Glucuronoxylan	15-35	β-D-Xylp	10	1→4
			4-O-Me-α-D- GlupA	1	1→2
			O-Acetyl	7	
Hardwood	Glucomannan	2-5	β-D-Manp	1-2	1→4
			β-D-Glcp	1	1→4
			O-Acetyl	1	

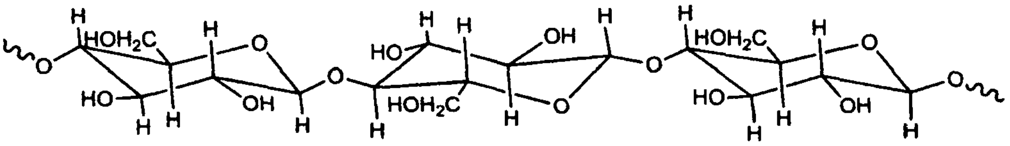


Figure 2.3: Partial molecular structure of cellulose [40]

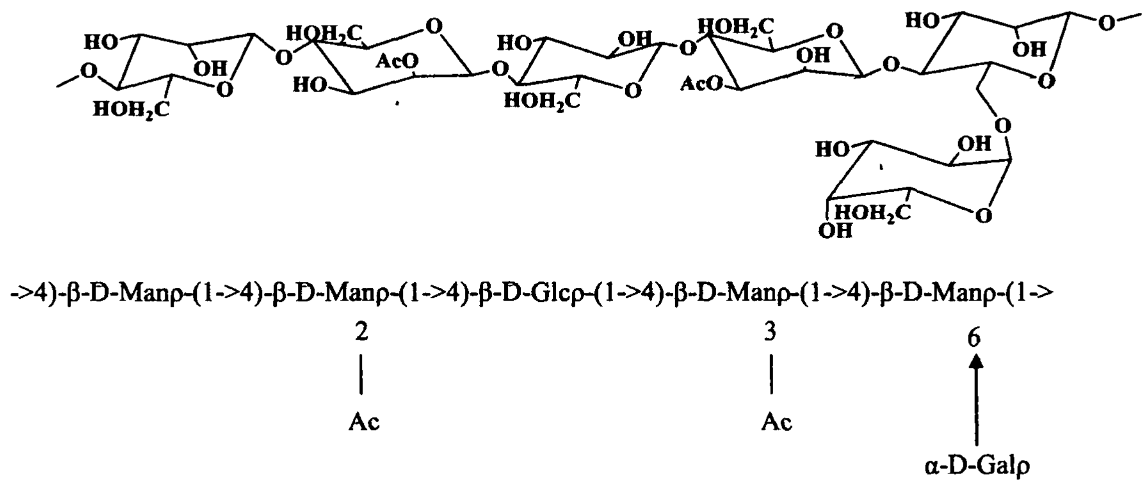


Figure 2.4 (a): Representative structural formula for softwood galactoglucomannan

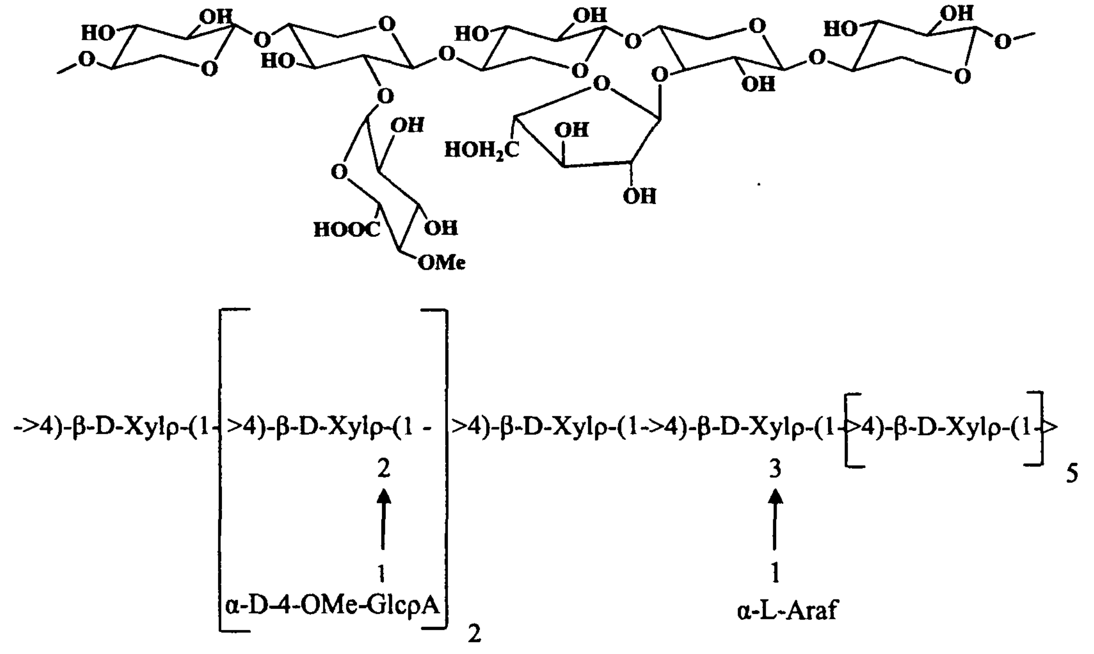


Figure 2.4(b): Representative structural formula for softwood arabinoglucuronoxylan

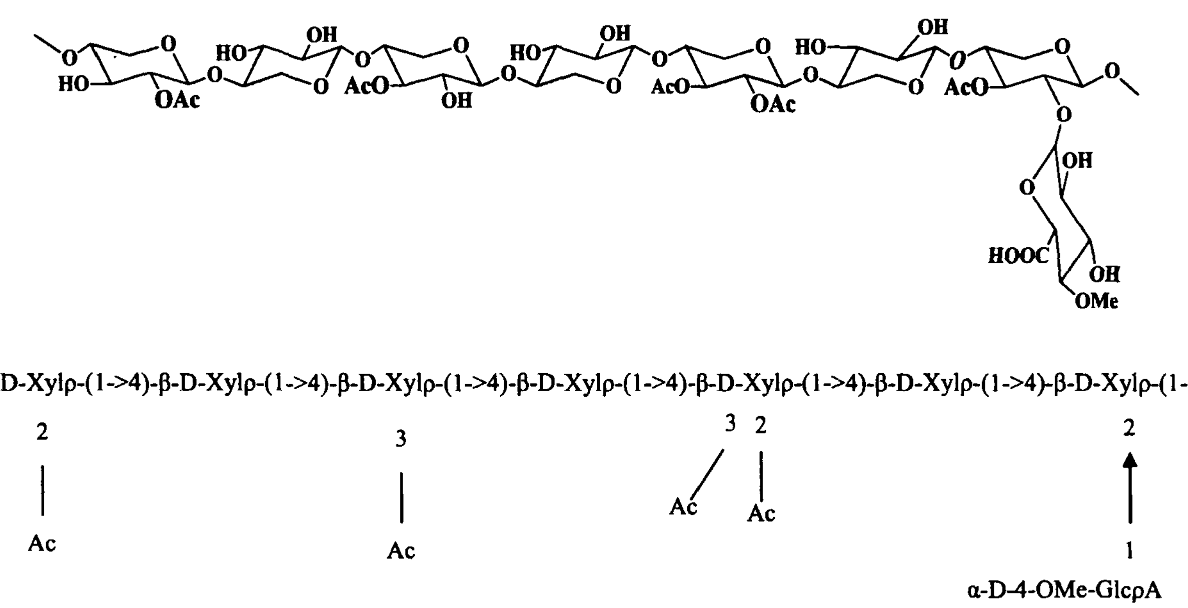


Figure 2.4(c): Representative structural formula for hardwood glucuronoxylan

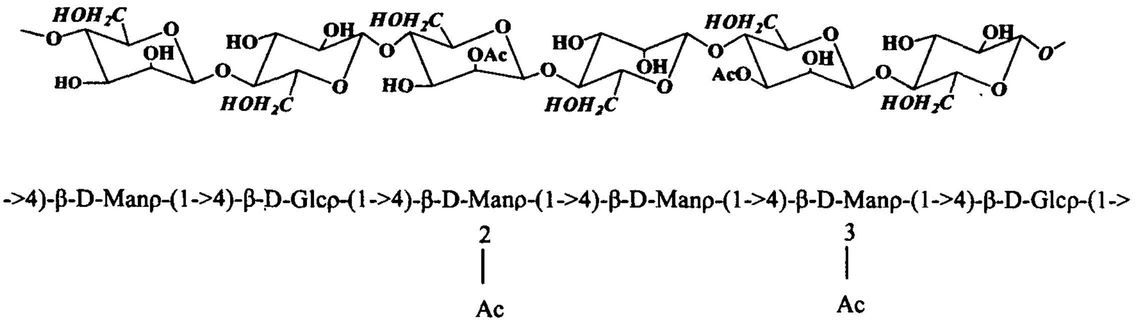


Figure 2.4 (d): Representative structural formula for hardwood glucomannan

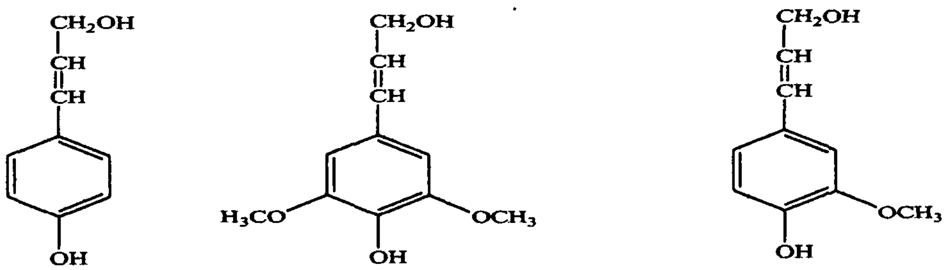
Figure 2.4 (a-d): Structures of abundant hemicelluloses found in hardwood and softwood [44]

2.1.3.1.3 Lignin

Lignin is one of the important and abundant chemical constituents of wood. Lignin constitutes 23% to 33% of the wood substance in softwoods and 16% to 25% in hardwoods [19]. Lignin is complex polyphenolic material arising from enzymic dehydrogenative polymerization of the phenylpropane units. The precursors involved in lignin biosynthesis are p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol

[39, 45] whose chemical structures are presented in Figure 2.5. Lignin precursors are linked together through ether (C-O-C) and carbon-carbon (C-C) bonds via β-O-4, 5-5, β-1, β-5, α-O-4, β-β, 4-O-5 linkages and the variation of the lignin structure are due to changes in frequency of these linkages. Lignin can be classified mainly into three categories on the basis of types of lignin precursors involved in its biosynthesis [46]. Softwood lignin or guaiacyl lignin consists almost exclusively of coniferyl alcohol and may contain small amounts of *p*-coumaryl alcohol (mainly in the compression wood), but no or only traces of sinapyl alcohol. Hardwood lignin or syringyl-guaiacyl lignin contains both coniferyl and sinapyl alcohol with proportions from approximately equal amounts, to three times higher levels of sinapyl alcohol. Some hardwood lignin may also contain small amount of *p*-coumaryl alcohol [47].

Lignin is an important constituent of wood from the point of biological function. It provides stiffness to the cell walls and acts as adhesive keeping different cells together in woody tissues. Lignin makes the cell wall hydrophobic and also protects wood against microbial degradation [47].



P-Coumaryl alcohol Coniferyl alcohol Sinapyl alcohol

Figure 2.5: Chemical structures of the lignin

2.1.3.2 Extractives

Extractives are non-structural and low molecular weight compounds present in wood. They include fats, waxes, alkaloids, proteins, simple and complex phenolics,

simple sugars, pectins, mucilages, gums, resins, terpenes, starches, glycosides, saponins, and essential oils [17, 48]. Extractive constitutes 4-10% of the dry weight of normal wood species that grow in temperate climates and may be as much as 20% for tropical species [49]. Some of them are soluble in water while others are soluble in neutral solvents (dichloromethane, ethanol-benzene and ethanol-toluene etc.). Softwoods contain higher extractive percentage than hardwoods [39]. They function as intermediates in tree metabolism, as energy reserves and protect trees from microbial attack. Besides,they contribute to wood properties such as color, odor, and decay resistance [17, 50].

2.1.4 Ash

Ash content in wood is defined as the inorganic residue remaining after combustion at a temperature of 575 ± 25 °C in the presence of abundant oxygen. Wood ash comprises of a variety of major (Ca K Mg Na, P, Si, Al, Fe, Cl, and Ti) and minor (As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Tl, V and Zn) inorganic elements. The elements that are responsible for the bulk make up of ash in wood are Ca, Mg and K [51]. These elements probably exist in wood as oxalates, carbonates, and sulfates, or are bound to carboxyl groups in pectic materials [39, 52]. The ash percentage may vary within different parts of a tree (roots, bark, trunk, and leaves) and among different tree species [53]. Hardwoods contain higher ash content than softwoods [54}. These variations in ash content can be attributed to different soil and climatic conditions in which the tree grows [55].

2.1.5 Energy value of wood fuel

Calorific value indicates the heating potential of fuelwood and is a measure of its energy content [56]. This value in wood is mainly related to the physicochemical composition of plant species like percentage of carbon, hydrogen, moisture and ash [36, 57-58 44]. In general, the percentage of carbon and hydrogen mainly contributes to the heating value in wood. [59].

Three different conventions are commonly used in deriving the heating value of biomass fuels: (1) gross calorific value (2) net calorific value and (3) usable heat content [60].

2.1.5.1 Gross Calorific Value and Net Calorific Value

If the products of combustion are condensed to ambient temperature, the latent heat of condensation of steam is also included in the measured heat. The total value calculated is known as higher or gross calorific value (HCV/GCV) and is defined as the total amount of heat liberated when one unit of the fuel is burnt completely and the combustion products are cooled to ambient temperature [61].

In actual practice, during combustion of a fuel the water vapors escape as such along with hot combustion gases and thus are not condensed. Hence a lesser amount of heat is liberated. This is called lower or net calorific value (LCV/NCV) and is defined as the amount of heat liberated when one unit of fuel is burnt completely and the combustion products are allowed to escape [61].

In standard test procedure, wood samples are usually oven-dried before calorimetric analysis. Values thus derived are termed as gross anhydrous calorific values (CV). Reported anhydrous CVs for wood range from 18.0 MJ/ kg to 24.0 MJ /kg. But CV may vary according to tree species and its components. CV is higher for resinous conifers (typically 20.0 - 23.0 MJ/Kg) than for hardwood species (typically 18.5-20.0 MJ/Kg) [60].

2.1.5.2 Usable heat content

Gross and net calorific values are useful measures of energy content in fuels. But on the contrary, they do not represent the usable heat energy which can finally be recovered by burning a fuel in a combustion chamber. In calculating the net calorific value, it is assumed that the gaseous products of combustion are discharged at ambient temperature (25^0C), so that no heat is lost except the latent heat of water vapor (typically 200^{0}C in an efficient furnace), and energy is lost in (1) superheated water vapor; (2) dry flue gases and (3) any excess air. These losses must be accounted for determining the usable heat content (recoverable heat energy) of wood as fuel [60].

2.1.6 Combustion quality of wood species

Heat of combustion is the most fundamental property with regard to fuel quality and is usually the best means to compare one fuel with another. Combustion is an oxidation reaction where the amount of heat liberated is related to the reduction state of the fuel i.e. the heat of combustion is dependent upon the chemical makeup of the fuel both at the molecular and atomic levels. For the various components in wood, the reduction state is in the following order: resins > lignin > cellulose and hemicelluloses. Normally, substances rich in reduced components give a high heat of combustion value. Thus, the heating value of woody material is generally modified to some extent by the amount of resinous extractives [62-63].Combustion quality of fuelwood is also dependent on its moisture content. Presence of moisture in fuel does not change its higher heating value, but the usable heat per unit mass does change (i.e. reduce) for the following reasons: firstly, there is simply less combustible substance per unit weight of the fuel; secondly fuel moisture also causes heat loss during combustion, because some energy must be consumed to vaporize water [62-63]. The ash in fuelwood adversely affects the heat of combustion by reducing the heating value per unit weight of the fuel. Wood ash is not problematic for domestic use of fuelwoods. But, it may create problems in industrial fuelwoods where boiler furnaces achieve high temperatures, producing slag and clinkers from melting and fusion of ash [63]. Thus, tree species having high ash content are less desirable for industrial fuelwood [63-64]. In addition, wood species having high moisture show poor combustion quality and are less desirable for use as fuelwood [55].

Along with these physico-chemical properties, combustion quality of fuelwood is also related to some of its combustion characteristics. The important combustion characteristics which affect fuelwood properties are ignition temperature, peak temperature, maximum combustion rate, mean combustion rate, burnout temperature etc.

2.2 Investigating fuelwood species in abroad

Anderson *et al.* [65] reported that chemical composition, specific gravity, fuel value and size are the most useful indices of woody biomass quality that influence its suitability for efficient conversion with respect to energy. According to Davidson [66], tree species with high wood calorific value, high specific gravity and capacity for rapid growth on a wide range of sites are suitable for bio-energy plantation. Recently, Moya and Tenorio [67] investigated 10 fast-growing species for plantation in Costa Rica with respect to the fuel characteristics such as calorific value and Fuel Value Index (FVI). They observed large variation in FVI among the fuelwood species. The calorific value of heart wood was significantly influenced by the amount of extractives (extracts in dichloromethane), carbon, nitrogen, lignin content and ash content. On the other hand, the calorific value in sapwood was affected by the amount of extractives (extracts in ethanol- toluene) and the amount of ash content. FVI was affected by the quantity of carbon, lignin, the extractives in sodium hydroxide and dichloromethane. In an another study, Hindi *et al.* [68] determined wood properties such as gross heat of combustion, specific gravity, void volume, ash content, total extractives, lignin and holocellulose of 6 Saudi tree species and reported the relationship of the above properties with wood heating value. Khider and Elsak [69] investigated 4 hardwood species (*Acacia mellifera, Acacia senegal, Eucalyptus tereticornis* and *Moringa oleifera*) from Blue Nile state, South East Sudan for energy production purposes. They determined heat values of the species with the help of a regression model derived from chemical components of the wood. In a similar study, Cuvilas *et al.* [70] investigated 8 hardwood species from three provinces (Cabo Delgado, Nampula in northern Mozambique, and Sofala in the central part) of Mozambique. They determined fuelwood properties, such as higher heating value, density, ash, lignin, carbohydrates, volatile matter, extractives, elemental composition (C, H, N, O, S, and Cl) , heavy metals for the wood species and also calculated FVI(based on higher heating value, density and ash). They reported that tree species with higher FVI exhibited good fuelwood qualities. Mainoo and Ulzen-Appiah [71] investigated 3 tree species from the semi deciduous rainforest ecological zone of Ghana and correlated fuelwood properties including growth, wood yield, specific gravity, calorific value, moisture, chemical composition and FVI with wood biomass productivity and energy potentials of the species for use as fuelwood. Ramos et al. [72] carried out a study in a rural community in NE Brazil to scrutinize resemblance between local preferences for fuelwoods and their physical characteristics. They observed a significant relationship between plants with the highest FVIs and the most preferred fuelwood plants in the region. Lamers and Khamzina [73] investigated 3 tree species suitable for photo-remediation of marginal land in the Aral Sea Basin, Uzbekistan. They quantitatively determined fuelwood properties, such as such as calorific value, wood density, ash, moisture, C and N content and also calculated FVI (based on calorific value, density and ash content). Similar study was also reported by Munalula and Meincken [74] investigating 5 wood species (*Acacia cyclops, Acacia erioloba, Eucalyptus cladocalyx, Pinus patula and Vitis vinifera*) from Western Cape of South Africa with regards to their calorific values and environmental impacts when burned. In the Investigation of fuelwood properties of 31 species from Papua New Guinea, Jonathan *et al.* [75] reported that calorific value and ash content are the two important fuelwood properties for identifying new and reinforcing the traditionally used fuelwood species as quality fuelwood.

2.3 Investigating fuelwood in India

Studies on fuelwood characteristics of tree species available in different parts of India are also reported by several researchers. Singh and Khanduja [76] investigated 13 firewood shrub species in northern India. The authors determined calorific value, density, ash, moisture, silica, carbon, nitrogen and biomass/ash ratio for the species. The study revealed that *Tamarix dioca, Carissa spinarum, Acacia calycina, Adhatoda* *vasica* and *Dedonia viscosa* could be used for intensive cultivation as firewood biomass in short rotations forestry. In a similar study, Bhatt and Todaria [77] investigated 33 high altitude vegetation, mountain trees and shrub confined to Garhwal Himalayas towards fuelwood characterization. Their findings suggested that temperate species offered better candidature as fuelwood species owing to high wood density, low ash content and low nitrogen percentage. They concluded that *Premna barbata, Daphniphyllum himalense*, *Pyracantha crenulata, Lyonia ovalifolia* and *Cotinus coggygria* possessed high FVI (correlated to high energy content, high wood density, low ash and water content) and may possibly be the most favorable species. Jain [78] investigated 26 perennial species grown in their natural habitat in Central India and 16 indigenous and exotic Pinus species from the Himalayan region at Kalika based on fuelwood properties like calorific value, density, ash, silica, moisture, nitrogen, volatile matter and FVI. In an another study, Jain [79] investigated 22 tree species grown in their natural habitat in Indian forests based upon fuelwood properties viz. calorific value, ash, density, silica, moisture, carbon, nitrogen, volatile matter and the FVI. The study revealed that *Osmanthus fragrans, Quercus incana, Machilus odoratissma, Logertroemia indica* and *Punica granatum* exhibited the best fuelwood qualities among the species examined. Negi and Todaria [80] investigated quantitative fuel characteristics of 33 trees and shrubs of Garhwal Himalaya. In their study, FVI was considered as a standard parameter to identify suitable tree species for fuelwood production. They reported that *Murraya exotica, Schlichera trijuga, Vlmus wallichiana, Flacourtia ramontchi, Rubus niveus, Callicarpa macrophylla,* and *Eleadendron glaucum* were the most suitable tree species for fuelwood production. In a similar study, Puri *et al.* [81] determined fuelwood properties (calorific value, ash, density, water content, nitrogen content) of 6 indigenous (*Acacia nilotica, Azadirachta indica, Casuarina equisetifolia, Dalbergia sissoo, Prosopis cineraria and Zizyphus mautitiana*) and 4 exotic (*Acacia auriculifonnis, Acacia tortilis, Eucalyptus camaldulensis* and *Eucalyptus tereticomti*) tree species (for tree parts such as stump, main stem, tree top, branches, foliage and bark) from Hisar region. They reported

that indigenous tree species were best suited due to their high density, low ash content and low nitrogen content. On the basis of FVI, they reported that *Acacia nilotica, Casuarina equisetifolia and Zizyphus mauritiana* were the most suitable fuelwood species among ten species studied. Goel and Bhel [82] investigated the fuelwood quality of 5 tree species suitable for plantation in alkaline soil sites of Banthra, Lucknow in relation to tree age for establishing harvest rotation cycles. They reported that *Prosopis juliflora* and *Acacia nilotica* were the most suitable species for short rotation fuelwood forestry programmes due to their high wood density, high biomass yield, low ash, low moisture content, and high heat of combustion at the juvenile stage. Jain and Singh [83] analysed 33 indigenous tree species grown in their natural habitat in subtropical forest of central India on the basis of fuelwood properties such as moisture, silica, ash, density, carbon, nitrogen, volatile matter and calorific value. FVI was also calculated to screen suitable species for potential production of fuelwood in these areas. They reported that *Acer oblongurn, Betula alonoides, Greviilea robusta, Limonia acidissima, Lyonia ovalifolia, Madhuca indica, Melia azedarch, Motinda tinctona, Myica sapida, Ptunus comuta, Pyrus pashia, Quercus langtnosa, Rhamnus triqueter* and *Stereospennum xylocarpum* exhibited better fuelwood qualities. Goel *et al.* [84] investigated the performance of 3, even-aged leguminous tree species (*Acacia nilotica, Acacia auriculiformis* and *Pithecellobium dulce*) on sodic soil sites at Banthra, Lucknow. In the study, they observed that *Acacia nilotica* has highest average girth at breast height (60.5 cm) and stand biomass (161 Mg ha^{-1}) despite its lowest plants survival after 15 years of growth. *A. nilotica* also showed superiority in respect to energy content in woody biomass (2467 GJ ha^{-1}) and fuel value index (1694) as compared to the other two species. The study concluded that species like *Acacia nilotica* could be selected as a promising species for afforestation of degraded soil sites, such as sodic soils, because of its higher biomass production potential, greater energy harvest, and efficiency to restore the soil quality suitable for climate-based productivity. Nirmal Kumar *et al.* [57] investigated 7 wood species (*Acacia nilotica, Cassia fistula, Acacia leucophloea, Prosopis cineraria, Tectona grandis, Butea* *monosperma* and *Sterculia urens*) from dry tropical forest, Udaipur and Bhilwara district of Rajasthan. In the study, fuelwood properties, such as density, ash content, and elemental composition (C, N, P, S, Pb, Al, As and Cd) of wood species were determined and correlated with the calorific value and evaluated in relation to their properties and environmental impact when burned. Their findings revealed that the wood with the highest calorific value does not necessarily constitute the best option as fuelwood, if elemental composition is taken into account. On the basis of overall determined properties they reported that all the species under study were preferable as fuelwood and their preference order were as *Acacia nilotica>Acacia leucophloea>Prosopis cineraria> Tectona grandis>Butea monosperma >Sterculia urens*. In another study, Nirmal Kumar *et al.* [85] investigated the fuelwood characteristics of 26 trees including shrub species from the dry deciduous forest in Aravally region, Rajasthan. On basis of FVI (based on calorific value, wood density and ash) they recommended *A. nilotica, T. grandis, B. monosperma, P. cineraria* and *Albizia lebbek* for inclusion in the energy plantation programme in this region. Chauhan and Soni [86] investigated about the biomass production, calorific value and chemical composition of different short rotation tree species and reported that short rotation tree species such as *Gmelina arborea, Eucalyptus tereticornis, Pongamia pinnata, Terminalia arjuna, Toona ciliate* exhibited better fuelwood properties and could be considered for inclusion in the energy plantation programme to minimize pressure on the traditional forests. Saravanan *et al.* [87] investigated *Melia dubia* wood species from different age groups (one, two, three, four and five year old) for assessing the fuel wood properties. Among the various tested age gradations of *Melia dubia* 5-year age old wood recorded the highest calorific value (3820 Kcal Kg^{-1}) and FVI (4125.60). From a comprehensive viewpoint, the study identified the prospects of 5-year*Melia dubia* with regard to energy properties and consequently its acquiescence for prospective energy utilities.

A large numbers of trees and shrubs grow well in natural habitats in the North Eastern region of India. But very little is known about their fuelwood characteristics.

Kataki and Konwer [88] investigated four indigenous perennial tree species namely *Albizzia lucida, Syzygium fruticosa, Pterospermum lanceaefolium and Premna bengalensis* grown in their natural habitat of north-east India. They reported that *Albizzia lucida, Syzygium fruticosum* and *Pterospermum lanceaefolium* exhibited better fuelwood properties and could be considered for inclusion in the energy plantation programme of north-east India. They further investigated fuelwood characteristics of 35 indigenous tree species grown in their natural habitat in north-eastern region of India [89]. They reported that *Acacia nilotica, Acacia auriculiformis, Albizzia lebbeck, Albizzia procera, Pinus kesiya* and *Elaeognus umbellata* were best suited as fuelwood and could be considered for inclusion in energy plantation programme in this region. Bhatt and Tomar [90] quantitatively analyzed 26 indigenous mountain fuelwood species of north-eastern Himalaya region. In the study, FVI was calculated by considering calorific value and density as positive criteria whereas ash content as negative criterion. They reported that tree species *Betula nitida, Machilus bombycina, Itea macrophylla, Cryptomeria japonica, Gmelina arborea, Simingtonia populnea, Macaranga denticulata* and *Schima wallichii* were prospective for fuelwood production. In a similar study, Bhatt *et al.* [30] investigated 25 indigenous trees and shrubs of the north-eastern Himalayan (NEH) region. On the basis of FVI, they reported that *Gaultheria fragrantissima, Litsea citrata, Myrica esculenta, Aesculus assamica, Daphniphyllum himalense, Mesua ferrea* and *Wendlandia tinctoria* were the most promising firewood species. In a similar study, Deka *et al.* [91] investigated 10 indigenous tree species of Assam, India preferred by its local people as fuelwood. In the study, fuelwood species were ranked on the basis of pair-wise comparison technique and FVI. The study revealed that the ranking order of the indigenous fuelwood species by pair-wise comparison technique used by the rural people of the sample areas of Assam has sufficient resemblance with those obtained from FVI. Bhatt *et al.* [92] quantitatively analysed 19 indigenous fuelwood species of eastern Himalaya, India to identify trees with potential for firewood production. FVI (calorific value X density/ash content) was calculated for fuelwood species. Over-all rank sum index (ORSI) for firewood species was also determined with the help of firewood characteristics (FVI), fuelwood production potentiality, and availability in the region. On the basis of ORSI, they reported that *Castanopsis indica, Phoebe attenuata, Macropanax undulatum, Ixonanthes khasiana, Morus laevigata, Caryota urens, Lithocarpus elegans*, and *Litsea laeta* were the most preferred firewood species.

2.4 Study on fuelwood properties and their influence on heating value

The selection of a particular tree species for various end uses is based mainly on its physical and chemical properties.

Specific gravity is one of the most important physical characteristics of wood because of its positive association with fuel value and cellulose content and negative association with moisture content [93-95]. Wood with higher specific gravity is generally less susceptible to decay. The specific gravity of the cell walls of all wood species is approximately 1.5. However, because of the porous nature of wood, specific gravity (based on oven dry weight and green volume) ranges from 0.29 to 0.54 for most of the softwood and from 0.31 to 0.80 for most of the hardwood [96]. Kumar et al. [97] reported an average density range of 0.55-0.58 g/cm^3 for lower age (2-6 years) and 0.73 g/cm^3 for a matured (20 years) Eucalyptus hybrid. A positive correlation between gross calorific value and density of wood and bark samples of 45 multipurpose tree species from the homegardens of Kerala, India was observed by Shanavas & Kumar [98]. Variations in wood density are directly associated with structural differences at the molecular, cellular and organ levels [99]. It differs among tree species [9], age group [97, 100], tree parts [99], height of the tree [101] and also influenced by environmental factors [35].

Moisture content is the most commonly used fuelwood property in relations to its utilization as a source of energy. A living tree obtains its moisture through water uptake from the soil where it is found as bound water in cell walls and free water in cell lumens [102]. Moisture content is an important characteristic in defining the ease of combustion of a fuelwood, the amount of smoke it produces, and its caloric energy

[103]. Higher moisture content makes the fuelwood less efficient since it reduces the net calorific value as well as usable heat content in it [60]. Lyons *et al.* [60] and Demirbas [104] reported a negative relationship between heating value and moisture content of different fuelwood species. On the other hand, Romas *et al* [72] observed a significant inverse correlation between moisture content and density in fuelwood species. According to Demirbas [103] moisture percentage in wood species varied between 41.27 to 70.20%. Chettri and Sharma [105] reported that the moisture content among 16 tree species from west Sikkim, north-east India, varied between 25.3±0.9 (*Rhododendron arboreum*) to 76.3±0.33% (*Symplocos ramosissima*). However, moisture content in wood species depends on many factors; the moisture sorption capacity of wood changes with the chemical composition of its cell wall constituents (cellulose, hemicelluloses and lignin) [24-25]. Apart from physiological differences that might cause variation in moisture content in different tree parts, seasonal changes, local climate, and geographic location also influence towards the difference in moisture content among different species [32, 106]. According to Nurm [102], moisture content varies from one tree part to another. It is often the lowest in the stem and increases towards the roots and the crown.

The heating values of biomass fuel can be determined experimentally and can be calculated from the ultimate and /or proximate analysis data [107]. Demirbus [108] reported that calculation of HHVs from their ultimate and proximate analysis data show mean differences from measured values ranging from 0.1% to 4.0%. Glove *et al.* [109] reported the relationship between heating value and chemical composition of selected agricultural and forest biomass. He found that regression model with the ultimate elemental composition as independent variable gave better correlation to measure gross heating value than those based on the proximate chemical composition.

C, H, N, O and S are the elements which make up the various components of wood (cellulose. hemicelluloses, lignin etc.). Generally, in wood, the elemental compositions of C, O, H and N are 45-50%, 40-45%, 4.5-6% and 0.3-3.5%

respectively on dry weight basis whereas the percentage of S is negligible (less than ~0.1%) [37,110]. C and H are the main heat producing elements and directly contribute to the heating value of fuelwood [37]. Obernberger [51], Sheng and Azevedo [111] reported that HHV of fuelwood increases with the increase of C and H contents. Tilmann [112] also observed a positive correlation between HHV and C content. On the other hand, Saidur [113} reported a negative relationship between HHV of fuelwood and O content while no relationship was observed between HHV and O content by Sheng & Azevedo [111]. N and S contents in fuelwood pollute the environment by producing oxides of N and S (NOx and SOx) during combustion [114].

Volatile matter (VM) in wood is the fraction released when it is heated at a high temperature without considering moisture while fixed carbon (FC) is the mass left after the release of volatiles, excluding ash. The share of VM is typically high in wood than that of FC. About eighty percent of wood energy actually originates from the combustion of VM or gases and twenty percent from the combustion of FC (glowing embers) [37]. Saidur et *al.* [113] reported that high FC and VM increase the heating value of fuelwood. On the other hand, Sheng and Azevedo [111] observed only a trend between the higher heating value and the volatile matte while no correlation is found between higher heating value and fixed carbon. According to Haykiri-Acma and Yaman [115] holocellulose (sum of hemicelluloses and cellulose) portion in wood mainly contribute to the formation of volatiles. Grønli *et al.* [116] reported that the FC is directly related to the lignin content. In another study, Gominho *et al.* [117} observed an inverse relationship between VM and FC. Telmo *et* al. [118] observed the variation of VM in 17 wood species between 74.75-86.3% and FC variation between 13.3-22.5%. Mitchual *et al.* [114] reported that among the 6 tropical hardwood species (*Triplochiton scleroxylon, Ceiba pentandra, Aningeria robusta, Terminalia superba, Celtis mildbreadii and Piptadenia africana*) VM varied from 75.23% (*Aningeria robusta*) to 83.70% (*Celtis mildbreadii*). Senelwa and Sims [31] observed higher percentage of VM in wood in comparison to its bark. They also reported that VM variations result from differences in volumetric percentage of the vessels in the different species and components.

Inorganic minerals remain in the oxidized form as ash after complete combustion of the fuelwood [119]. A high ash percentage reduces heating value of fuelwood, because a considerable amount of the fuelwood cannot be contributed towards energy [57,120-121]. Khider and Elsaki [69] reported that ash content in fuelwood is negatively correlated with heating value and holocellulose having correlation coefficients of -0.756 and -0.676 respectively. Nasser *et al.* [122] also observed a significant inverse correlation between ash content and heating value in fuelwood. According to Kumar *et al.* [97] higher ash amount is found in lower age trees. Werkelin *et al.* [123] observed that the ash amount varies within the tree parts and highest ash concentration is found in tree foliage (shoots and leaves). Demirbas [124] found significant variation in ash content (0.86 to 9.21%) among six indigenous fuelwood species: *Picea orientalis*, *Fagus orientalis*, *Prunus laurocerasus*, *Quersus pedunculata*, *Carpinus betulus*, and *Carpinus orientalis* that grow under similar agro-climatic conditions. In another study, Rai *et al.* [125] reported that among 66 tree species (from Sikkim, northeast India) ash content varied between 0.23-3.72%.

Woody biomass is composed of biopolymers that consist of various types of cells and the cell walls are built of cellulose, hemicelluloses and lignin [103]. The percentages of these polymeric constituents for softwood and hardwood, as reported by McKendry [126] are listed in Table 2.1

Table 2.2: Cellulose, hemicelluloses and lignin percentages for softwood and hardwood (Wt. %)

Type of wood	Cellulose (%)	Hemicelluloses (%)	Lignin (%)
Softwoods	35–40	25–30	27–30
Hardwoods	45–50	20–25	20–25

Heating value of wood depend on the relative proportion of these biochemical constituents namely cellulose, hemicelluloses and lignin. Cellulose and hemicelluloses which are composed entirely of sugar units have relatively low heat content due to their high level of oxidation while lignin have a lower degree of oxidation and a considerably higher heat of combustion [88, 127-128]. In other words, Lignin is richer in carbon and hydrogen, the main heat producing elements in wood and hence lignin has a higher heating value than carbohydrates [110, 49]. Typically, holocellulose (cellulose + hemicelluloses) have a higher heating value of ~18.60 kJg^{-1}, whereas lignin has a higher heating value of 23.26-26.58 $kJg^{-1.}$ In general, the HHV of fuelwood increase with increase of their lignin content [129]. Demirbas [103], Telmo and Lousada [49], Vargas-Moreno *et al.* [130] observed a significant positive correlation between higher heating value of fuelwood and lignin. On the other hand, Demirbas [131] found no relationship between HHV and holocellulose of fuelwood. In a related study, Kataki and Konwer [88], Shanavas & Mohan [98] reported that density of wood species increase with increase of lignin content.

The heat of combustion of wood depends upon its chemical composition. Softwood of Pinus species contains a high amount of resin, waxes and lignin, which give a high heat of combustion [132-136]. Chandler *et al.* [137] reported the greater higher heating value of softwood than hardwood, as softwood contains more resins or extractive content. According to Kollman and Cote [138], extractives are more abundant in the heartwood than in the sapwood. Demirbas [103] reported that the higher heating values of the extractive-free tee parts are lower than those of non-extracted parts, which is the indication of positive relation between extractives and higher heating value. Demirbas [104] and White [58] also reported the positive relationship between extractives and higher heating value. According to Kumar *et al.* [127] the higher heat of combustion of extractives is due to its lower degree of oxidation in comparison with cellulose and hemicellulose. Nasser and Aref [139] reported that the extractive contents in six Acacia species varied from 9.94% (*Acacia ehrenbergiana*) to 13.82% (*Acacia tortilis*) where they found a significant correlation between extractives and heating value of fuelwood species. In another study, Nasser *et al.* [122] observed highly significant correlations between the heating value and ethanol-benzene extractives whereas no significant correlation was found between heating value and total extractives as well as between water extractives and heating value. Howard [135] also observed a positive correlation between the alcohol/benzene extractives and heating value of loblolly pine. According to White [58], there are many different types of extractives and their higher heating values probably vary widely. He reported that terpenes and resin as the two classes of extractives that significantly affect the heating value of wood fuels. Howard [135] determined the higher heating value of resin portion of the extractives and found 34.89-37.21MJ/kg.

2.5 Study on thermal degradation of wood/biomass

Analysis of the thermal degradation of biomass fuels is decisive in combustion and fire research for both fundamental and practical investigation. Wongsiriamnuay and Tippayawong [140] investigated the thermal degradation of giant sensitive plants (*Mimosa pigra* L.) or Mimosa under oxidative environment in different heating rates (10, 30 and 40°C) by using thermogravimetric method. The results indicated that there were three degradation steps in the TG/DTG curve: first one due to dehydration between the temperature range of 30-150°C, second one due to volatilization & oxidative degradation between the temperature range of 200-3700°C and third one due to char combustion between the temperature range of 375-500°C. They reported that mass loss and mass loss rates were strongly affected by heating rate They further reported that average devolatilisation and combustion rates were increased with increasing heating rates whereas, activation energy showed minor increase with increasing heating rates. Brostow *et al.* [141] studied 6 wood species by using combined thermogravimetric and differential thermal analysis (TG/ DTA) to evaluate their combustion properties in terms of the amount of energy released, ignition temperature, and the cleanness of burning. They observed that *Quercus rubra* burned to the hottest temperature among all the samples and also left the least amount of ash behind. They also observed that there was no correlation between the wood density and the parameters characterizing the burning process. In a similar study, the relation of the TG/DTG parameters with chemical properties, extractives and moisture content of 10 fast growing tree species was reported [142]. They observed little influence of extractives and chemical properties on combustion process, but moisture content influenced greatly on thermal stability and combustion process. Investigation on ignition behaviour and combustion characteristics (maximum combustion rate, burnout temperature, ignition index and combustion index) of various biomass fuels was also reported by many researchers [143-145]. Jiricek *et al.* [146] investigated the ignition and combustion behavior of biomass and biomass blends in various additive weight ratios. In the study, non-isothermal thermogravimetry was applied to determine the combustion characteristic of 6 samples, namely wheat straw, rape straw, flax straw (leftover after scutching), pulp-mill lignin, garden peat, and hardwood charcoal. According to the authors, the addition of a suitable additive could increase the combustion efficiency; since the additive contains a catalyst which is a carrier of oxygen. The results indicated that the Combustion Characteristic Factor (CCF) for all the biomass fuels chosen in this study were near to or greater than 2 with an exception for pulp mill lignin and peat while for the blends the CCF was between the original values. However for the additive, CCF values were highest indicating that blending biomass with the additives could lead to better combustion. The study revealed that the addition of oxygen to the primary air and the particle size of the samples influence the combustion process. It was also observed that the volatilization rate and the heat release were affected on addition of additive to biomass and the combustion residue was reduced at the same final combustion temperature.

Knowledge of the composition and specialization of inorganic elements in fuel is of vital importance for studies of combustion related topics, such as ash and deposit formation as well as sulphur and chlorine retention in ash.

The disposal of wood ash is a growing problem as environmental regulations become more stringent and landfill sites become less available and more expensive

[147]. Wood ash has been used in a variety of agricultural applications as it is an excellent source of potassium, lime and other plant nutrients [147-150]. Wood ash has also been used as a binding agent, a glazing base for ceramics, a road base, an additive in cement manufacturing and an alkaline material for the neutralization of different types of acidic wastes [151].

Etiegni and Campbell [152] made a study to evaluate the temperature dependence of wood ash yield and chemical components. They reported that wood ash decreased by approximately 45% as the combustion temperature increased from 538 to 1093^{0}C. They also observed that potassium, sodium, zinc and carbonate content decreased with increase of temperature whereas other metal ions remained constant or increased. Wood ash leachate was found to certain 92% hydroxide and 8% carbonate. It was also reported that total dissolved solids of the ash increased by 500% as the p^H decreased from 13 to 5.

The ash from biomass fuels contains only trace amount of heavy metals, which makes it fairly easy to dispose of. Some of the heavy metals are found to be good fertilizers [148-149, 153-155] and can be used as mineral nutrient for forest and agricultural soils. From a study on the characteristics of ashes from wood and straw, Olanders *et al.* [156] concluded that Potassium content was 3 times higher in straw ash than in wood ash or bark ash. They also observed that ash from wood or bark had higher percentage of carbonate content. $CaCO_3$ and SiO_2 were identified as the major crystalline compound in the wood or bark ash, while the straw ash was dominated by $CaCO_3$, KCl, K_2SO_4 and SiO_2. The higher percentage of ash content in bark and leaves were reported as 2.6-5.7% and 3.6-11.2%, respectively as compared to 0.4-1.2% in wood. According to Senelwa and Sims [31], higher ash content in bark and leaves was due to the concentration of potassium in the actively metabolizing portions of the tree crown and leaf area where nutrients from the soil are fixed prior to relocation to other parts of the plant. Shafizadeh [157] also observed that bark produced more ash than wood. He indicated that silica and other insoluble inorganic compounds in plant act as a heat sink, while the other soluble ionic compounds could have a catalytic effect on the gasification and combustion of biomass fuels. Wood ash is dominated by calcium, silicon, aluminum, potassium and magnesium [148, 152].

Many ash-forming inorganic species are associated with organic compounds in biomass fuels. During combustion the organic structures are decomposed and the ash formers are released. Alkaline earth metals leave the combustion zone as solid particles while the alkali metals are transported in vapour form as chlorides, hydroxides or oxides [158]. These compounds can react with SO_2 in the combustion gas and form sticky sulphate particles, which adhere to heat exchange surface and form hard deposits [158].

References

1. Sharpe, G.W. *Introduction to forestry*, 4th edition, MacGraw-Hill Book Company, New York, 1976, pp. 554.
2. Zerbe, J. I. Biofuels: Production and Potential, Report of the forum for applied research and public policy/winter, pp. 38-47, 1998, downloaded from URL: www.marioloureiro.net/ciencia/biomass/biofuel.pdf on 12/03/2013.
3. Cecelski, E., J., et al. Household Energy and the Poor in the Third World, in *Resources for the Future*, Washington, DC, 1979.
4. Bose, R. K. Biomass energy resources assessment through rural energy surveys—a common approach, in *Commonwealth Science Council Technical Publication Series No. 188*, Wereko-Brobby, C. Y., eds., Commonwealth Science Council, London, pp. 85-123, 1985.
5. Bhatt, B. P., & Sachan, M. S. Firewood consumption along an altitudinal gradient in mountain villages of India, *Biomass and Bioenergy* **27**, 69–75, 2004.
6. Maikhuri, R. K. Fuel wood consumption pattern of different tribal communities living in Arunachal Pradesh in North-East India, *Bioresource Technology* **35**, 291–6, 1991.
7. Banerjee, S., et al. Population growth, energy utilization pattern and environmental degradation: a micro study, *Demography India* **121** (2), 281–90, 1992.
8. Jungerius, P. *Perception and use of physical environment in societies*. Geographical paper no.93, Department of Geography, University of Reading, Reading, U. K., 1985.
9. Deka, D. *Fuelwood characteristics of some indigenous tree species of Assam*, Ph.D. Thesis, Tezpur University, India, 2004.
10. Ayensu, S. E. *Firewood Crops: Shrub and Tree Species for Energy Production*, Report of an Ad Hoc Panel of the Advisory Committee on Technology Innovation Board on Science and Technology for International Development Commission on International Relations, National academy of sciences, Washington, D. C., 1980.

11. Wikipedia, the free Encyclopedia, downloaded from http://en.wikipedia.org/wiki/Wood on 19/03/2014.
12. The free Dictionary by Ferlax, downloaded from http://encyclopedia2.thefreedictionary.com/Wood on 19/03/2014.
13. Baysal, E. Surface characteristics of CCA treated scots pine after accelerated weathering, *Wood Research* 57(3), 375-382, 2012.
14. .Parham, R. A., & Gray, R. L. Formation and structure of wood, in The Chemistry of Solid Wood, R. Rowell, eds., American Chemical Society, Washington DC, 1984.
15. Tillman, D. A., *et al.* Properties of wood fuel, in Wood Combustion, Principle, Processes and Economics, Academic Press, New York, 1981, 18.
16. Shmulsky, R., & David, J. P. Forest Products and Wood Science: An Introduction, Sixth Edition, John Wiley & Sons, West Sussex, UK, 2011.
17. Sjöström, E. Wood chemistry-fundamentals and applications, Academic press, Orlando, USA, 1993.
18. Butterfield, B. The structure of wood: Form and Function, in Primary Wood Processing-Principles and Practice, J. C. F Walker, eds., Springer, Dordrecht, the Netherlands, 2006.
19. Miller, R. B. Wood Handbook-Wood as an Engineering Material. Forest Products Laboratory, Gen. Tech. Rep. FPL–GTR–113, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1999.
20. Wiedenhoeft, A. C., & Miller, R. B. Structure and function of wood, in Handbook of Wood Chemistry and Wood Composites, R.M. Rowell, eds., CRC Press, Boca Raton, 2005.
21. Downloaded from http://www.paperonweb.com/dict.htm on 12/05/2013.
22. Downloaded from http://www.bbc.co.uk/schools/gcsebitesize/design/electronics/materialsrev2.shtml on 10/04/2012.

23. Biomass heating: A practical guide for potential users, The Carbon Trust, UK, 2009, downloaded from https://www.carbontrust.com/media/31667/ctg012_biomass_heating.pdf on 01/02/2014.
24. Chauhan, S. S., & Nagaveni, H. C. Moisture adsorption behaviour of decayed rubber wood, *The Journal of the Institute of Wood Science* **19** (1), 1-6, 2009.
25. .Stokke, D. D., *et al. Introduction to wood and natural fiber composites*, Wiley, West Sussex, U.K., 2014.
26. Skaar, C. *wood –water relations,* Springer- Verlag, Berlin, 1988.
27. Laurila, J., *et al.* Compression drying of energy wood, Fuel Processing Technology 124, 286–289, 2014.
28. Espenas, L. D. *Some wood-moisture relations: Information Reviewed and Reaffirmed.* United States department of agriculture forest service: Forest products laboratory .Madison 5, Wisconsin, 1951.
29. Abbot, P. G., & Lowore, J. D. Characteristics and management potential of some indigenous firewood species in Malawi, *Forest Ecology and management* **119** (1–3), 111–121, 1999.
30. Bhatt, B. P., & Tomar, J. M. S. *et al.* Characteristics of some firewood trees and shrubs of the North Eastern Himalayan region, India. *Renewable Energy* **29**, 1401–5, 2004.
31. Senelwa, K., & Sim, R. E. H. Fuel characteristics as short rotation forest biomass, *Biomass and Bioenergy* **17**, 127-140, 1999.
32. Hakkila, P. Polttohakepuun kuivuminen metsassa. Summary: Forest seasoning of wood intended for fuel chips, *Communicationes Instituti Forestalis Fenniae* **54** (4), 82, 1962.
33. Skaar, C. *Water in wood*, Syracuse wood Science Series. *No.1*, Syracuse University Press, Syracuse, New York, 1972.

34. Jozsa, L. A., & Middleton, G. R. *A discussion of wood quality attributes and their practical implications*, Special Publication No. SP-34, Forintek Canada Corp., Vancouver, B.C. 1994.
35. Zobel, B., & Talbert, J. *Applied forest tree improvement*, Springer-Verlag Berlin, 1984.
36. Montes, C. S., *et al.* Calorific value of *Prosopis africana* and *Balanites aegyptiaca* wood: Relationships with tree growth, wood density and rainfall gradients in the West African Sahel, *Biomass and Bioenergy* **35**, 346-353, 2011.
37. Chung, Y. J. Comparison of combustion properties of native wood species used for fire pots in Korea, *Journal of Industrial and Engineering Chemistry* **16**, 15–19, 2010.
38. Henriksson, G., *et al.* The tree, in *Wood Chemistry and Wood Biotechnology*, Ek, M., *et al*, eds., Walter de Gruyter GmbH & Co. Berlin. 2009.
39. Rowell R. M., *et al.* Cell Wall Chemistry, in *Handbook of Wood Chemistry and Wood Composites* , R.M. Rowell, eds., USDA, Forest Service, Forest Products Laboratory, CRC Press, Madison, WI. 2005.
40. Pettersen, R. C. The Chemical composition of wood, in *The Chemistry of Solid Wood*, R. Rowell, eds., American Chemical Society, Washington D.C., 1984.
41. Fengel, D., & Wegener G. *Wood chemistry, ultrastructure, reactions*, Walter de Gruyter. Berlin, Germany, 1989.
42. Dall'Ora, M. *Reactivity and burnout of wood fuels*, Ph.D. Thesis, Technical University of Denmark, Denmark, 2011.
43. Goring, D. A. I., & Timell, T. E. Molecular weight of native celluloses, *Tappi*, **45** (6), 454–460, 1962.
44. Teleman, A. Hemicelluloses and Pectins, in *Wood Chemistry and Biotechnology*, M. Ek, *et al.*, Walter de Gruyter GmbH & Co., Berlin, 2009.
45. Stenius, P. *Forest Products Chemistry*, Fapet Oy, Helsinki, 2000.

46. Chen, C. L. Lignins: Occurrence in Woody tissues, isolation, reactions, and structure, in *Wood Structure and Composition*, M. Lewin, & I.S. Goldstein, eds., New York, Marcel Dekker Inc., 1991, 183-261.
47. Henriksson, G. Lignin, in *Wood Chemistry and Biotechnology*, M. Ek, et al., Walter de Gruyter GmbH & Co., Berlin, 2009.
48. Carrillo-Parra, A. *Technological investigation of Prosopis laevigata wood from north east Mexico*, Ph.D. Thesis, Forest Sciences and Forest Ecology, University of Gottingen, Nuevo León, México, 2007.
49. Telmo, C., & Lousada, J. The explained variation by lignin and extractive contents on higher heating value of wood, *Biomass and Bioenergy* **35**, 1663 -1667, 2011.
50. Rowell, R. *The chemistry of solid wood. Advances in chemistry*, vol. 207. American Chemical Society, ISBN 0-8412-0796-8, Washington, 1984.
51. Obernberger, I., *et al.* Chemical properties of solid biofuels—significance and impact, *Biomass and Bioenergy* **30**, 973–982, 2006.
52. Hon, D. N. S., & Shiraishi, N. *Wood and Cellulosic Chemistry*, Marcel Dekker, New York, 1991.
53. Young, H. E., & Guinn, V. P. Chemical elements in complete mature trees of seven species in Maine. *Tappi* **49** (5), 190–197, 1966.
54. Anon. Woody biomass properties, 2010, downloaded on 10/03/2014 from http://www.extension.org/pages/26517/woody-biomass-properties
55. Demirbas, T., & Demirbas, C. Fuel Properties of Wood Species, *Energy Sources* **31**, 1464–1472, 2009.
56. Biomass heating: A practical guide for potential users, The Carbon Trust, UK, 2009, downloaded from https://www.carbontrust.com/media/31667/ctg012_biomass_heating.pdf on 01/02/2014
57. Nirmal Kumar, J. I., *et al.* An assessment of Indian fuelwood with regards to properties and environmental impact. *Asian Journal on Energy and Environment* **10** (02), 99-107, 2009.

58. White, R.H. Effect of lignin content and extractives on higher heating value of wood, *Wood Fiber Science*, **19** (4), 446–452, 1987.
59. Khan, A. A., *et al.* Biomass combustion in fluidized bed boilers: Potential problems and remedies, *Fuel Processing Technology* **90**, 21-50, 2009.
60. Lyons J. G., *et al.* A procedure for estimating the value of forest fuels, *Biomass* **8**, 283 – 300, 1985.
61. Senapati, M. R. *Advanced Engineering Chemistry*, Laxmi Publications, New Delhi, India, 2006.
62. Wickens, G.E. (ed.). *Economic Botany: Principles and Practices*, Kluwer Academic Publishers, Dordrecht, the Netherlands, 2001.
63. Wang, S., *et al.* Qualitative Evaluation of Fuelwood in Florida-A Summary Report, *Economic Botany* **36** (4), 381-388, 1982.
64. Demirbas, A. Combustion of Biomass, *Energy Sources* **29**, 549–561, 2007.
65. Anderson, H.W., *et al.* Internal biomass characteristics for efficient energy conversion, in *IEA/ENOR Joint Workshop Proc.*, D. J. Morgan et al. eds., Uppsala, Sweden, 1984
66. Davidson, J. *Bioenergy tree plantation in the tropics: ecological implications and impacts*, International union for the conservation of nature and natural resources, Switzerland, 1987.
67. Moya, R., & Tenorio, C. Fuelwood characteristics and its relation with extractives and chemical properties of ten fast-growth species in Costa Rica, *Biomass and Bioenergy* **56**, 14-21, 2013.
68. Hindi, S. S. Z., *et al.* Gross Heat of Combustion for Some Saudi Hardwoods, *International Journal of Science and Engineering Investigations* **1**(5), 10-14, 2012
69. Khider, T. O., & Elsak, O. T. Heat value of Four Hardwood Species from Sudan, *Journal of forest productions & industries*, **1**(2), 5-9, 2012.
70. Cuvilas, C., *et al.* The Characterization of Wood Species from Mozambique as a fuel, *Energy Sources* 36(8) 851–857, 2014.

71. Mainoo, A. A., & Ulzen-Appiah, F. Growth, wood yield and energy characteristics of *Leucaena leucocephala, Gliricidiasepium* and *Senna siamea* at age four years, *Ghana Journal of Forestry* **3**, 69-78, 1996.
72. Ramos, M. A., *et al.* Can wood quality justify local preferences for firewood in an area of caatinga (dryland) vegetation? *Biomass and Bioenergy* **32**, 503-509, 2008.
73. Lamers, J. P. A., & Khamzina, A. Fuelwood production in the degraded agricultural areas of the Aral Sea Basin, Uzbekistan, *Bois et Forets des Tropiques* **297**, 47-57, 2008.
74. Munalula, F., & Meincken, M. An evaluation of South African fuelwood with regards to calorific value and environmental impact, *Biomass and Bioenergy* **33**, 415-420, 2009.
75. Jonathan, M. et al. A study on burning characteristics of some preferred fuelwood tree species in Papua New Guinea, 2009. URL:http://webistem.com/psi2009/output_directory/cd1/Data/articles/000090.pdf. on 21/7/2013
76. Singh, B., & Khunduja, S. D. Wood Properties of Some Firewood Shrubs in Northern India, *Biomass* **4**, 235-238, 1984.
77. Bhatt, B. P., & Todaria, N. P. Fuelwood Characteristics of Some Mountain Trees and Shrubs, *Biomass* **21**, 233-238, 1990.
78. Jain, R. K. Fuelwood characteristics of certain hard wood and softwood tree species of Central India, *Bioresource Technology* **41**, 129 – 133, 1992.
79. Jain, R. K. Fuelwood characteristics of some tropical trees of India, *Biomass and Bioenergy* **4** (6), 461-464, 1993.
80. Negi, A. K. & Todaria, N.P. Fuelwood evaluation of some Himalayan trees and shrubs, *Energy* **18** (8), 799-801, 1993.
81. Puri S., et al. Fuelwood value index in components of ten tree species of arid region in India, *Industrial Crops and Products* **3**, 69-74, 1994.
82. Goel, V. L., & Behl, H. M. Fuelwood quality of promising tree species for alkaline soil sites in relation to age, *Biomass and Bioenergy* **10** (1), 57-61, 1996.

83. Jain, R. K., & Singh, B. Fuelwood characteristics of selected indigenous tree species from central India, *Bioresource Technology* **68**, 305-308, 1999.
84. Goel, V. L., et al. Species Selection for Afforestation of Sub-Standard Soil Sites with Particular Reference to Biomass Production and Soil Rehabilitation, *Journal of Sustainable Forestry* **23** (3), 97-114, 2006.
85. Nirmal Kumar, J.I., *et al.* An evaluation of fuelwood properties of some Aravally mountain tree and shrub species of Western India, *Biomass and Bioenergy* **35**, 411-414, 2011.
86. Chauhan, S. K., & Soni, R. Chemical composition and fuel wood characteristics of fast growing tree species in India, *Geophysical Research Abstracts* **14**, EGU2012-10046, 2012.
87. Saravanan, V. *et al.* Evaluation of Fuel Wood Properties of Melia dubia at Different Age Gradation, *Research Journal of Agriculture and Forestry Sciences* **1**(6), 8-11, 2013.
88. Kataki, R. K., & Konwer, D. Fuelwood characteristics of some indigenous woody species of north-east India, *Biomass and Bioenergy* **20**, 17-23, 2001.
89. Kataki, R. K., & Konwer, D. Fuelwood characteristics of indigenous tree species of north-east India, *Biomass and Bioenergy* **22**, 433 – 437, 2002.
90. Bhatt, B. P., & Tomar, J. M. S. Firewood properties of some Indian mountain tree and shrub species, *Biomass and Bioenergy* **23**, 257-260, 2002.
91. Deka, D., *et al.* Ranking of Fuelwood Species by Fuel Value Index, *Energy Sources* **29**, 1499–1506, 2007.
92. Bhatt, P. B., *et al.* Fuelwood Characteristics of Some Firewood Trees and Shrubs of Eastern Himalaya, India, *Energy Sources* **32**, 469-474, 2010.
93. Farmer, R. E. Wood density- Growth relationships in North American poplar, in *Improvement of feedstock quality*, R. L. Gambles, eds., Proceedings of an IEA/BA Task V Workshop, Toronto, Canada, pp.1-18, 1991.

94. Kenny, W. A. Variation in some chemical characterizes in three North American species of Salix, in *Improvement of feedstock quality*, W. A. Kenny et al. eds., Proceedings of an IEA/BA Task V Workshop, Toronto, Canada, pp. 48-56, 1990.
95. Ranney, J. W., *et al.* Manipulation of wood chemical traits for energy: an assessment, in *Improvement of feedstock quality*, W. A. Kenny *et al.* eds., Proceedings of an IEA/BA Task V Workshop, Toronto, Canada, pp. 33-47, 1990.
96. Resch, H. Densified wood and bark fuels, in *Energy from forest biomass*, W. R. Smith, ed., Academic Press, New York, 1982.
97. Kumar, R., *et al.* Effect of tree-age on calorific value and other fuel properties of Eucalyptus hybrid, *Journal of Forestry Research* **21**(4), 514 –516, 2010.
98. Shanavas, A., & Kumar, B. M. Fuelwood characteristics of tree species in homegardens of Kerala, India, *Agroforestry Systems* **58**, 11–24, 2003.
99. Henry, M. *et al.* Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa, *Forest Ecology and Management* **260**, 1375–1388, 2010.
100. Tharakan, P. J., *et al.* Energy feedstock characteristics of willow and hybrid poplar clones at harvest age, *Biomass and Bioenergy* **25** (6), 571-580, 2003.
101. Githiomi, J. K., & Kariuki, J. G. wood basic density of Eucalyptus grandis from plantations in central rift valley Kenya: Variation with age, height level and between sapwood and heartwood, *Journal of Tropical Forest Science* **22** (3), 281–286, 2010.
102. Nurm, J. Measurement and evaluation of wood fuel, *Biomass and Bioenergy* **2** (1-6) 157-171, 1992.
103. Demirbas, A. Biorefineries-For Biomass Upgrading Facilities, Springer-Verlag London, 2010.
104. Demirbas, A. Relationships between heating value and lignin, moisture, ash, and extractive contents of biomass fuels, *Energy Exploration and Exploitation* **20**, 105–111, 2002.

105. Chettri, N., & Sharma, E. A scientific assessment of traditional knowledge on firewood and fodder values in Sikkim, India, *Forest Ecology and Management* **257**, 2073–2078, 2009.

106. Diaz, L. F., & Golueke, C. G. Residues and Wastes, in *Biomass conversion process for energy and fuels*, S. S. Sofer, & O. R. Zabrosky, eds., Plenum Press New York, 1981, 103-12.

107. Kucukbayrak, S., *et al.* Estimation of calorific value of Turkish lignite, *Fuel* **70**, 979, 1991.

108. Demirbas, A. Calculation of higher heating values of biomass fuels, *Fuel* **76** (5), 431 – 434, 1997.

109. Glove, A. D., *et al.* Relationship between heating value and chemical composition of selected agricultural and forest biomass, *Japanese Journal of Tropical Agriculture* **38** (1), 1-7, 1994.

110. Vos, J. Biomass Energy for Heating and Hot Water Supply in Belarus, project submitted to UNGP/GEF, 2005, The Netherlands, downloaded from http://un.by/pdf/Study%20Tour%20Biofuel%20Report%20English.pdf on 22/07/2012.

111. Sheng, C. & Azevedo, J. L. T. Estimating the higher heating value of biomass fuels from basic analysis data, Biomass *and Bioenergy* **28**, 499–507, 2005.

112. Tillman, D. A. *Wood as an energy resource*, Academic Press, New York, 1978.

113. Saidur, R., *et al.* A review on biomass as a fuel for boilers, *Renewable and Sustainable Energy Reviews* **15**, 2262–2289, 2011.

114. Mitchual, M. J., *et al.* Evaluation of Fuel Properties of Six Tropical Hardwood Timber Species for Briquettes, *Journal of Sustainable Bioenergy Systems* **4**, 1-9, 2014.

115. Haykiri-Acma, H., & Yaman, S. Comparison of the combustion behaviors of agricultural wastes under dry air and oxygen, World Energy Congress 2011-Sweden, 8-13 May 2011, Linkoping, Sweden, 251-256.

116. Grønli, M. G., *et al.* Thermogravimetric Analysis and Devolatilization Kinetics of Wood, *Industrial & Engineering Chemistry Research* **41**, 4201-4208, 2002.

117. Gominho, J., *et al.* Chemical and fuel properties of stumps biomass from Eucalyptus globulus plantations, *Industrial Crops and Products* **39**, 12– 16, 2012.

118. Telmo, C., *et al.* Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood, *Bioresource Technology* **101**, 3808–3815, 2010.

119. Senelwa, K. A. *The air gasification of woody biomass from short rotation forests: Opportunities for small scale biomass-electricity systems*, Ph.D. Thesis, Massey University, New Zealand, 1997.

120. Jenkins, B. M., *et al.* Combustion properties of biomass, *Fuel Processing Technology* **54** (1–3), 17–46, 1998.

121. Klasnja, B., *et al.* Wood and bark of some poplar and willow clones as fuelwood, *Biomass and Bioenergy* **23**, 427 – 432, 2002.

122. Nasser, R. A., *et al.* 2014. Fuel characteristics of Vine purings (*Vitis vinifera* L.) as a potential source for energy, *BioResource* **9** (1), 482-496, 2014.

123. Werkelin, J., *et al.* Chemical forms of ash-forming elements in woody biomass fuels, *Fuel* **89**, 481-493, 2010.

124. Demirbas, A. Fuelwood Characteristics of Six Indigenous Wood Species from the Eastern Black Sea Region, *Energy Sources* **25**, 309–316, 2003.

125. Rai, Y. R., *et al.* Fuelwood value index of woody species from Mamlay watershed in south Sikkim, India, Forests, *Trees and Livelihoods* **12**, 209-219, 2002.

126. McKendry, P. Energy production from biomass (part 1): overview of biomass, *Bioresource Technology* **83**, 37–46, 2002.

127. Kumar, M., *et al.* Effect of carbonisation conditions on the yield and chemical composition of *Acacia* and *Eucalyptus* wood chars, *Biomass and Bioenergy* **3**, 411–417, 1992.

128. Nordin, A. Chemical and elemental characteristics of biomass fuels, *Biomass and Bioenergy* **6**, 339–347, 1994.

129. Demirbas, A. Combustion characteristics of different biomass fuels, *Progress in Energy and Combustion Science* **30**, 219–230, 2004.

130. Vargas-Moreno, J. M., *et al.* A review of the mathematical models for predicting the heating value of biomass materials, *Renewable and Sustainable Energy Reviews* **16**, 3065–3083, 2012.

131. Demirbas, A. Relationships between lignin contents and heating values of biomass, *Energy Conversion and Management* **42**, 183–8, 2001.

132. Martin, R. E. *Thermal and other properties of bark and their relationship to fire injury of tree stems,* Ph.D. Thesis, University of Michigan, Ann Arbor, 1963.

133. Hough, W.A. Caloric value of some forest fuels of the southern United States. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, Res. Note SE-120, 1969.

134. Howard, E. T. Some observations on southern pine needles as related to utilization, Final Report FS-SO-3201-1.36 USDA Forest Service, South Forest Experiment Station, Alexandria, LA, 1971.

135. Howard, E.T. Heat of combustion of various southern pine materials, *Wood Science* **5**(3), 194-197, 1973.

136. Koch, P. Utilization of the Southern Pines, in *Agriculture Handbook No.420,* Vol.1, USDA Forest Service, Washington, DC, 1972.

137. Chandler C., *et al.* Fire in Forestry, in *Forest Fire Behaviour and Effects*, Wiley, New York, 1983.

138. Kollman, F., & Cote, W. *Principles of wood science and Technology, vol. 1: Solid wood*, Springer, New York, 1968.

139. Nasser, R .A. & Aref, I. M. Fuelwood characteristics of six Acacia species growing wild in the southwest Saudi Arabia as affected by geographical location, *BioResources* **9** (1) 1212-1224, 2014.

140. Wongsiriamnuay, T., & Tippayawong, N. Thermogravimetric analysis of giant sensitive plants under air atmosphere, *Bioresource Technology* **101**, 9314–9320, 2010.

141. Brostow, W., *et al.* Combustion properties of several species of wood, *Wood Chemistry & Chemical Technology* **3** (3), 173-176, 2009.

142. Moya, C., & Tenorio, R. Thermogravimetric characteristics, its relation with extractives and chemical properties and combustion characteristics of ten fast-growth species in Costa Rica, *Thermochimica Acta* **563**, 12– 2, 2013.

143. Vamvuka, D., *et al.* Measurements of Ignition Point and Combustion Characteristics of Biomass Fuels and their Blends with Lignite, Proceedings of the European Combustion Meeting, 2011, downloaded from https://www.academia.edu/1626568/Measurements_of_Ignition_Point_and_Combustion_Characteristics_of_Biomass_Fuels_and_their_Blends_with_Lignite on 20/05/2014.

144. Haykiri-Acma, H. Combustion characteristics of different biomass materials, *Energy Conversion and Management* **44**, 155–162, 2003.

145. Kumar, R. *et al.* Fuel properties and combustion characteristics of Lantana camara and Eupatorium spp. *Current science* **97** (6), 930-935, 2009.

146. Jiricek, I., *et al.* A thermogravimetric study of the behavior of biomass blends during combustion, *Acta Polytechnica* **52** (3), 2012.

147. Campbell A. G. Recycling and disposing of wood ash. *Tappi Journal* **73** (9), 141 – 146, 1990.

148. Lerner R. B., & Utzinger, J. D. Wood ash as soil liming material, *HortScience* **21**(1), 76 – 78, 1986.

149. Naylor, M. L., & Schmidt, E. J. Agricultural use of wood ash as a fertilizer and liming material, *Tappi Journal*, **69** (10), 114 – 119, 1986.

150. Etiegni, L. Wood ash recycling and land disposal. Ph.D. Dissertation, Forest products Departments, University of Idaho, Moscow, Idaho, 1990.

151. Liodakis, S., *et al.* Ash properties of some dominant Greek forest species, *Thermocamichimica Acta* **437**,158-167, 2005.

152. Etiegni, L., & Campbell, A. G. Physical and chemical characteristics of wood ash, *Bioresource Technology* 37, 173 – 178, 1991.

153. Ferm, A., *et al.* Effect of wood bark ash on the growth and nutrition of Scots pine afforestation in central Finland, *Plant and Soil* **147**, 305 – 316, 1993.

154. Hakkila, P. *Recycling of wood and bark ash: a state-of-the-art review for Programme Group C under the IEA Forest Energy Agreement*, Finnish Forest Research Institute, Dept. of Forest Economics, Helsinki, Finland, 1986.

155. Wattez, J, & Courty, M. A. Morphology of ash of some plant materials, in *Soil Micromorphology*, Fedoroff, N. *et al.* eds., AFES, Plaisir, France, 1987.

156. Olanders B., & Steenari, B. Characterization of ashes from wood and straw, *Biomass and Bioenergy* **8** (2), 105 – 115, 1995.

157. Shafizadeh, F. Basic Principles of Direct Combustion, in *Biomass conversion processes for energy and fuel*, S. S. Sofer and O. R. Zaborsky, eds., Plenum Press, New York, pp. 105 – 112, 1981.

158. Steenari, B.M. & Lindquist, O. Utilisation of high Calcium Oxide and alkali metal content fuels at thermal power plants, *in VTT symp. 108 low-grade fuels*, M. Korhomen, eds., 1989.

Chapter 3

Materials & Methods

Chapter 3
Materials & Methods

The flow diagram of systematic methodologies for the present investigation has been presented in Figure 3.1.

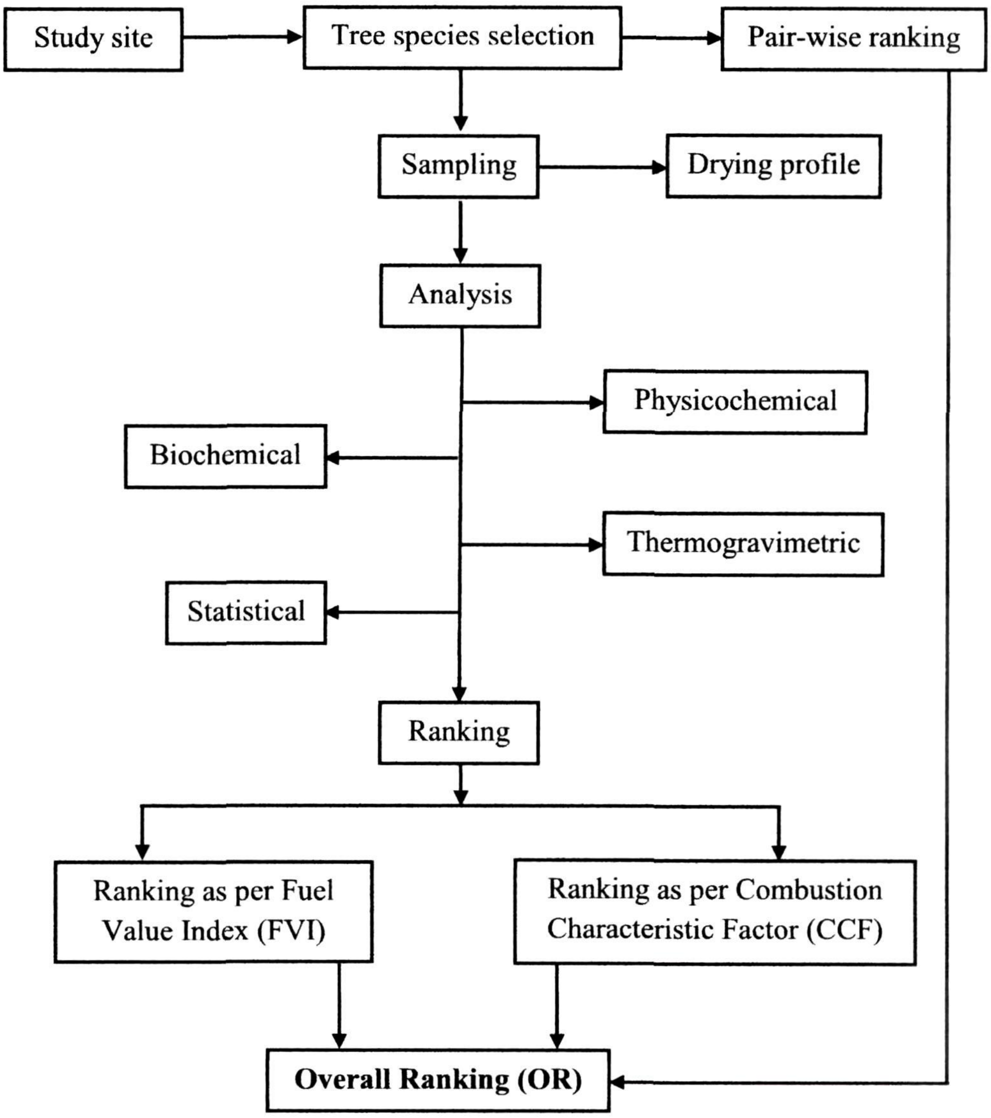


Figure 3.1: Flow diagram of systematic methodologies

3.1 Study site

The sites selected for the study were the forests and different localities of the state of Arunachal Pradesh, located in the North-East India (Figure 3.2). The state is situated between 26° 28′ and 29° 30′ North latitudes and 91° 30′ and 97° 30′ East longitudes. Bio-geographically it is situated in the eastern Himalayan province, the richest bio-geographical province of the Himalayan zone. The entire territory is a complex hill system with varying elevations ranging from 50 m in the foothills and gradually ascending to about 7000 m, traversed throughout by a number of rivers and rivulets [1].

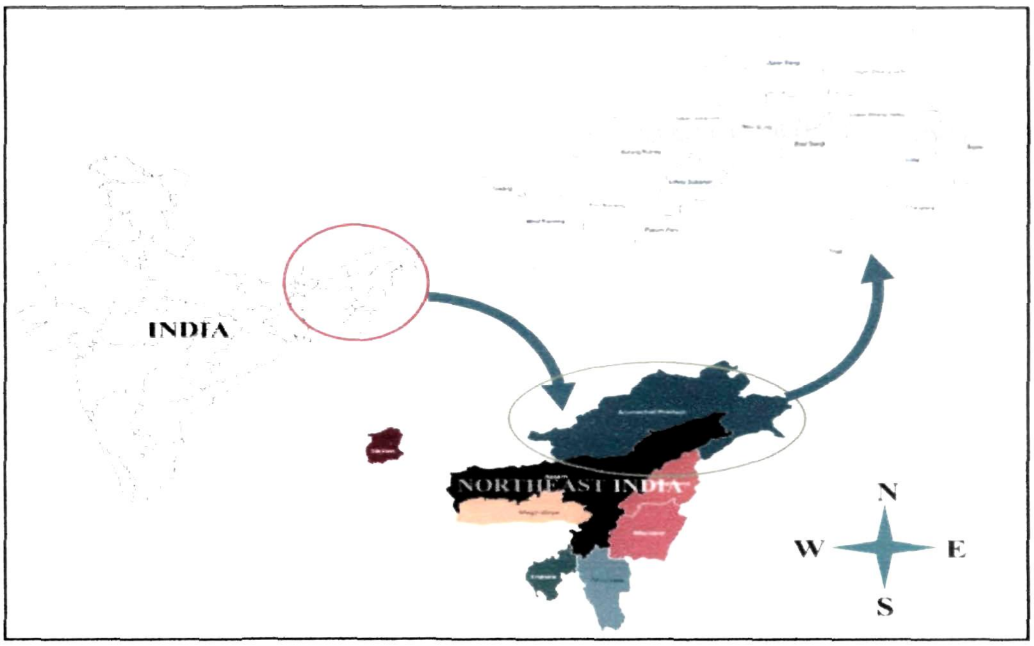


Figure 3.2: Map showing the location of study site

The climate of Arunachal Pradesh is humid to per humid subtropical, characterized by the high rainfall and high humidity of the sub-Himalayan belt. However, a temperate climate prevails in the lower Himalayan region and the greater

Himalayan region is perpetually covered with snow. The average annual rainfall varies from 1380 to 5000 mm. The minimum temperature is around 0°C in winter months in the Bomdila and Twang areas, while it rises to 35°C during summer months in the Namsai and Tezu areas of Lohit district. The mean annual air temperature is 23.8°C in the plains and 16.2°C in the hilly regions [2]. Different kinds of soils are present in Arunachal Pradesh and predominating four soil orders are Inceptisols, Entisols, Ultisols and Alfisols [2]. Details of geographical location, physiography and characteristics of soils under different agro-ecological sub regions of the state are presented in Annexure I. The vegetation of Arunachal Pradesh falls under four broad climatic categories and can be classified into five broad forest types with a sixth type of secondary forests [1]. Forest distribution in different districts of Arunachal Pradesh according to the types along with the state map is presented in Annexure II.

3.2 Selection of tree species

A total of twenty six (26) indigenous hardwood tree species grown in their natural habitats were collected from the forests and different localities of Arunachal Pradesh during the months of November and December, 2010. On the basis of the consideration of local user's preference for the best fuelwood species among the tree species grown in a particular locality, the tree species were identified and selected for the present study. The species were *Castanopsis indica, Macaranga pustulata, Dysoxylum binectariferum, Bridelia retusa, Myrsine semiserrata, Celtis australis, Dysoxylum procerum, Terminalia myriocarpa, Syzygium cerasoides, Kydia calycina, Mallotus phillipensis, Albizia odoratissima, Litsea polyantha, Mimusops elengi, Bauhinia variegata, Premna integrifolia, Talauma hodgsonii, Pterospermum acerifolium, Vitex altissima, Schima wallichii, Alnus nepalensis, Qurcus lanata, Qurcus leucotrichophora, Rhododendron arboreum, Myrica esculenta* and *Ehretia acuminata.*

3.3. Characteristics of the tree species

Characteristics of the selected tree species on the basis of their botanical description, wood quality, availability etc. are described elsewhere [1, 3-7]. Availability of the selected tree species in different forest types and districts of Arunachal Pradesh is presented in Annexure-II. Botanical descriptions of the tree species are presented below:

a) Botanical name: ***Castanopsis indica* DC.**

Vernacular name: Hinguri

Family: Fagaceae

Figure 3.3(a): ***Castanopsis indica***

A middle sized or large tree. Bark grayish, warty, somewhat deeply fissured vertically, with exfoliating scales, 1.27cm thick. Leaves 7.62-19.05 by 3.30-7.62cm elliptic-oblong or oblong-lanceolate, acute or acuminate, spinous-serrate, coriaceous, glabrous above, rusty-tomentose beneath; lateral nerves 14-20 on either half, conspicuous beneath, sub parallel; midrib depressed above and pubescent; base rounded or obtuse, occasionally unequal sided; petiole 0.76-1.27 cm long. Male spikes in lax panicles, longer than the leaves, stamens 12. Female spikes axillary, solitary. Flowers solitary. Ripe involucers 2.54-3.81 cm in diameter, thin walled, densely covered with straight unequal radiating subulate pubescent spines, the longest above 1.27 cm long. Nut ovoid 0.76-1.27 cm. Wood hard, grayish white, coarse grained, durable, used as firewood, for making charcoal etc.

b) Botanical name: ***Macaranga pustulata*** **King ex Hook.**

Vernacular name: Jaglo, Moralia

Family: Euphorbiaceae

Figure 3.3 (b): ***Macaranga pustulata***

Middle sized evergreen tree, often gregarious; young parts rusty-tomentose; stem fluted. Bark grayish or grayish brown, with horizontal wrinkles, 0.76 cm thick. Leaves peltate, 7.62-30.48 by 6.35-25.4 cm, broad-ovate, acuminate, denticulate or entire, sub-coriaceous, above, glaucescent and dotted with numerous red minute orbicular glands beneath; basal nerves 57, radiating; lateral nerves 10-12 on either side of midrib, slightly arcuate; base rounded, truncate or cordate; petiole 5.08-20.32 cm long; stipules small fugacious. Male panicles slender, 10.16-15.24 cm long, each bract subtending a cluster of 5-8 pubescent flowers; calyx-segments 2-3; stamens 6-30. Female panicles shorter; calyx-segments 3-4. Ovary 2 celled; style short. Capsule 0.63 cm across, blackish, didynamous, clothed with minute waxy orbicular glands. Wood moderately hard, used as very good firewood.

c) Botanical name*:* *Dysoxylum binectariferum* Hook. f. et. Bedd.

Vernacular name: Bandardima

Family: Meliaceae

Figure 3.3(c): ***Dysoxylum binectariferum***

A tree with 15 m in height and 1.2 m in girth; young shoots and inflorescence minutely pubescent. Bark grey outside, nearly smooth and warty on young stems, afterwards with light vertical fissures and horizontal wrinkles peeling off in thin papery flakes, pale yellowish brown inside, mottled with coarse strands of darker brown. Leaves alternate, estipulate; rachis 12.5-19 cm long, stout, angular, swollen at base, pubescent; leaflets 6-8, alternate, 7.62-19.05 by 6.35-8.89 cm, obliquely ovate-oblong, short-usually abruptly acuminate, entire or with obscure distant teeth, thinly coriaceous, glabrous and dark-green above, pale underneath; petioles 0.50-0.76 cm long, channeled. Flowers pale-white, about 0.63 cm long, tetramerous. Calyx thick, cup-shaped, subentire, about half as long as petals. Petals velvety outside. Staminal tube mealy. Disk much exceeding the ovary, glabrous inside, 8-toothed; anthers 8. Ovary hairy. Capsule 5.08-6.35 cm long, globose with a narrowed base, smooth, at first pale-yellow, turning deep-orange, 4-celled, 4-seeds; seeds shining purple with a large yellow hilum; aril white; cotyledons green, plumule hairy. Wood moderately hard, fine grained, used for furniture, house constriction, firewood etc.

d) Botanical name: *Bridelia retusa* (Baill) Spreng.

Vernacular name: Kuhir

Family: Euphorbiaceae

Figure 3.3(d): *Bridelia retusa*

A middle to large deciduous tree. Bark darkish-grey, rough outside, exfoliating in irregular flakes, about 1.27 cm thick; inside light red, finally fibrous and soft with faint streaks of lighter tissue. Leaves variable, 6.35-20.32 by 2.54-12.7 cm, elliptic, elliptic-lanceolate, ovate or obovate, acute or obtuse, entire or slightly crenulate rigidly coriaceous, dark-green and glabrous above, glaucous but pubescent on the nerves beneath. Flowers up to 0.50 cm across, greenish yellow. Male flowers: calyx segments triangular, acute; petals coarsely toothed or lobed. Female flowers: pedicels lengthening in fruit; calyx-segments triangular; outer disc annular; petals oblong or ovate, entire or undulate; styles 2, free, bifid from about half way. Wood hard, durable, used as firewood, for making house posts, agricultural implements etc.

e) Botanical name: *Myrsine semiserrata* Wall.

Vernacular name: Kalikath

Family: Myrsinaceae

Figure 3.3(e): *Myrsine semiserrata*

A small tree or big shrub. Bark ashy grey outside, reddish-brown inside with somewhat regular narrow streaks of lighter tissue. Leaves 5.08-12.7 by 1.52-3.30 cm, lanceolate-serrate or sparingly cuspidate-serrate towards the apex, coriaceous, glabrous; lateral nerves slender, 11-13 on either half; base cuneate; petiole 0.25-0.76 cm long. Flowers pinkish, usually 4-merous, 0.25 cm across, in dense axillary fascicles or below leaves; pedicels 0.50-2.03 cm long, glabrous. Calyx persistent. Anthers large, sessile, style short. Fruit 0.50-0.76 cm across, globose, filled with watery juice, bluish or pinkish purple when ripe on filiform pedicels. Wood moderately hard, used firewood and making charcoal.

f) Botanical name: *Celtis australis* Linn.

Vernacular name: Nonibhola, Mohita

Family: Ulmaceae

Figure 3.3(f): *Celtis australis*

Middle to large deciduous tree; branchlets drooping. Bark bluish or greenish grey, smooth, with small horizontal wrinkles; inside white, mottled with brown. Leaves alternate, 3.81-12.7 by 2.03-5.08 cm, ovate or ovate-lanceolate or ovate-elliptic, acuminate, serrate or entire towards the base, coriaceous, dark green and glabrous above, often seabird, more or less pubescent beneath. Petiole 0.25-0.76 cm long; stipules about 0.76 cm long, subulate, caduceus. Sepals 4-5. Ovary sessile. Drupe ovoid or ellipsoid about 0.76 cm long, more or less rogues, woolly at the base; peduncles 1.27-5.08 cm long. Wood fairly hard, durable, used for firewood.

g) Botanical name: *Dysoxylum procerum* Hiern.

Vernacular name: Lali

Family: Meliaceae

Figure 3.3(g): *Dysoxylum procerum*

A fairly large evergreen tree. Bark greenish-grey or grayish-brown. Leaflet 7-13, opposite or alternate, 15.24-30.48 by 6.35-11.43 cm, obovate or elliptic-oblong, slightly oblique at the base, thinly coriaceous, glabrous; petioles stout, 0.50-1.27 cm long. Panicles erect, stiff, 30.48-66.04 cm long with short horizontal puberulous branches; bracts subulate; pedicels very short, bracteolate; bud pubescent. Flowers 0.76-1.27 cm long, cream-white, fragrant Calyx pubescent; short. Petals 4, oblong, valvate. Anthers 8, subsessile. Disk about one-third to two-thirds the length of the staminal tube, hairy at the mouth, encircling the hairy ovary; style slightly exceeding the staminal tube. Capsule up to 6.35 cm long, pyriform; seeds 2-3, black and shining with an orange aril. Heart wood reddish, fine grained, used for doors, windows, furniture, firewood etc.

h) Botanical name: *Terminalia myriocarpa* Heurck & Muell.

Vernacular name: Hollock, Jhaluka

Family: Combretaceae

Figure 3.3(h): *Terminalia myriocarpa*

A very large evergreen tree with pendulous branchlets; outer bark grey or brown, rough, peeling in vertical flakes; inside red, pale yellow towards the cambium, fibrous. Leaves 10.16-22.86 cm, oblong-lanceolate to elliptical oblong, acute or shortly acuminate, denticulate or entire; petiole thick, about 0.63-0.76 cm long with 1-2 elongated glands near the top. Flowers about 0.38 cm across, pink, each in the axils of small lanceolate or deltoid subulate bracteoles. Spikes slender, lax, arranged in ample panicles, upper bracts spathulate, lower gradually larger and leafy. Limb of calyx tube expanded, glabrous or nearly so outside, pubescent within; teeth erect; disc with few or no hairs; ovary pubescent. Drupe about 0.38 cm long, yellow, 3 cornered, the lateral corners developing into short wings; 0.76-1.27 cm across the wings. Wood hard, durable, used as firewood, for making furniture, doors, windows etc.

i) Botanical name: *Syzygium cerasoides* (Roxb.) Chatt. & Kanjilal

Vernacular name: Kyamuna

Family: Myrtaceae

Figure 3.3(i): *Syzygium cerasoides*

Small tree, bark is brown or reddish brown, twins quadrangular. Leaves broadly elliptic ovate or round, nearly oblong-oblanceolate or ovate, 12-15 by 7-15 cm, acuminate, secondary nerves irregular, 7-15; petiole 1-2.5 cm. Flowers white, sessile, in ternate trichotomous lateral panicles, mostly from old leaf scars. Calyx-tube 3.7-4.5 mm long and broad, lobes 4, sub-acute to obtuse, deciduous. Fruit globular to depressed globular, attaining about 10 by 10-12 mm, excavated at the apex, seed solitary, attaining about 8mm diameter, testa adhering somewhat to the pericarp and also to the glandular surface of the uniformly textured cotyledons. Radical basal or lateral. Wood reddish brown, hard, used as firewood, for making agricultural implements etc.

j) Botanical name: *Kydia calycina* Roxb.

Vernacular name: Pichola

Family: Malvaceae

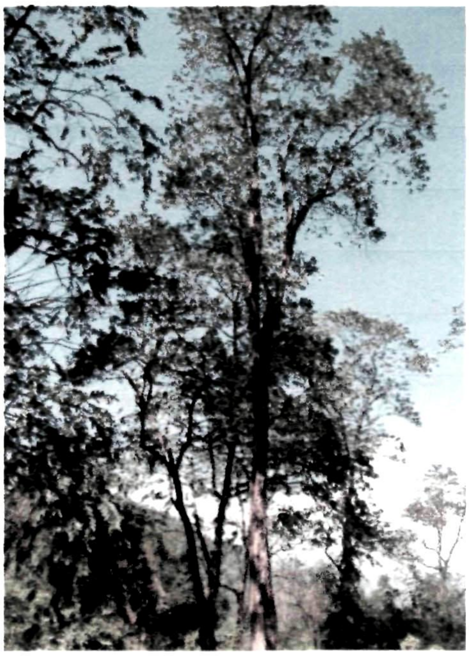


Figure 3.3(j): *Kydia calycina*

A tall sized fast growing deciduous tree. Bark grey, exfoliating in long strips, reddish inside, green underneath the corky layer, innermost layers fibrous and lace-like. Leaves 7.62-16.51 cm long, suborbicula or orbicular, often broader than long, palmately 5-7 nerved and generally with as many lobes; base slightly cordate or truncate, glabrate above, downy pale beneath; petiole 2.54-10.66 cm long. Flowers generally white, 1.27-1.77 cm across, numerous, polygamaous, generally dioecious, in much branched axillary and terminal panicles; pedicels slender, 1.27-1.77 cm long, generally tufted, stellate- downy; bracteoles 4-6, oblong or obovate, accrescent, persistent, downy at first, afterwards hispid with the bases of fallen hairs, prominently veined and spreading. Sepals ovate, acute, accrescent and incurved over the fruit. Petals clawed. Capsule depressed-globose, about 0.50 cm across, buff or yellow-villous. Wood white, soft, used in building construction, as firewood, for making charcoal etc.

k) Botanical name: *Mallotus phillipensis* (Lamk) Muell. & Arg.

Vernacular name: Senduri gooti, Kamala, Losan

Family: Euphorbiaceae

Figure 3.3(k): *Mallotus phillipensis*

A small to medium-sized evergreen tree up to 25 m tall and with a bole up to 50 cm in diameter. Bark thin, grayish-brown or darkish-grey. Leaves 7.62-17.78 by 3.81-6.35 cm, alternate, ovate, ovate-oblong or lanceolate, acuminate, entire or slightly dentate, glabrous above, pubescent beneath and with numerous close-set orbicular red glands. Petiole 1.27-8.89 cm long, rusty-pubescent with a pair of glands at the junction with the blade. Inflorescence brown to red. Flowers small, dioecious. Male flowers clustered in erect terminal spikes which are often panicled, sessile or almost so. Female flowers usually solitary, sessile or nearly so in short spikes; sepals almost free, lobed when ripe, covered with a crimson powder, consisting of stellate hairs and grains of resinous substance. Seeds globose, black, 0.40-0.50 cm across. Wood moderately hard, used for rafters, tool handles, firewood etc.

l) Botanical name: *Albizia odoratissima* Benth.

Vernacular name: Jati koroi, Hiharu

Family: Leguminosae

Figure 3.3(l): *Albizia odoratissima*

A large deciduous tree with spreading crown. Bark grey or brownish-grey to nearly black and rough outside, inside red with white streaks, soft, about 1.90 cm thick in old stems. Leaf-rachis 10.16-20.32 cm long. Pinnae 3-5 pairs, 7.62-16.51 cm long. Leaflets 7-20 pairs, 1.52-3.17 by 0.50-1.01 cm. Flowers sessile, fragrant. Calyx very small, campanulate, densely pubescent outside; teeth obsolete or minute. Corolla 0.38-

0.76 cm long, funnel shaped, hairy; lobes lanceolate, about 0.25 cm long. Stamens pale-yellow, about 2.03 cm long. Pod 12.7-30.48 by 1.77-3.04 cm, shortly stipitate, thin, flexible, tomentose when young, reddish brown or dusky greenish brown, broadly but rather indistinctly reticulate. Seeds 8-12. Wood hard, durable used for house building, agricultural implements, as firewood.

m) Botanical name: ***Litsea polyantha Juss.***

Vernacular name: Sualu, Muga

Family: Lauraceae

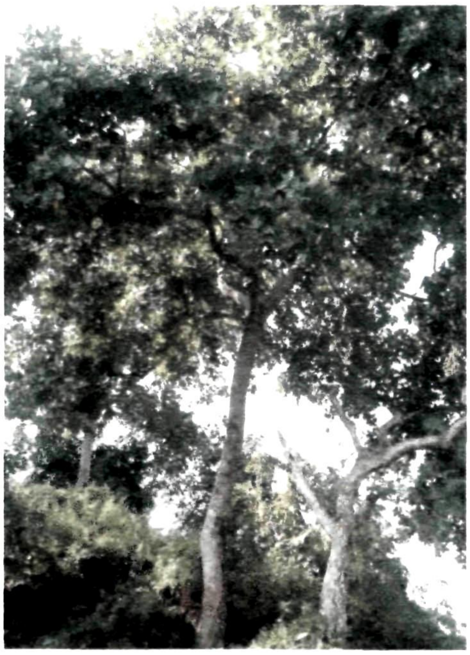


Figure 3.3(m): ***Litsea polyantha***

A middle sized deciduous tree with spreading crown. Bark grayish-brown, somewhat rough 1.77-2.03 cm thick. Leaves 7.62-20.32 by 3.30-10.16 cm, obovate-oblong, oblanceolate or elliptic-oblong, acute or rounded, coriaceous, dark green and glabrescent above, glaucous and rusty-pubescent beneath; petioles 1.27-2.54 cm long, pubescent. Flowers greenish yellow, about 0.50 cm across, in pedunculate umbelate heads; peduncles 0.50-1.27 cm long; pedicels villous, about 0.25 cm long; bracts 5, nearly free. Stamens 9-13; filaments villous; glands stipitate. Fruit ovoid, 0.76-1.01 cm long, blackish when ripe, supported by the persistent perianth and the thicked pedicels. Wood used as cheap timber and as firewood.

n) Botanical name: *Mimusops elengi* Linn

Vernacular name: Bokul

Family: Sapotaceae

Figure 3.3(n): *Mimusops elengi*

An evergreen middle sized handsome tree often planted as avenue tree; young parts rusty pubescent. Bark grey, fissured. Leaves 6.35-10.16 by 3.17-5.08 cm, elliptical, acuminate, chartaceous, shining, glabrous; petiole 1.27-2.54 cm long. Flowers 8-merous, about 7.62 cm across, creamy white, fragrant, star-like, solitary or in fascicles. Calyx rarely in two rows (rarely 3+3). Corolla caduceus, lobes usually 24 in two rows, all lanceolate and almost similar. Stamens 8; staminode rather petaloid, membranous, fimbriate; anthers lanceolate, extrorse, apicular. Overy hirsute, 6-8 celled; style subulate. Fruit rather variable, usually globose, ovoid or ellipsoid, about

2.54 cm long, yellow orange. Seeds usually solitary, ovoid, compressed, slaty brown, shining. Wood light red colour, hard, durable, used for house posts, firewood etc.

o) Botanical name: *Bauhinia variegata* Linn.

Vernacular name: Bogakatra, Kurol, kotora, Kanchon

Family: Leguminosae

Figure 3.3(o): *Bauhinia variegata*

A moderate sized tree with dark grey or brown somewhat rough bark. Leaves 6.60-15.24 cm long, as broad as long or sometimes broader, usually deeply cordate, 11-15, nerved, thinly coriaceous, grey glaucous and puberulous along the nerves beneath; petiole 2.54-3.81 cm long. Flowers are large, pure white, 5.08-7.62 cm across when fully opened. Calyx covered with grey and somewhat sticky pubescent tube, 1.27-2.54 cm long, slender; limb spathaceous, 5 toothed at the apex, 1.52-3.04 cm. Petals 3.81-5.08 cm long, obovate or obovate-oblong. Stamens usually 5, rarely fewer; filament stout, unequal, incurved. Ovary with a long stipe which is extruded 1.27-1.77 cm beyond and adnate at the bottom to the calyx tube, covered with mealy pubescence and with spreading hairs along the sutures; style short. Pod 15.24-25.40 by 1.77-2.28 cm, hard flat, glabrous, prominently veined when dry, slightly falcate and dehiscent. Seeds 10-15. Wood moderately hard, used as cheap timber, as firewood etc.

p) Botanical name: ***Premna integrifolia*** **Linn.**

Vernacular name: Genderi

Family name: Verbenaceae

Figure 3.3(p): ***Premna integrifolia***

A small tree or large shrub; trunk and larger branches are thorny. Bark yellowish green, lenticellate, white inside. Leaves 5.08-10.16 by 2.54-6.35 cm, oblong-ovate or broadly elliptic or oblong-ovate, entire, undulate, sometimes coarsely dentate towards the apex, sub-obtuse or very shortly acudentate, glabrous on maturity; lateral nerves 4-5 on either half; base rounded or sub-acute; petiole 1.01-1.77 cm long. Flowers are small, greenish yellow. Calyx 2-lipped; one lip 2-toothed; the other subentire. Corolla sub equally 4-lobed. Drupe 0.50 cm across, globose, endocarp, obscurely veryucose. Wood light-creamy brown, moderately hard.

q) Botanical name: *Talauma hodgsonii* Hk. f. &Th.

Vernacular name: Boramthuri, Dat-bhola

Family: Magnoliaceae

Figure 3.3(q): *Talauma hodgsonii*

A small tree with a few spreading branches. Bark greenish grey, warty. Otherwise smooth, with distant horizontal wrinkles, often with large white patches; inside brownish-yellow, fibrous, 0.50-0.76 cm thick. Leaves 20.32-50.80 by 10.16-20.32 cm, oblanceolate, rounded or suddenly apiculate, thinly coriaceous, quite glabrous, red and erect when young. Petiole 2.54-6.35 cm long, terete, with a faint scar of fallen stipules, much swollen at the base. Flowers large, terminal. Sepals, greenish-purple. Petals greenish-white at the base, bright-red above. Fruit ovoid, 10.16-15.24 by 6.35-8.89 cm. Carpels beaked, woody, dehiscent by the vertical suture, separating from the axis leaving the red seeds attached to it at the upper end of the empty pits by an elastic cord. Wood grey, hard, even-grained, used for house constriction, firewood etc.

r) Botanical name: *Pterospermum acerifolium* Willd.

Vernacular name: Hatipaila, larubondha,

Family: Sterculiaceae

Figure 3.3(r): *Pterospermum acerifolium*

An evergreen tree up to 25 m in height and 2.5 m in girth. Bark dark-brown and rather rough outside, inside deep purplish red. Leaves 20.32-38.10 by 15,24-30.48 cm ; very variable in size and shape even in the same twig, somewhat obliquely obovate or orbicular, glabrous and deep green above, grayer brownish tomentose beneath; petiole 10.16-30.48 cm long, striate; stipules multifid, caducous. Flowers solitary or 2-3flowered cymes, 12.70-15.24 cm across, fragrant; peduncles about 1.27 cm long; bracteoles multifid, deciduous. Calyx-segments 10.16-12.70 by 0.76-1.27 cm, linear, very fleshy. Filaments 15, 2.54-3.81 cm long, filiform, glabrous, in threes against each calyx-segment, with a staminode 5.08-7.62 cm long between, all forming a tube about 2.54 cm long below the ovary and adnate to the gynophores. Ovary oblong, obscurely 5-angled, brown-shaggy. Wood strong, durable, reddish brown, used for firewood.

s) Botanical name: *Vitex altissima* Linn.

Local name: Ahoi

Family: Verbenaceae

Figure 3.3(s): *Vitex altissima*

A middle sized tall deciduous tree up to 30 m in height. Bark grayish, about 2.54 cm thick. Leaves 3-foliolate; petioles winged up to 10.16 cm long. Leaflets 6.35-20.32 by 2.03-4.57 cm; lateral leaflet lanceolate or oblanceolate, long acuminate, entire; lateral nerves numerous with finely reticulate venation; base acute or cuneate; petiole 0-0.25 cm long. Flowers white tinged with blue or violet, in panicles with spiciform interrupted branches of small grey pubescent cymes; bracts small, caduceus. Calyx about 0.30 cm long; teeth short, triangular. Corolla about 0.50 cm long, woolly.

Ovary fulvous-villous .Drupe about 0.63 cm across, irregularly globose, purplish, often dotted with white specks supported by the accrescent calyx. Wood hard, yellowish-brown, used for timber, firewood etc.

t) Botanical name: *Schima wallichii* Choisy.

Local name: Makori sal, Noga-bhe

Family: Ternstrcemiaceae

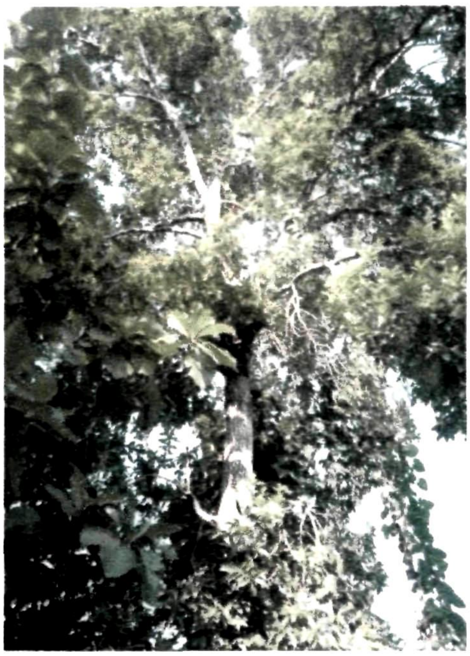


Figure 3.3(t): *Schima wallichii*

A large tree up to 28 m. in height and 3.5 in girth with a narrow crown in youth but develop to a very large spread one after height is completed. Bark surface ruggedly cracked into small, thick, angular pieces, red-brown to dark grey; inner bark with skin-irritating fibers, bright red in colour, 1.77-3.81 cm thick. Branchlets lenticellate, buds and young parts adpressed pubescentor villous. Leaves 8.89-24.13 by 3.55-8.12 cm, oblong or elliptic-lanceolate, acute or acuminate, usually entire, thinly coriaceous; glabrous and shining above. Petioles 1.52-2.03 cm long, sharply margined, more or less pubescent. Flowers white, scented, axillary, solitary, 3.04-5.08 cm diameter. Sepals 5, imbricate. Petals 5, connate and silky pubescent outside towards the base. Stamens many; ovary hairy towards the bottom, upper portion glabrous. Fruit a woody subglobose capsule, 1.27-1.77 cm diameter, silky, opens by 5 valves. Seeds 2-6 in each cell. Wood moderately hard, durable, good for firewood and making charcoal.

u) Botanical name: *Alnus nepalensis* D. Don.

Vernacular name: Uttis

Family: Betulaceae

Figure 3.3(u): *Alnus nepalensis*

A large deciduous tree height up to 25-30 m; bark compact, silvery-grey; branchlets glabrous; young shoots usually pubescent. Leaves alternate,6.35-17.78 by 3.81-8.89 cm, elliptic or elliptic- lanceolate, acute, entire or somewhat denticulate, coriaceous, glabrous above, slightly pubescent along the nerves beneath when young, usually glaucescent and dotted with resinous minute dots; lateral nerves 10-18 on either half; base narrowed or rounded; petiole 0.76-2.03 cm long. Male catkins 10.16-

25.4 cm long, terminal, drooping, panicled; flowers supported by bracts and bracteoles; bracts 3-flowered with usually 4 bracteoles adnate each bract; sepals 4; stamens 4; Female spikes 0.50-0.76 cm long, erect. Wood light, used as firewood.

v) Botanical name: ***Quercus lanata*** **Sm.**

Vernacular name: Safed banjh

Family: Fagaceae

Figure 3.3(v): ***Quercus lanata***

Trees to 30 m tall, evergreen. Bark thick, brown-ash grey, lenticellate, peeling into thin plates; inside slightly fibrous, deep pinkish 1 cm thick. Young branchlets densely grayish brown pubescent, glabrescent. Petiole 0.5-1.5 cm, grayish brown tomentose, glabrescent; leaf blade narrowly ovate-lanceolate to narrowly elliptic, 9-20 × 3-8.5 cm, densely with grayish stellate hairs but glabrescent, adaxially densely pubescent especially on midvein, base rounded to broadly cuneate, margin sharply serrate, apex acuminate; secondary veins 12-17 on each side of midvein; tertiary veins abaxially conspicuous. Cupule cupular, 0.6-1 × 0.8-1.5 cm, enclosing 1/4-1/2 of nut, wall ca. 1 mm thick. Nut ovoid-conical, 1.5-2 × 1-1.2 cm, glabrous; scar ca. 4 mm in diam., slightly raised; stylopodium ca. 1 mm. Wood hard, red-brown in colour, used for firewood and making charcoal.

w) Botanical name: *Qurcus leucotrichophora* A. Camus

Vernacular name: Lal banjh

Family: Fagaceae

Figure 3.3(w): *Qurcus leucotrichophora*

An evergreen tree with height up to 30 m. Bark smooth, tan-brown, lightly furrowed and corky with age. Leaves oblong or ovate - lanceolate, stiff leathery, white or grey tomentum beneath; sharply toothed, 6-16 cm long, dense white-woolly hairs on the underside; lateral nerves 13-16 on either half; base acute, obtuse or rounded; petiole 1-1.5 cm long. Male spikes dense hairy and clustered, female flowers usually sessile. Flowers arise in catkins. Male catkins are woolly-haired. Fruits acorn 1.1-1.8 cm. long, 0.9-1.2 cm. wide; ovoid, mucronate, glabrous; singly or paired; enclosed 1/3 to ½ cup; cup sessile, 1 cm in diameter. Wood hard, red-brown in colour, used for firewood and making charcoal.

x) Botanical name: *Rhododendron arboreum* Sm.

Vernacular name: Gurans.

Family: Ericaceae

Figure 3.3(x): *Rhododendron arboreum*

A medium sized or small evergreen tree. Bark reddish brown, corky, peeling off in small flaks; blaze reddish brown or pinkish with white lines; branchlets glabrate. Leaves crowded at the ends of branches 9.14 by 1.90-4.44 cm, narrow elliptic or oblong-lanceolate, acute, margins recurved. Petiole 0.76-1.77 cm long. Flowers red. Pedicels 0.50-1.01 cm long. Calyx subrotate: lobes unequal, about 2.54 cm long, acute. Corolla companulate, 3.04-3.81 cm long, slightly zygomorphic. Stamens 10. Overy white or grey, woolly, 0.38 cm long, with a purple line at the base, usually 10 ribbed, 10 celled, with a false dissepiment between each, about 3.81 cm long, tinged with red; stigma dilated. Capsule 2.54 cm long, cylindrical, longitudinally ribbed and curved, mealy. Seeds ellipsoid, minute. Wood soft, used for making charcoal, furniture, as fuelwood, etc.

y) Botanical name: ***Myrica esculenta*** Buch.-Ham. ex D. Don.

Vernacular name: Kaphal

Family: Myricaceae

Figure 3.3(y): ***Myrica esculenta***

A small or moderate sized evergreen tree. Bark grayish-brown, rough, vertically wrinkled, finely fibrous, 0.76 cm thick; extremities pubescent. Leaves 5.08-15.24 by 1.27-3.81 cm, lanceolate, oblanceolate or obovate, nearly entire or sharply spinous-serrate, obtuse or acute, coriaceous, glabrous above, with resinous dots beneath; lateral nerves 12-20 on either half, anastomosing at the ends to form a marginal vein; base acute; petiole 0.50-1.52 cm long. Male spikes sometimes with female flowers at the top. Fruit about 2.54 cm long ellipsoid or ovoid, tubercled, reddish or cheese colored when ripe. Wood moderately hard, used for furniture, house construction, Fuelwood etc.

z) Botanical name: *Ehretia acuminata* R.Br.

Vernacular name: *Gual*

Family: Boraginaceae

Figure 3.3(z): *Ehretia acuminata*

A large tree; stems more or less fluted. Bark grey with vertical fissures, 1.27 cm apart, 0.76 cm thick, composed of many fibrous ribbons; blaze whitish, rapidly turning dirty brown. Leaves 5.08-15.24 by 2.54-6.35 cm, elliptic, elliptic-oblong, acuminate, acute, and sharply serrate, chartaceous, glabrescent, shining above; lateral nerves 8-10 on either half; petiole 1.27-3.81 cm long. Flowers white with an unpleasant smell. Calyx small, ciliate. Corolla tube short; lobes 0.30 cm, reflexed; style bifid for less than half its strength. Drupe 3.04-0.40 cm in diameter, ellipsoid with two 2-celled Pyrenees, 4-seeded. Wood light brown, moderately hard, used for house building and firewood.

3.4 Field sampling

26 different tree species of the age groups of 5 to 10 years old were selected for the study. Three randomly selected trees of each of the species were sampled from a particular locality. For each species, 20 cm long sample (branch stem) having 7-10 cm diameter was cut outside the bark. Each sample was labeled and bagged immediately in a polyethylene bag and sealed to avoid loss of moisture from the freshly cut trees. The sealed samples were brought to the laboratory within 12 h following collection. Samples of each of the tree species collected from different localities were thoroughly mixed to make a representative sample. The sampling localities for each of the tree species are presented in Annexure-II. The collected tree species were also sampled to study the drying profile of the species.

3.5 Drying profile

Drying profiles to observe the drying rates of the tree species were prepared. All the freshly cut stem samples were weighed accurately within 12 h of cutting. They were then left to dry in the sun for 8 weeks. A drying profile of each of the samples was maintained by recording the weight loss of the samples at one-week interval.

3.6 Pair-wise comparison (PWC) ranking of fuelwood

Key informants were used to identify fuelwood qualities according to Kumar [8]. 20 key informants with equal number of men and women were selected from each locality considering their experience with firewood utilization as source of energy. Pair-wise ranking was done to identify the firewood property and ranked species accordingly [9]. Finally, a ranking matrix for 26 species using indigenously preferred ten quality criteria was drawn and scores were assigned to the species according to their comparative ranking value.

3.7 Analytical test on firewood properties.

3.7.1 Sample preparation

A disc of 2 cm thickness and 4 cm diameter was taken from each of the freshly cut tree species without removing the bark portion and kept in an oven for moisture removal. The oven-dried disc taken from each of tree species was then ground (using a Wiley mill) to pass a 0.4 mm (40 mesh) screen (as per TAPPI T257 Om- 85 methods). The ground sample of individual tree species was kept in air- tight containers for further analysis.

3.7.2 Preparation of extractive free samples

Wood extractives are materials soluble in neutral solvents and are not generally considered as part of the wood substances. These materials should be removed before any chemical analysis of wood substances.

Ethanol-benzene mixture was used to extract waxes, fats, some resins, and possibly some portions of wood gums. Hot water was used to extract tannins, gums, sugars, starches and colouring matter. The procedures for ethanol-benzene and hot water soluble extractives are described below:

3.7.2.1 Determination of total extractives content

Total extractives content was determined according to the method reported by Senelwa et al. [10]. The extractives content are distinguished into two categories — organic (non-polar) solvents soluble extractives (i.e. ethanol: benzene mixture and ethanol, OEC), and water (polar solvent) soluble extractives. The sum of polar and non-polar solvent soluble extractives content was taken together as total extractives content (TEC).

Approximately 2 g of oven dry ground sample of particle size 180-250 μ was weighed and taken into a filtering thimble having coarse porosity. The tip of the thimble was closed with loose cotton to prevent expulsion of the sample. The thimble was then placed into a soxhlet apparatus attached to a 250 ml extraction flask fitted with a condenser. To determine OEC, the samples were extracted with 125 ml (95% ethanol and benzene in ratio 33: 67) for 4 h followed by another 4 h extraction with 125 ml of 95% ethanol. The ethanol was drained off and evaporated to constant weight. The samples were further boiled in distilled water at 100 °C (boiling water bath) for 3 h and then oven dried at 80 °C to constant weight. OEC and TEC were determined as % weight loses after extraction with organic solvent (ethanol and benzene mixture) followed by hot water extraction.

3.7.3. Proximate analysis

Proximate analysis gives the relative amount of ash, fixed carbon and volatile matter in a fuel as a percentage of its oven-dry weight. The detail procedure is given below:

3.7.3.1 Determination of Moisture Content

The moisture content was determined according to the method described in the Forestry Hand Book [11] and ASTM D4442-07. Approximate 10 g of sample was weighed immediately upon sampling and then air-dried. This air-dried sample was taken immediately in an aluminum moisture box and kept in an oven heated at 105 ± 3^0C until constant weight was obtained. The difference of the oven dry weight of the sample and the fresh weight of the sample was used to determine the percentage of moisture content as follows:

$$Moisture\ content\ (\%) = \frac{Fresh\ weight - Oven\ dry\ weight}{Fresh\ weight} \times 100$$

For each sample, the estimation was done in triplicate and the mean value was reported.

3.7.3.2 Determination of Ash content:

For determination of ash content, TAPPI standard method, T211 om-85, was followed [12]. At first, an empty 25 ml. silica crucible was heated in a muffle furnace at 575 ± 25°C for 15 min. and allowed to cool in a desiccator for 45 min. and then weighed accurately. Representative sample of each of the plant parts was made oven-dry, weighed and transferred into the crucible and kept in a muffle furnace at 575 ± 25°C to ignite for a period of 3h or longer to burn away the carbon, completion of which was indicated by the absence of black particles. Crucible was then removed from the furnace and kept in a desiccator and weighed accurately. The percentage of ash content was calculated as follows:

$$Ash\ content\ (\%) = \frac{Weight\ of\ ash}{Weight\ of\ sample} \times 100$$

For each sample, the estimation was done in triplicate and the mean value was reported.

3.7.3.3 Determination of Volatile matter

Volatile matter of wood samples was determined by the method described in ASTM Test No. D-271-48. A platinum crucible of 10 ml capacity was taken and its surface was cleaned by rubbing with fine steel wool. The crucible was heated in a furnace at 950°C for 2 min and then cooled in a desiccator for 15 min. The weight of the platinum crucible was measured. The crucible was filled up to 1/2 to 3/8 inch with the ground oven dried samples and the gross weight was recorded. Following this the crucible was heated in a muffle furnace at 950 °C for 2 min. The crucible was removed from the furnace and cooled in air for 5 min and then cooled in a desiccator for 15 min. For each sample, the estimation was done in triplicate and the mean value is reported. The percentage of weight loss of the samples was reported as volatile matter and calculated as follows:

$$Volatile\ matter\ (\%) = \frac{Weight\ loss\ of\ dry\ sample}{Net\ weight\ of\ dry\ sample} \times 100$$

3.7.3.4 Determination of Fixed carbon content

Fixed carbon content of wood and wood base materials (bark) was determined by simple calculation as given in ASTM Test No. D-271-48. The calculation was done as follows:

% F.C. (on dry basis) = 100 - [volatile matter (%) + ash (%)]

3.7.4 Ultimate analysis of the samples

Carbon, hydrogen and nitrogen contents of the wood and bark samples were determined by using an elemental analyzer (PE 2400 C, H, N, -analyzer, Perkin Elmer). Chlorine and sulphur were not considered since they are known to be negligible for wood and wood base materials. Oxygen was determined by difference between the total weight of the sample and the combined weight of C, H, N and ash content in it [13].

3.7.5 Determination of Specific gravity

Specific gravity of the samples was determined as per ASTM – D 2395-93 (volume by water/ mercury immersion method).

Procedure:

Weight: The weight of the specimen was measured to a precision of ± 0.2%. Before weighting the specimen it was dried in an oven maintained at 103 ± 20 °C.

Volume: The volume of oven-dried specimen was determined by measuring the volume of water displaced by it.

Mode of measurement:

A container was placed holding enough water to completely submerge the specimen on the pan of an automatic balance. The specimen was held by means of a sharp, pointed, slender rod so that the specimen was completely submerged without touching the sides of the container. The weight added to the automatic balance was equal to the weight of water displaced by the specimen. The weight in grams was numerically equal to the volume in cubic centimeters.

Calculation

Specific Gravity: Specific gravity was calculated as follows:

Sp. gr. = KW/V

Where

W = weight of specimen at derived moisture content

V = Volume of specimen at desired moisture content and

K = Constant whose value was determined by the units used to measure weight and volume as follows:

K = 1, when weight was in g and volume was in cm^3.

For each sample, the estimation was done in triplicate and the mean value was reported.

3.7.6 Determination of Biochemical constituents of the samples

Cellulose, hemicelluloses and lignin were determined by using the Fibertec I and M Systems (Foss AB, Denmark) as described by Van Soest [14]. This method is based on subsequent steps of chemical treatments to solubilise "non-fibre" components and final determination of the residue obtained. Before the determination of biochemical constituents, ground samples were extracted with acetone (100%) at 5°C and water at 60–70°C. Extractions were repeated several times. The residues were dried and used for the determination of acid detergent fibre (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL).

NDF was determined after treatment with a neutral detergent solution (sodium lauryl sulphate and EDTA), and the residue consisted of cellulose, hemicelluloses and lignin. ADF was determined after treatment of the residue with an acid detergent solution (cetyltrimethylammonium bromide in sulphuric acid solution). The residue consisted of cellulose and lignin. Finally, ADL was determined after initial treatment for ADF measurement followed by removal of the cellulose fraction through extraction using 72% H_2SO_4. This residue contains only lignin. A fraction of acid-soluble lignin and cellulose could be lost during the procedure. Acid-resistant residue was recovered by filtration on a glass crucible with an asbestos filter, carefully washed and dried at 70°C for 24h to constant weight. This acid insoluble residue is insoluble lignin (hereafter called 'lignin'). After weighing, the residue was ashed at 525±25°C for at least 5 h and lignin was calculated after correcting for mineral elements.

Simple subtraction rules were used to calculate cellulose and hemicelluloses: ADF –ADL = cellulose and NDF–ADF = hemicelluloses. The results for lignin, cellulose and hemicelluloses were expressed as percentage of dry mass of wood species (% dw). For each sample, the estimation was done in triplicate and the mean value was reported.

3.7.7 Determination of Gross calorific value (GCV)

Gross Calorific value (GCV) was determined by using an auto bomb calorimeter (Changsha Kaiyuan Instruments Co, 5E-1AC/ML). About 1 g of oven dried sample tablet was completely combusted in an adiabatic bomb at 3.4 MPa Oxygen pressure. The instrument displayed the GCV of each samples after each run. The mean value of the triplicate samples was reported.

3.7.8 Determination of Gross Calorific Value (GCV), Net Calorific Value (NCV) and Usable Heat Content (UHC) at green moisture:

GCV, NCV and UHC of wood species at their green moisture were calculated by the method reported by Lyons *et al* [15] as follows

GCV (at green moisture) = $C_{ga} \times (1\text{-}m)$ MJ/kg

NCV (at green moisture) = $17.28 - 19.72\ m$ MJ/kg

UHC (at green moisture) = $14.64 - 17.43\ m$ MJ/kg

Where C_{ga} = GCV (oven dry weight), m = moisture content, as a fraction of wet weight

3.7.9 Ash analysis for elemental determination

The analysis of ash for determination of elements like Ca, Mg, Na, K, P, Si, Mn, Cu, Zn, Cd, Pb etc. was done by using an Atomic Absorption Spectrophotometer (Thermo Scientific, iCE 3000 C113500100v1.30). For this, 500 ± 5.0 mg ground extractive free samples were digested in a muffle furnace at 500°C for 4 hrs. Ash samples were digested by using Nitric-Perchloric acid as per the procedure recommended by the AOAC [16]. For this, 1 gm. of ash sample was transferred in a 250 ml digestion tube and 10 ml HNO_3 was added to it. The mixture was boiled for 30-40 min and then cooled. Again, 5 ml 70% perchloric acid was added to it and boiled gently until dense white fumes appeared. The mixture was then cooled and 20 ml distilled water was added to it. The mixture was re-boiled and cooled to ambient temperature. Finally, the mixture was filtered through Whitman no. 42 filter paper and the filtrate obtained was transferred to a volumetric flask. The final volume was then adjusted to 25 ml by addition of distilled water.

3.7.10 Fuel value index calculation

The fuel value index (FVI-I) was calculated by the method reported by Purohit and Nautiyal [17] as follows:

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ \left(\frac{g}{cm^3}\right)}{Ash\ content\ \left(\frac{g}{g}\right) \times Moisture\ content\ \left(\frac{g}{g}\right)} \qquad \text{(I)}$$

Fuel Value Index (FVI-II) of the fuelwood species was calculated by using the modified method reported by Bhatt and Todaria [18], where

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ \left(\frac{g}{cm^3}\right)}{Ash\ content\ \left(\frac{g}{g}\right)} \qquad \text{(II)}$$

Fuel Value Index (FVI-III) of the fuelwood species was calculated by Deka *et al.* [19] is as shown below:

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ \left(\frac{g}{cm^3}\right)}{Moisture\ content\ \left(\frac{g}{g}\right)} \qquad \text{(III)}$$

3. 7.11 Thermogravimetric analysis

The fuelwood samples were subjected to thermogravimetric analysis in an air atmosphere at heating rate of 10 °C/min. 10 mg sample for each species was heated at the preselected heating rate from ambient temperature to 1000 °C in a Pyris diamond TG/DTA analyzer (PERKIN ELMER). In the experiment air was fed at a constant flow rate of 100ml min^{-1}. The continuous on-line records of weight loss and temperature were obtained to plot the TG curves and the derivative thermogravimetric (DTG) curves.

3.7.11.1 Combustion characteristics

The important combustion characteristics such as Peak temperature, Burnout temperature (T_{BO}), Maximum combustion rate $(dw/dt)_{max}$ and Mean combustion rate $(dw/dt)_{mean}$ were determined from TGA data and TG/DTG curves. Mean Combustion rate is the mean value of Combustion rate in the temperature range (i.e. from the temperature at which degradation start and at which it finish). Burnout temperature (T_{BO}) is the temperature at the end of combustion where combustion rate is less than 1%. Ignition temperature (T_i) was determined from TG/DTG curves according to Wang *et al.* [20] and is shown in Figure 3.4.To determine the ignition temperature, two points on the TG curve should first be identified. One (marked as P) is the point at which a vertical line from the sharp DTG peak (highest dw/dt value) crosses the TG curve. The other (marked as S) is the point at which volatilization begins. A tangent to the TG curve at P and another horizontal tangent to S are drawn. The point at which these lines cross is marked as IG, which corresponds to the ignition temperature.

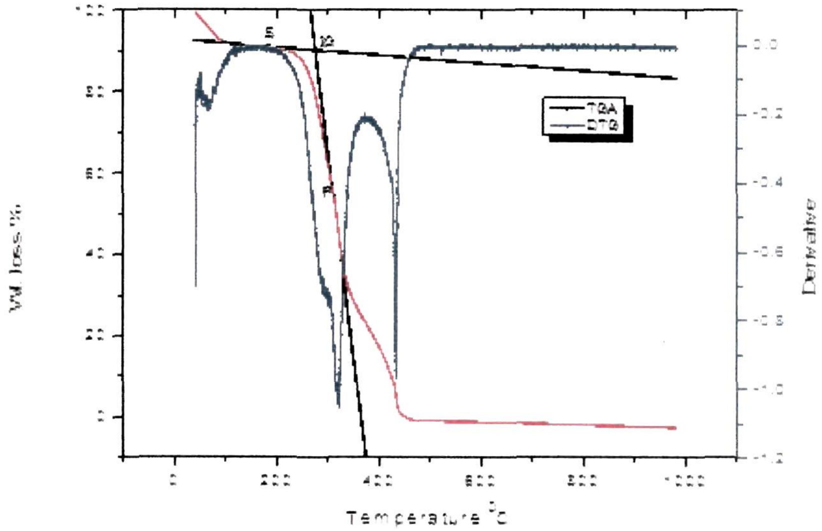


Figure 3.4: Determination of ignition temperature

3.7.11.2 Combustion Characteristic Factor (CCF)

Combustion Characteristic Factor (CCF) of the fuelwood species were calculated according to the method reported by Wang *et al.* [20] and Jiricek *et al.* [21] as shown below:

$$Combustion\ characteristic\ factor\ (S) = \frac{(\frac{dw}{dt})_{max} \times (\frac{dw}{dt})_{mean}}{T_i^2 \times T_{BO}}$$

Where $(\frac{dw}{dt})_{max}$ = Maximum combustion rate

$(\frac{dw}{dt})_{mean}$ = Mean combustion rate

T_i = Ignition temperature

T_{BO} = Burnout temperature

3.7.12 Statistical analysis

The statistical analysis has been carried out using SPSS software.

3.7.13 Overall ranking (OR)

An overall ranking of studied fuelwood species was obtained on the basis of PWC, FVI and CCF ranking.

References:

1. Sinha, G.N. Forest and Forestry in Arunachal Pradesh, SFRI information BulletinNo.27, Issued by Director, State Forest Research Institute & Mission Director, State Bamboo Mission, Arunachal Pradesh, India, 2008.
2. Maji. A. K., et al. Soil information system of Arunachal Pradesh in a GIS environment for land use planning, *JAG* **3** (1), 69-77, 2001.
3. Gupta, R. K. *Textbook of Systematic Botany,* 5th ed., Atmaram and Sons, Delhi, India, 1981.
4. Dutta, A. C. *Dictionary of Economic and Medicinal Plants*, Assam printing works Pvt. Ltd., Jorhat, Assam, India, 1985.
5. Dutta A. C. *Botany for Degree Students*, Oxford University Press, Delhi, 1989.
6. Kanjilal, U. N., et al. *Flora of Assam,* Vol. I, II, IV& V, OMSON publication, New Delhi, 1997.
7. Wu, Z. Y., & Raven, P. H. (ed.).*Flora of China*, Vol. 4 (Cycadaceae through Fagaceae), Science Press, Beijing, and Missouri Botanical Garden Press, St. Louis, 1999.
8. Kumar, K. Conducting key informant interviews in developing countries: A.I.D. programme designs and evaluation methodology report No. 13, USAID, Washington DC, 1989.
9. Abbot, P., et al. Defining Firewood quality: A comparison of quantitative and rapid appraisal technique to evaluate firewood species from a Southern Africa Savanna, *Biomass and Bioenergy* **12**(6), 429 –437, 1997.
10. Senelwa, K., & Sims, R. E. H. Fuel characteristics of short rotation forest biomass. *Biomass and Bioenergy* **17**, 127 – 140, 1999.
11. Wenger K. F. (ed.), *Forestry Hand Book.* Second Edition, John Wiley and Sons. Inc. pp. 565 – 635, 1984.
12. TAPPI Test methods. Atlanta (USA). Technical Association for Paper & Pulp Industries (TAPPI) publication.

13. Chun, Y. J. Comparison of combustion properties of native wood species used for fire pots in Korea, *Journal of Industrial and Engineering Chemistry* **16**, 15–19, 2010.
14. Van Soest, P.J. Nutritional Ecology of the Ruminant. Ruminant Metabolism, Nutritional Strategy, the Cellulytic Fermentation and the Chemistry of Forages and Plant Fibers, Cornell University Press, Ithaca, London, pp.426 , 1987.
15. Lyons, J. G., et al. A procedure for estimating the value of forest fuels, *Biomass* **8**, 283 – 300, 1985.
16. AOAC. Helrich, K. (ed.). *AOAC official methods of analysis*. 15th ed., Association of Official Analytical Chemists, Inc., Arlington, Virginia, USA, pp. 84–85, 1990.
17. Purohit, A. N., & Nautiyal, A. R. Fuelwood Value Index of Indian mountain tree species, *International Tree Crops Journal* **4**, 177-182, 1987.
18. Bhatt, B.P., & Todaria, N.P. Fuelwood characteristics of some mountain species, *Forest Ecology and Management* **47**, 363 – 366, 1992.
19. Deka, D., et al. Ranking of Fuelwood Species by Fuel Value Index, *Energy Sources* **29**, 1499–1506, 2007.
20. Wang, et al. Thermogravimetric studies of the behavior of straw with added coal during combustion, *Biomass and Bioenergy* **33**, 50-56, 2009.
21. Jiricek, I., et al. A thermogravimetric study on the behavior of biomass blending during combustion, *Acta polytechnic* **52** (3), 39-42, 2012.

Chapter 4

Results & Discussion

Chapter 4

Results & Discussion

A total of 26 tree species from Arunachal Pradesh, India was selected for fuelwood characterization. The state has the highest forest coverage (61.5%, in the context of North-Eastern India). Besides, the reserved forests, wood lots, farm forests are also seen everywhere in the state. Because of the soil fertility and heavy rainfall in the state, a large number of tree and shrubs species grow well in their natural habitats. But there is conspicuous lack of knowledge of their fuelwood characteristics.

The present study deals with screening of the most promising fuelwood species of the state, based on the knowledge gathered by the rural users from their long experiences for selecting the firewood and also from the laboratory analytical tests on fuelwood characteristics. Ash analysis was carried out to examine the possibility of using them as fertilizers. Ash analysis may also be helpful for their disposal.

The results obtained in this study have been presented into seven parts as follows:

Part I: Ranking of the traditionally preferred 26 indigenous fuelwood species on the basis of pair-wise comparison (PWC).

Part II: Ranking of fuelwood species on the basis of Fuel Value Index (FVI) and its comparison with pair-wise comparison (PWC) ranking.

Part III: Drying behaviour of the fuelwood species and the effect of moisture content on heating value.

Part IV: Proximate, ultimate and biochemical composition analysis of the tree species and their fuelwood qualities along with statistical analysis.

Part V: Ash analysis of the fuelwood species.

Part VI: Ranking of fuelwood species on the basis of Combustion Characteristic Factor (CCF).

Part VII: Overall ranking (OR) of fuelwood species on the basis of PWC, FVI and CCF.

Chapter 4: Part-I

4.1 Ranking of the traditionally preferred 26 indigenous fuelwood species on the basis of pair-wise comparison (PWC)

Ten quality criteria such as fast drying, hot flame, ember production, flame not smoky, easily flammable, non-sparking, weight when dry, easiness of splitting, low moisture when fresh cut and insect/termite resistance were taken into consideration for pair-wise comparison of tree species on the basis of the local people's choice for preferred fuelwood species. Abbot *et al.* [1] also reported a similar study for pair-wise comparison of preferred indigenous tree species in Malawi.

Table 4.1 presents the results of the PWC ranking process. Twenty six species were ranked by above ten criteria. The rank of each species and criterion is presented in the right-hand column and bottom row respectively. It was observed that no one species had all the desirable fuelwood characteristics. From Table 4.1, it is seen that the most important criteria for ranking of fuelwood were 'fast drying', 'hot flame', 'ember production' and 'flame not smoke' in comparison to others (based on criterion rank)

'Fast drying' was the criterion most frequently used by the respondents in the ranking of fuelwood species. After fresh cut, they generally keep firewood on open space and use it for burning after keeping 6 – 8 weeks for sun drying. It is seen from Table 4.1, the tree species having the fastest drying rate were *R. arboreum, A. nepalensis* and *L. polyantha* whereas *C. indica* and *S. cerasoids* showed a comparatively slower drying rate in comparison to other tree species.

'Hot flame' was another important criterion frequently mentioned by the respondents for ranking the preferred fuelwood species. According to the respondents, fuelwood species burning with hot flame were more suitable for quick cooking process (hot flame is indicative of sufficient heat generation). Among 26 fuelwood species investigated in the study, *Q. leucotrichophora*, *V. altissima*, *D. procerum* produced maximum hot flame during burning whereas, tree species such as *C. indica, B.*

Table 4.1: Ranking matrix for fuelwood species using 10 quality criteria based on local users preference

Name of species	Species quality criteria*										Score	Rank**
	Fast drying	Hot flame	Ember production	Flame not smoky	Easily flammable	Non-sparking	weight when dry	Easiness of splitting	Low moisture when fresh cut	Insect/ termite resistance		
C. indica	4	4	3	3	4	7	5	4	4	3	41	25
M. pustulata	8	7	6	7	6	7	6	7	7	5	66	6
D. binectariferum	8	8	6	6	6	6	6	5	7	6	64	8
B. retusa	7	7	6	7	5	4	6	6	4	3	55	14
M. semiserrata	7	7	4	5	6	5	5	4	5	3	51	18
C. australis	8	6	6	6	6	6	5	7	6	6	62	10
D. procerum	8	9	9	8	8	7	7	6	7	6	75	1
T. myriocarpa	7	6	4	5	5	3	6	4	5	5	50	19
S. cerasoids	5	5	6	4	5	5	4	4	4	6	48	20
K. calcyna	7	5	4	6	5	4	4	6	4	2	47	21
M. phillipensis	6	7	4	5	3	4	3	7	4	3	46	22
A. odoratissima	6	8	7	6	5	7	5	3	6	6	59	12
L. polyantha	9	8	7	8	8	7	7	7	6	4	71	3
M. elengi	8	6	6	5	6	6	8	5	5	6	61	11
B. variegata	6	4	3	4	4	5	6	6	3	3	44	23
P. integrifolia	7	5	3	4	5	4	4	4	5	2	43	24
T. hodgsonii	6	6	5	5	6	5	6	5	5	5	54	15
P. acerifolium	7	6	7	5	4	6	6	4	4	3	52	17
V. altissima	8	9	9	7	8	8	8	6	7	3	73	2
S. wallichii	7	6	6	5	6	6	5	5	4	6	56	13
A. nepalensis	9	7	4	7	5	4	3	8	3	3	53	16
Q. lanata	8	8	9	7	8	7	8	7	6	7	75	1
Q. leucotrichophora	8	9	7	6	6	7	7	6	7	7	70	4
R. arboreum	9	8	8	6	5	7	5	6	7	6	67	5
M. esculenta	7	7	7	6	5	7	6	5	7	6	63	9
E. acuminata	7	7	8	7	6	5	7	5	6	7	65	7
Total criterion score	187	175	154	150	146	149	148	142	138	122		
Criterion Rank	1	2	3	4	6	5	7	8	9	10		

* For each of the quality criterion 10 point (maximum) is presented

** Ranking ranges from 1 (best score) to 25 (worst score).

variegata, K. calcyna, and *S. Cerasoids* and *P. Integrifolia* produced low hot flame (Table 4.1).

'Ember production' from fuelwood was an important criterion used by respondents. According to them, long-lasting ember was able to provide uniform heat and consequently more effective for cooking, space heating during winter season and brick burning. The suitable species found for ember production as preferred by respondents were *Q. lanata, V. altissima* and *D. procerum* while *C. indica, B. variegata, P. integrifolia, M. semiserrata, M. phillipensis, T. myriocarpa, A. nepalensis* and *K. calcyna* were less preferred tree species for ember *production* (Table 4.1).

'Less smoky flame' was another criterion preferred by the users. Rural household kitchens normally do not have access to proper ventilation for efficient removal of flue gas/smoke produced during combustion of fuelwood. Therefore, they categorized this as one of the important criteria. Fuelwood species such as *C. indica, B. variegata, P. integrifolia* and *S. cerasoids* were found to produce comparatively more smoke during combustion in comparison to the other species under investigation (Table 4.1).

'Easily flammable' was one of the criteria mentioned by the respondents. Easily flammable fuelwood species requires less effort to catch fire and thereby reduces the problem of initial burning. Usually, most of the local users initiate fuelwood burning processes with the help of dry biomass materials such as jute stick, rice straw, dry bamboo etc. From Table- 4.1, it is seen that *L. polyantha, V. altissima, D. procerum,* and *Q. lanata* were found to be easily flammable in comparison to other fuelwood species.

'Non-sparking' was considered another fuelwood quality criterion by local users for ranking of fuelwood species. Because, sparking from the firewood during burning is considered an undesired quality which may create hazards to nearby or around the burning places. In the present study, respondents did not mention this criterion frequently for selection of firewood. They indicated that except one or two species, most of the species had very little sparking behaviour. From Table 4.1, it is seen that *V. altissima, C. indica, M. pustulata, D. procerum, A. odoratissima, L. polyantha, Q. lanata, Q. leucotrichophora, R. arboreum* and *M. esculenta* were some of the tree species displaying low sparking behavior in comparison to others.

'Weight when dry' was also an important criterion for proper selection of fuelwood species. According to respondents those fuelwood species retained their weight after drying for a certain period were excellent for cooking and space heating. But, they found this criterion less important which they considered to be incompatible for the most favoured fuelwood characteristics such as fast drying, hot flame, ember production etc. (Table- 4.1). The present investigation revealed that fuelwood species such as *Q. lanata, V. altissima, M. elengi, D. procerum, L. polyantha, Q. leucotrichophora,* and *E. acuminata* retained considerable weight after drying in comparison to other fuelwood species (Table 4.1).

'Easiness of splitting' is also taken into consideration by local users for selecting proper fuelwood species. Local users use to cut fuelwood into pieces before cooking and space heating applications. Fuelwood species those split easily are preferable owing to labor savings. Fuelwood species suitable for this quality criterion were *A. nepalensis, L. polyantha, Q. lanata, M. phillipensis, C. australis* and *M. pustulata* (Table 4.1).

'Low moisture when fresh cut' was not considered to be much important by the respondents for selection of firewood. Rural people generally do not use fresh cut firewood. After cutting the trees they keep them for several weeks for drying before use. But, in general, low moisture content is preferable from fuelwood selection point of view which may be indicative for requiring less time to use firewood after fresh cut. Among all the fuelwood species, *V. altissima, Q. leucotrichophora, D. procerum, M. pustulata, D. binectariferum, M. esculenta* and *R. arboreum* (Table 4.1) were found to have low moisture content when freshly cut.

'Insect/termite resistance' was not considered as a significant criterion by the respondents while selecting fuelwood species. Following felling of trees and their subsequent splitting into pieces, the wood pieces are sun dried. Users' store these sun dried wood pieces for several days prior to utilization. During the storage period, fuelwood are susceptible to insect/termite attacks resulting in lowering of fuelwood quality. Therefore, fuelwoods with high insect/termite resistance are better candidates for cooking and space heating applications. In the present investigation *E. acuminata, Q. lanata, Q. leucotrichophora, M. esculenta, R. arboreum, S. wallichii, M. elengi, A. odoratissima, S. cerasoids, D. procerum, C. australis* and *D. binectariferum* were more resistant to insect/termite attacks in comparison to the others (Table 4.1).

Considering the above 10 quality criteria for selecting quality firewood species based on local people's preference by PWC, the 10 best fuelwood species in descending order is as follows:

Q. lanata ~ D. procerum, V. altissima, L. polyantha, Q. leucotrichophora, R. arboreum, M. pustulata, E. acuminate, D. binectariferum and *M. esculenta* (Table 4.1).

Chapter 4: Part-II

4.2 Ranking of fuelwood species on the basis of Fuel Value Index (FVI) and its comparison with pair-wise comparison (PWC) ranking

Fuel Value Index (FVI) is an important parameter for screening desirable fuelwood species [2]. FVI depends upon calorific value and density as positive character and moisture and ash contents as negative characters. Purohit and Nautiyal [3]; Bhatt and Badoni [4]; Bhatt and Todaria, [5]; Jain [6]; Abbot *et al.* [1] and Deka *et al.* [7] in similar studies also considered the above parameters to determine the FVI of tree species.

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ (\frac{g}{cm^3})}{Ash\ content\ \left(\frac{g}{g}\right) \times Moisture\ content\ (\frac{g}{g})} \qquad (1)$$

In the present study, FVI of the fuelwood species was calculated using formula No.1 and the results are presented in Table 4.2 under column FVI-I. In general fuelwood species having high calorific value, high density, low ash and moisture contents are known as ideal fuelwood species. From Table 4.2, it is seen that *Q. lanata* (4748.17) has the highest FVI-I among all the species under investigation followed by *D. procerum* (4091.38), *Q. leucotrichophora* (3521.55), *R. arboreum* (3009.7), *D. binectariferum* (2991.84), *M. esculenta* (2437.34), *M. pustulata* (2331.22) etc. With low moisture and ash contents, *Q. lanata* possesses the highest calorific value (20.22 MJ/kg) and density (0.86 g/cm^3).

FVI of the fuelwood species was calculated by using the modified method reported by many researchers [5, 7] where calorific value and density were considered as positive characters and ash content alone as negative character. The formula used

Table 4.2: Green moisture content, ash content, density, Calorific value and FVI of fuelwood species

Tree species name	Green moisture content (%, wt) MC	Ash content (%, oven dry wt.) A	Density (g/cc, oven dry wt. D	Gross calorific value (MJ/kg, oven dry wt.) GCV	FVI-1 $\frac{GCV \times D}{MC \times A}$	FVI-II $\frac{GCV \times D}{A}$	FVI-III $\frac{GCV \times D}{MC}$
C indica	38 68 ±2 59	3 91 ± 0 11	0 67 ± 0 02	18 50 ± 0 08	819 56	317 06	32 04
M pustulata	52 82 ± 0 92	1 02 ± 0 02	0 66 ± 0 01	19 03 ± 0 27	2331 22	1231 35	23 77
D binectariferum	38 52 ± 0 23	1 22 ± 0 07	0 72 ± 0 01	19 53 ± 0 25	2991 84	1152 45	36 5
B retusa	51 29 ± 0 94	1 66 ± 0 18	0 55 ± 0 02	19 22 ± 0 16	1241 58	636 74	20 6
M semiserrata	39 23 ± 0 14	1 98 ± 0 52	0 71 ± 0 02	18 66 ± 0 12	1705 64	668 68	33 77
C australis	40 06 ± 2 36	1 42 ± 0 11	0 54 ± 0 05	18 98 ± 0 19	1801 73	721 12	25 56
D procerum	42 79 ± 3 96	0 70 ± 0 19	0 61 ± 0 01	20 09 ± 0 02	4091 38	1750 00	28 63
T myriocarpa	39 67 ± 2 23	3 24 ± 0 16	0 61 ± 0 01	17 94 ± 0 11	851 42	337 65	27 57
S cerasoids	43 99 ± 2 82	2 10 ± 0 04	0 63 ± 0 01	19 52 ± 0 38	1331 21	585 23	27 93
K calcyna	50 07 ± 2 41	1 91 ± 0 37	0 45 ± 0 04	19 68 ± 0 08	926 03	463 35	17 67
M phillipensis	40 89 ± 1 46	4 34 ± 0 25	0 69 ± 0 03	17 87 ±0 07	694 81	284 1	30 15
A odoratissima	42 12 ± 1 96	1 97 ± 0 18	0 75 ± 0 03	19 07 ± 0 53	1723 68	725 88	33 95
L polyantha	50 89 ± 8 35	0 72 ± 0 22	0 43 ± 0 01	19 35 ± 0 04	2270 83	1155 55	16 34
M elengi	36 78 ± 1 24	1 97 ± 0 12	0 60 ± 0 01	19 11 ± 0 05	2162 7	795 43	42 6
B variegata	51 84 ± 0 66	6 13 ± 0 31	0 51 ± 0 05	16 83 ± 0 19	274 01	139 96	16 55
P integrifolia	48 85 ± 0 93	4 26 ± 0 05	0 55 ± 0 05	18 01 ± 0 06	475 99	232 39	26 2
T hodgsonii	47 25 ± 3 01	1 48 ± 0 07	0 65 ±0 02	19 40 ± 0 51	1803 23	852 02	26 68
P acerifolium	51 10 ± 0 87	2 21 ± 0 12	0 49 ± 0 02	18 50 ± 0 27	802 7	409 95	17 72
V altissima	38 23 ± 1 28	2 10 ± 0 16	0 81 ± 0 03	19 14 ± 0 14	1931 09	738 09	40 55
S wallichii	40 13 ± 1 81	1 69 ± 0 17	0 75 ±0 04	18 76 ± 0 16	2074 62	832 54	35 06
A nepalensis	54 58 ± 1 49	1 36 ± 0 08	0 34 ±0 04	18 21 ± 0 23	834 1	455	11 34
Q lanata	38 55 ± 1 65	0 95 ± 0 13	0 86 ± 0 01	20 22 ± 0 01	4748 17	1830 42	41 96
Q leucotrichophora	34 34 ± 0 98	1 29 ± 0 36	0 80 ± 0 02	19 15 ± 0 11	3521 55	1209 3	45 42
R arboreum	51 22 ± 1 18	0 89 ± 0 02	0 70 ± 0 03	19 60 ± 0 09	3009 71	1541 57	26 78
M esculenta	47 71 ± 4 19	1 05 ± 0 05	0 65 ±0 01	18 79 ± 0 23	2437 34	1162 85	25 6
E acuminata	44 53 ± 1 12	1 18 ± 0 42	0 60 ± 0 02	19 37 ± 0 35	2211 8	984 91	26 09

for computation of FVI in this method is as below and the results are presented in Table- 4.2 under the column FVI-II.

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ (\frac{g}{cm^3})}{Ash\ content\ \left(\frac{g}{g}\right)} \qquad (II)$$

From the Table 4.2, the calculation of FVI-II for the tree species shows that *Q. lanata* (1830.44) has the highest FVI followed by *D. procerum* (1750.00), *R. arboreum* (1541.57), *M. pustulata* (1231.35), *Q. leucotrichophora* (1209.3), *M. esculenta* (1162.85), *L. polyantha* (1155.55), *D. binectariferum* (1152.45), *E. acuminata* (984.91), *T. hodgsonii* (852.02) etc.

The removal of % ash content from the index of fuelwood quality provides a FVI which is more simple to determine but equally effective. Deka *et al.* [7] have also calculated FVI of fuelwoods considering calorific value and density as positive characters and moisture content alone as negative character. In this method the formula used for computation was as below:

$$FVI = \frac{Calorific\ value\ \left(\frac{KJ}{g}\right) \times Density\ (\frac{g}{cm^3})}{Moisture\ content\ \left(\frac{g}{g}\right)} \qquad (III)$$

The results of FVI of the tree species calculated using formula no. III are also presented in Table 4.2 under column FVI-III. In this calculation, highest FVI was found for *Q. leucotrichophora* (45.42) followed by *M. elengi* (42.60), *Q. lanata* (41.96), *V. altissima* (40.55), *D. binectariferum* (36.50), *S. wallichii* (35.06), *A. odoratissima* (33.95), *M. semiserrata* (33.77), *C. indica* (32.04), *M. phillipensis* (30.15) etc.

Ranking of the tree species on the basis of Fuel Value Indexes (FVI-I, FVI-II, FVI-III) and the ranking of the same tree species found on the basis of PWC are presented in Table 4.3. The ranking relationship of individual FVI with PWC is presented in Figure 4.1 (a-c).

Table 4.3: Fuelwood ranking as per FVI and PWC

Sl. no.	Fuelwoods species	Ranking on the basis of FVI			Ranking on the basis of Pair-wise comparison (PWC)
		FVI- I	**FVI-II**	**FVI-III**	
1	*C. indica*	22	23	9	25
2	*M. pustulata*	7	4	20	6
3	*D. binectariferum*	5	8	5	8
4	*B. retusa*	18	17	21	14
5	*M. semiserrata*	16	16	8	18
6	*C. australis*	14	15	19	10
7	*D. procerum*	2	2	11	1
8	*T. myriocarpa*	20	22	13	19
9	*S. cerasoids*	17	18	12	20
10	*K. calcyna*	19	19	23	21
11	*M. phillipensis*	24	24	10	22
12	*A. odoratissima*	15	14	7	12
13	*L. polyantha*	8	7	25	3
14	*M. elengi*	9	12	2	11
15	*B. variegata*	26	26	24	23
16	*P. integrifolia*	25	25	16	24
17	*T. hodgsonii*	13	10	15	15
18	*P. acerifolium*	23	21	22	17
19	*V. altissima*	12	13	4	2
20	*S. wallichii*	11	11	6	13
21	*A. nepalensis*	21	20	26	16
22	*Q. lanata*	1	1	3	1
23	*Q. leucotrichophora*	3	5	1	4
24	*R. arboreum*	4	3	14	5
25	*M. esculenta*	6	6	18	9
26	*E. acuminata*	10	9	17	7

From Table 4.3, it is seen that ranking of tree species on the basis of FVI-I and FVI-II are almost similar whereas they differ with FVI-III ranking. Similarly, the FVI-I & FVI-II ranking were also in close proximity with the PWC ranking. However, no similarity was observed for the aforesaid rankings with FVI-III ranking (Table 4.3 and Figure 4.1a-c).

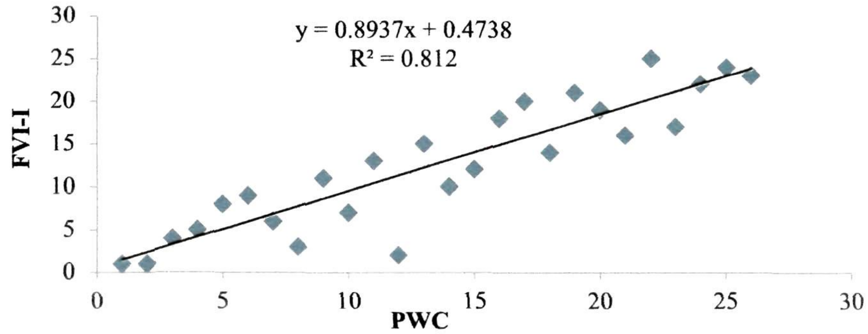


Figure 4.1a: Ranking relationship between FVI-I and PWC

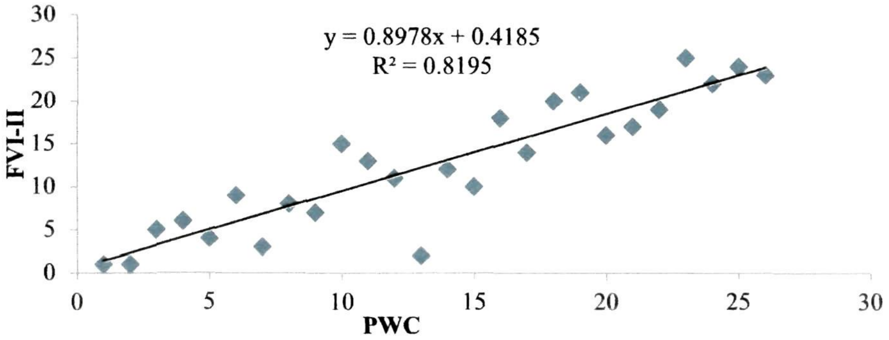


Figure 4.1b: Ranking relationship between FVI-II and PWC

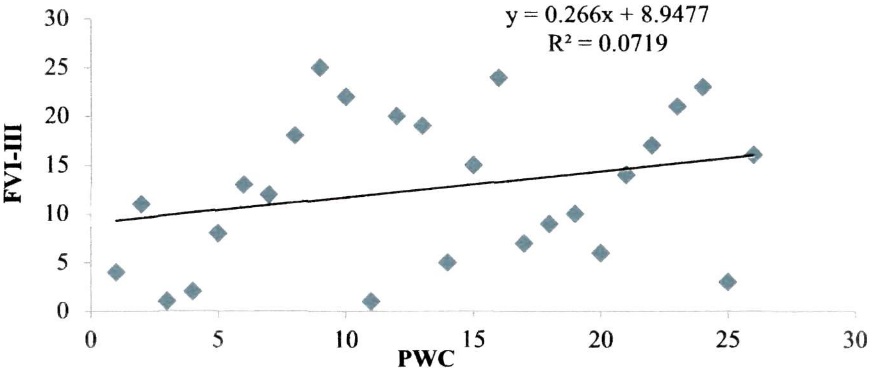


Figure 4.1c: Ranking relationship between FVI-III and PWC

From Table 4.3 and Figure 4.1a-b, it is seen that the FVIs (FVI-I, FVI-II) having more proximity to PWC ranking were calculated considering calorific value and density as positive characters. For calculating FVI-I, moisture and ash content were considered as negative characters. But for FVI-II, ash content was only considered as negative character. The common people's preference for selection of fuelwood species is based mainly on the characteristics such as fast drying, ember production, hot flame etc. Moisture content is not an important characteristic for them. They keep the tree species for sundry at least 6-8 weeks before use as firewood. On the other hand, moisture content in wood species varies with the dimension of branches, season of the year, storage and so on. Thus, moisture content may not be considered as an intrinsic value of a fuelwood species [8-9]. Therefore, FVI-II can be easier to resemble with PWC ranking. However, Table 4.1 and Table 4.2 show that people's preferences are also determined by a series of minor properties, which are not considered by either of the FVI.

From Table 4.1, it is seen that the decreasing order of ranks of the preferred fuelwood species under study on the basis of PWC ranking is as follows:

Q. lanata, D. procerum, V. altissima, L. polyantha, Q. leucotrichophora, R. arboreum, M. pustulata, E. acuminata, D. binectariferum, M. esculenta, C. australis, M. elengi, A. odoratissima, S. wallichii, B. retusa, T. hodgsonii, A. nepalensis, P. acerifolium, M. semiserrata, T. myriocarpa, S. cerasoids, K. calcyna, M. phillipensis, B. variegata, P. integrifolia and *C. indica.*

Again, from Table 4.3, it is seen that the decreasing order of ranks of the preferred fuelwood species under study on the basis of FVI (FVI-II) is as follows:

Q. lanata, D. procerum, R. arboreum, M. pustulata, Q. leucotrichophora, M. esculenta, L. polyantha, D. binectariferum, E. acuminata, T. hodgsonii, S. wallichii, M. elengi, V. altissima, A. odoratissima, C. australis, M. semiserrata, B. retusa, S. cerasoids, K. calcyna, A. nepalensis, P. acerifolium, T. myriocarpa, C. indica, M. phillipensis, P. integrifolia and *B. variegata.*

Chapter 4: Part-III

4.3 Drying behaviour of the fuelwood species and the effect of moisture content on heating value

4.3.1 Drying behavior of fuelwood species

Drying behavior of fuelwood is important from end use point of view especially for heating appliances. A wood species which releases higher moisture (i.e. fast drying behavior) after a certain period of sundry is considered as suitable firewood. In our study, branches of fuelwoods (size 20 cm in length and diameter 7-10 cm) were allowed to sundry for 8 weeks. The percent of weight loss by each of the wood species were recorded after an interval of one week and the results are presented in Table 4.4. As the seasons also affect the drying behavior [10] of fuelwood, the climatic data during the experimental tenure were recorded and are presented in Table 4.5. From the Table 4.4, after 1st week of sundry the highest percentage of weight loss was observed in *A. nepalensis* (21.25%) and lowest in *Q. leucotrichophora* (7.71%). In the 2nd week of sundry, the highest weight loss was observed for *A. nepalensis* (29.43%) and lowest weight loss for *V. altissima* (11.12%). In the 3rd week, the highest weight loss was recorded for *A. nepalensis* (34.33%) and lowest for *Q. leucotrichophora* (16.73%). Similarly in the 4th, 5th, 6th and 7th and 8th week of sundry, the highest weight loss was observed for *A. nepalensis* and lowest for *Q. leucotrichophora.*

Initially (up to 4th week) the rate of moisture loss was observed faster in the studied fuelwood species although with variations rates among different species. A slow decrease was evident after 5th week of sundry. After the 8th week of sundry the highest percentage of moisture released was found in *A. nepalensis* (46.96%) and lowest in *Q. leucotrichophora* (27.15%). According to previous reports moisture content of air dried wood species differed slightly and varied from 6.6% to 7.8% [11]. In our investigation moisture retained in the fuelwood species after the 8th week of sundry was found to be from 7.19 to12.22%. The highest moisture was retained in *B. retusa* (12.22%) while lowest in *Q. leucotrichophora* (7.19%). In our study, the final moisture percentage retained in the dried fuelwood species was independent of the green moisture content, besides fuelwood species exhibiting fast drying rate were almost same with those for PWC ranking.

The differences in drying rates of fuelwood species may be due to wide range of free and bound water in the plant cells. Upon drying, the free water is lost immediately. Depending upon the free water loss from the lumen the rate of drying in the initial period may vary [12]. Below the fiber saturation point (FSP), wood begins to lose moisture in the form of bound water trapped within the cell walls and slowly comes to equilibrium moisture content with the ambient air. The equilibrium moisture content depends on the temperature and relative humidity of the ambient air [13]. Hence, prevailing climatic condition of a particular region or location may play an important role on drying rates of fuelwood species.

Table 4.4: Weight loss (%) of tree species after sundry in regular interval of periods

Species name	Green moisture (%)	Weight loss (%) after sundry in regular interval of periods								Percentage green moisture released **	Percentage green moisture retained *
		1st week	2nd week	3rd Week	4th week	5th week	6th week	7th week	8th week		
C. indica	38.68 ± 2.59	10.74	16.76	20.06	23.92	26.57	28.23	29.94	30.54	30.54	08.14
M. pustulata	52.82 ± 0.92	19.34	25.60	30.94	34.09	37.02	39.22	40.51	41.10	41.10	11.72
D. binectariferum	38.52 ± 0.23	08.99	13.99	17.98	21.62	24.98	26.89	28.41	28.38	28.38	10.14
B. retusa	51.29 ± 0.94	14.04	20.08	25.94	28.89	31.83	35.58	37.95	39.07	39.07	12.22
M. semiserrata	39.23 ± 0.14	10.18	17.70	21.86	24.94	26.75	28.09	29.90	30.44	30.44	08.79
C. australis	40.06 ± 2.36	08.98	14.70	18.66	22.83	26.70	28.69	30.26	30.87	30.87	09.19
D. procerum	42.79 ± 3.96	08.76	14.75	19.71	24.06	27.59	30.39	32.40	33.22	33.22	09.57
T. myriocarpa	39.67 ± 2.23	09.29	15.16	19.66	22.08	24.47	26.40	29.44	31.32	31.32	08.35
S. cerasoids	43.99 ± 2.82	10.45	16.88	21.55	24.88	27.56	31.06	32.71	33.15	33.15	10.84
K. calcyna	50.07 ± 2.41	15.75	21.67	26.26	30.51	34.28	38.24	40.28	41.11	41.11	08.96
M. phillipensis	40.89 ± 1.46	12.72	17.69	21.60	24.12	26.57	28.72	29.59	30.40	30.40	10.49
A. odoratissima	42.12 ± 1.96	08.76	14.22	18.82	22.36	24.06	27.04	29.97	31.43	31.43	10.69
L. polyantha	50.89 ± 8.35	17.94	21.58	29.07	33.77	37.73	40.90	42.03	42.39	42.39	08.50
M. elengi	36.78 ± 1.24	12.02	16.56	19.95	21.18	22.19	25.19	26.92	27.57	27.57	09.21
B. variegata	51.84 ± 0.66	11.98	18.44	23.98	27.81	31.33	35.59	38.46	40.17	40.17	11.67
P. integrifolia	48.85 ± 0.93	14.72	20.88	24.65	28.71	32.23	35.09	37.04	37.62	37.62	11.23
T. hodgsonii	47.25 ± 3.01	13.28	21.14	25.23	29.43	33.31	35.38	36.79	37.26	37.26	09.99
P. acerifolium	51.10 ± 0.87	10.93	18.63	24.78	29.11	32.61	35.71	38.13	39.92	39.92	11.18
V. altissima	38.23 ± 1.28	07.88	11.12	16.80	19.21	23.05	25.60	27.74	28.78	28.78	09.45
S. wallichii	40.13 ± 1.81	08.50	14.89	18.21	21.42	25.28	27.20	29.01	30.07	30.07	10.06
A. nepalensis	54.58 ± 1.49	21.25	29.43	34.33	38.27	41.08	44.12	46.19	46.96	46.96	07.62
Q. lanata	38.55 ± 1.65	10.67	16.61	20.27	23.28	25.80	28.06	29.70	30.24	30.24	08.31
Q. leucotrichophora	34.34 ± 0.98	07.71	12.00	16.73	19.16	22.58	25.01	26.88	27.15	27.15	07.19
R. arboreum	51.22 ± 1.18	18.21	25.82	32.27	35.55	37.17	40.22	41.98	42.29	42.29	08.93
M. esculenta	47.71 ± 4.19	14.21	19.17	24.19	28.98	30.89	33.11	35.24	36.33	36.33	11.38
E. acuminata	44.53 ± 1.12	13.08	18.59	22.64	26.10	29.82	32.89	34.75	35.47	35.47	09.06

**Percentage green moisture released = Green moisture loss (%) after 8th week of sundry

* Percentage green moisture retained = Green moisture (%) – Green moisture loss (%) after 8th week of sundry

Table 4.5: Climatic data recorded during the drying period (8 weeks), 2010

Study period		Temperature (°C)		Atmospheric humidity (%)		Rainfall (mm)
Months	**Weeks**	**Minimum**	**Maximum**	**8.30 A.M.**	**5.30 P.M.**	
November	First	22.79	23.49	75.50	73.63	nil
	Second	22.11	22.82	71.62	69.13	5.0
	Third	20.51	21.19	82.62	78.00	nil
	Fourth	20.66	21.38	84.33	82.00	nil
Monthly average		21.52	22.22	78.52	75.69	1.3
December	First	18.14	18.89	88.57	72.75	nil
	Second	17.90	18.46	91.42	81.25	8.0
	Third	16.48	17.38	85.50	68.00	nil
	Fourth	16.10	17.03	90.00	67.14	nil
Monthly average		17.15	17.94	88.87	72.28	2.0

4.3.2 Effect of moisture content on heating values of fuelwood species

Moisture content varies in different fuelwood species owing to differences in the hygroscopicity of different fiber complexion. Such differences may influence the suitability of biomass for various applications. The economic value of fuelwood is dependent on its moisture content [14-15]. Moisture does not contribute to the heating value but reduces the heat available from fuel by (i) lowering the initial gross calorific value of the wood (ii) reducing the combustion efficiency (since heat is absorbed in evaporation of water in the initial stages of combustion which lowers both the flame temperature and the radiant heat transfer) and (iii) by the hydrolysis effect of hot water. Water at or near boiling point promotes hydrolysis of wood resulting in the production of H_2O and CO_2 [14].

The calculated heating values like Gross calorific values (GCV), Net calorific values (NCV) and Usable heat content (UHC) of fuelwood species at their green moisture content (i.e. fresh cut moisture content prior to oven drying) are presented in Table 4.6. The calculation was done as per the formula reported by Lyons *et al.* [16].

In the present investigation no direct relationship was found between the green moisture (fresh cut moisture content) and gross calorific value (oven dry weight) of the fuelwood (Table 4.6). But the moisture content influences the GCV, NCV and UHC of fuelwood species calculated at their green moisture point (when not oven dried). These heating values (GCV, NCV and UHC) decreased with the increase in green moisture content of the fuelwood species. The GCV (oven dry weight) of the studied fuelwood species varied from 16.83 MJ/kg to 20.22 MJ/kg. On the contrary, the GCV at green moisture decreased and varied from 8.27 MJ/kg to 12.57 MJ/kg. For the NCV (at green moisture) this range further decreased to 6.52-10.51 MJ/kg. The UHC at green moisture decreased to a lower range from 5.13 MJ/kg to 8.65 MJ/kg. *Q. lanata* showed the highest GCV (at oven dry weight) whereas *B. variegata* showed the lowest. On the other hand, GCV, NCV and UHC values calculated at their green moisture were highest for *Q. leucotrichophora* owing to low green moisture content (34.34%) [Table 4.6]. It signifies that the species with low green moisture content are more desirable as firewood for getting effective and usable heat.

Table 4.6: Heating values of fuelwood species at their green moisture content [16]

Species name	Green moisture (%, wt.)	Gross calorific value (Oven dry wt.) MJ/kg	Gross calorific value*(at green moisture) MJ/kg	Net calorific value** (at green moisture) MJ/kg	Usable Heat content*** (at green moisture) MJ/kg
C indica	38.68 ± 2.59	18.50 ± 0.08	11.34	9.65	7.89
M pustulata	52.82 ± 0.92	19.03 ± 0.27	8.72	6.86	5.43
D binectariferum	38.52 ± 0.23	19.53 ± 0.25	12.00	9.68	7.93
B retusa	51.29 ± 0.94	19.22 ± 0.16	9.36	7.17	5.70
M semiserrata	39.23 ± 0.14	18.66 ± 0.12	11.34	9.54	7.80
C australis	40.06 ± 2.36	18.98 ± 0.19	11.26	9.26	7.55
D procerum	42.79 ± 3.96	20.09 ± 0.02	10.49	7.86	6.31
T myriocarpa	39.67 ± 2.23	17.94 ± 0.11	10.82	9.46	7.73
S cerasoids	43.99 ± 2.82	19.52 ± 0.38	10.93	8.61	6.97
K calcyna	50.07 ± 2.41	19.68 ± 0.08	9.83	7.41	5.91
M phillipensis	40.89 ± 1.46	17.87 ±0.07	10.58	9.23	7.53
A odoratissima	42.12 ± 1.96	19.07 ± 0.53	11.04	8.97	7.30
L polyantha	50.89 ± 8.35	19.35 ± 0.04	9.50	7.24	5.77
M elengi	36.78 ± 1.24	19.11 ± 0.05	12.08	10.03	8.23
B variegata	51.84 ± 0.66	16.83 ± 0.19	8.30	7.06	5.60
P integrifolia	48.85 ± 0.93	18.01 ± 0.06	9.21	7.65	6.13
T hodgsonii	47.25 ± 3.01	19.40 ± 0.51	10.23	7.96	6.40
P acerifolium	51.10 ± 0.87	18.50 ± 0.27	9.05	7.20	5.73
V altissima	38.23 ± 1.28	19.14 ± 0.14	11.82	9.74	7.98
S wallichii	40.13 ± 1.81	18.76 ± 0.16	11.23	9.37	7.65
A nepalensis	54.58 ± 1.49	18.21 ± 0.23	8.27	6.52	5.13
Q lanata	38.55 ± 1.65	20.22 ± 0.09	12.04	9.68	7.92
Q leucotrichophora	34.34 ± 0.98	19.15 ± 0.11	12.57	10.51	8.65
R arboreum	51.22 ± 1.18	19.60± 0.01	9.86	7.18	5.71
M esculenta	47.71 ± 4.19	18.79 ± 0.23	9.82	7.87	6.32
E acuminata	44.53 ± 1.12	19.37 ± 0.35	10.74	8.50	6.88

*Gross CV at moisture content (m), $C_g = C_{ga} \times (1\text{-}m)$ (MJ/Kg)
Where, C_g = Gross CV, C_{ga} = Gross anhydrous CV, m = moisture content, as a fraction of wet weight

** Net Heating value, $C_n = 17.28 - 19.72\ m$ (MJ/Kg)

*** Usable Heat Content = $14.64 - 17.43m$

Chapter 4: Part-IV

4.4 Proximate, ultimate and biochemical composition analysis of the tree species and their fuelwood qualities along with statistical analysis

4.4.1 Proximate & Ultimate analysis

Proximate analysis is the easiest and most widely used standard test method for characterizing a solid fuel [17]. It includes the determination of moisture, ash, volatile matter and fixed carbon. Ash is the non-combustible inorganic part left after complete combustion of fuelwood while volatile matter and fixed carbon indicate the percentage of the solid fuel (oven dry weight) burnt in the gaseous and solid state respectively [18-20]. From a combustion stand point, the volatile matter (VM) and fixed carbon (FC) content predict the requirement for the division of air flow between over fire or secondary air and under fire or primary air. This division of air flow has been useful in smoke abatement and air pollution control. Ash content predicts the residue handling requirements in a combustion process [16, 21].

The large amount of volatile matter associated with wood is a result of high number of functional groups and low number of aromatic structure in wood. It has been reported by various investigators that wood with high amount of volatile matter, resin, wax and lignin content produces more heat during combustion [2, 15, 22].

Ultimate analysis is used to calculate the quantity of oxygen (combustion air) required to sustain combustion reactions. Combustion is a series of chemical reactions by which carbon is oxidized to water. The pathways of combustion are determined largely by the structure of combustible molecules, particularly as it determines the location and accessibility of the carbon and hydrogen. Similarly, the higher heating value is determined by the relative proportion of carbon in a solid fuel [23]. Higher carbon content influences positively to the heating values of the fuel. It also permits the estimation of the amount of water formed by burning hydrogen present in the fuel.

Because fuelwood is almost sulphur free and low in nitrogen content, it provides minimal SOx and NOx pollutants in the atmosphere.

It was of some interest to carry out the proximate and ultimate analysis of the wood samples of the tree species and to examine the effect of fixed carbon, volatile matter, ash, carbon, hydrogen, nitrogen and oxygen contents on the fuel quality of the tree species.

The results for proximate analysis of the studied fuelwood species are presented in Table 4.7. Ash content of the studied fuelwood species varied from 0.70 to 6.13% and was highest in *B. variegata* (6.13%) whereas, lowest in *D. procerum* (0.70%). Ash content of fuelwood directly affects the heating value and its high percentage in fuelwood makes it less desirable for use as a fuel [24-25]. Moreover, it reduces the amount of combustible matter in wood. The results of the study showed that *D. procerum* having the lowest ash content of 0.70% correspond to higher GCV of 20.09 MJ/kg and *B. variegata* with highest ash content of 6.13% correspond to the lower GCV of 16.83MJ/kg (Table 4.2 & 4.7). It can be seen form the Table 4.7 and Figure 4.2 that the GCV decreased with the increase in ash content of fuelwood species. Similar findings have been previously reported by Montes *et al.* [26], Nasser *et al.* [27], Khider and Elsaki [28].

VM in wood is the fraction released when it is heated at a high temperature without considering moisture while FC is the mass left after the release of volatiles, excluding ash. The share of VM in wood is typically high in comparison to its FC [29]. It is seen from the Table 4.7 that the VM was highest in *B. variegata* (77.70%) and was lowest in *Q. lanata* (72.07%). Haykiri-Acma and Yaman [30], Rowell R.M [31], Kandiyoti *et al.* [32] reported that holocellulose (sum of hemicelluloses and cellulose) portion in wood mainly contributes to the formation of VM. From the Table 4.7, it is seen that the FC was highest for *Q. lanata* (26.98%) whereas lowest value was for *B. variegata* (16.17%). Considering the Table 4.6 and Table 4.7, it is observed that the higher FC content may be responsible for the higher GCV of the studied tree species.

Table 4.7 Proximate and Ultimate analysis

Name of the species	Ultimate analysis (oven dry wt.)				Proximate analysis (oven dry wt.)		
	C (%)	H (%)	N (%)	O (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)
C. indica	44.75	5.64	2.15	43.55	3.91 ± 0.11	74.09	22.00
M. pustulata	46.29	6.33	2.30	44.02	1.02 ± 0.02	74.79	24.19
D. binectariferum	46.43	6.25	2.38	43.72	1.22 ± 0.07	73.8	24.98
B. retusa	45.92	6.21	2.33	43.56	1.66 ± 0.18	74.72	23.62
M. semiserrata	44.34	5.96	2.28	46.14	1.98 ± 0.52	75.2	22.82
C. australis	46.24	5.99	2.14	44.03	1.42 ± 0.11	76.05	22.53
D. procerum	47.44	6.31	2.34	43.41	0.70 ± 0.19	72.42	26.88
T. myriocarpa	44.23	5.65	2.90	45.98	3.24 ± 0.16	78.4	18.36
S. cerasoids	46.71	5.91	2.59	42.69	2.10 ± 0.04	73.7	24.2
K. calcyna	46.51	5.89	2.40	43.29	1.91 ± 0.37	72.08	26.01
M. phillipensis	43.71	5.55	1.75	44.65	4.34 ± 0.25	78.7	16.96
A. odoratissima	45.33	6.06	2.78	43.86	1.97 ± 0.18	74.2	23.83
L. polyantha	46.97	6.21	2.90	43.20	0.72 ± 0.22	73.6	25.68
M. elengi	46.64	6.16	3.56	41.67	1.97 ± 0.12	75.4	22.63
B. variegata	42.33	5.32	2.86	43.36	6.13 ± 0.31	77.7	16.17
P. integrifolia	44.24	5.75	2.43	43.32	4.26 ± 0.05	76.72	19.02
T. hodgsonii	46.82	6.34	2.67	42.69	1.48 ± 0.07	73.8	24.72
P. acerifolium	45.02	5.96	2.58	44.23	2.21 ± 0.12	76.4	21.39
V. altissima	46.11	6.1	1.65	44.28	2.10 ± 0.16	72.6	25.3
S. wallichii	45.01	5.9	1.72	45.68	1.69 ± 0.17	76.00	22.31
A. nepalensis	45.67	5.91	2.15	44.91	1.36 ± 0.08	73.11	24.53
Q. lanata	48.19	6.23	1.55	44.03	0.95 ± 0.13	72.07	26.98
Q. leucotrichophora	46.00	6.26	1.32	44.93	1.29 ± 0.02	73.3	25.41
R. arboreum	46.99	6.53	2.11	44.37	0.89 ± 0.36	73.8	25.31
M. esculenta	44.19	6.13	2.45	45.98	1.05 ± 0.05	75.4	23.55
E. acuminata	46.89	6.08	1.91	43.44	1.18 ± 0.42	73.36	25.46

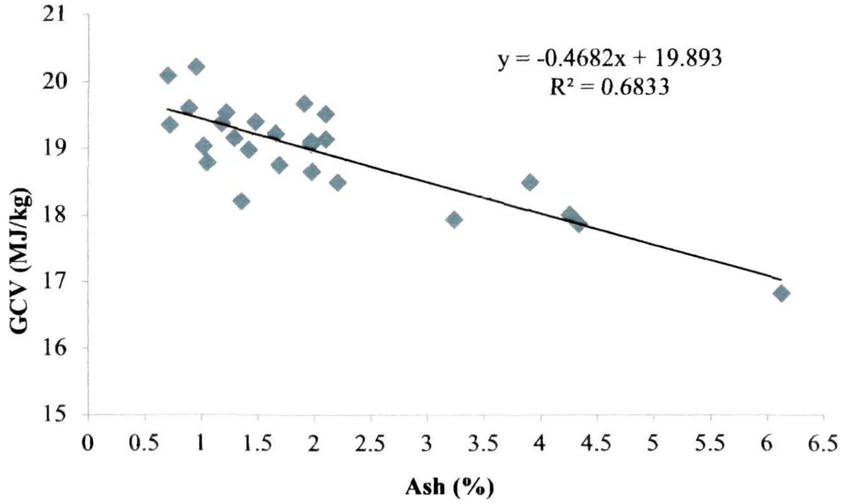


Figure 4.2: Relationship between ash content and GCV

In the present investigation (Table 4.7), carbon content of the studied fuelwood species varied from 42.33 to 48.19% whereas hydrogen content varied from 5.32 to 6.53%. Carbon content was highest in *Q. lanata* (48.19 %) and was lowest in *B. variegata* (42.33%). Hydrogen content was highest in *R. arboreum* (6.53%) with lowest value in *B. variegata* (5.23%). Oxygen content of the fuelwood species varied from 41.67 to 46.14% and was highest in *M. semiserrata* (46.14%) and lowest in *M. elengi* (41.67%). Nitrogen content varied between 1.32 - 3.56 % and was highest in *M. elengi* (3.56%) whereas, lowest in *Q. leucotrichophora* (1.32%).

The present study reveals that GCV (Table 4.2 and Table 4.7) of fuelwood species increases with the increase in carbon and hydrogen contents. Similar result was also reported by Sheng and Azevedo [17]. The heat content is related to the oxidation state of the fuelwood species in which carbon atoms generally dominate and overshadow small variations of hydrogen content [33]. A positive relationship between carbon content and GCV is shown in Figure 4.3. Tillman [23] also observed a positive correlation between GCV and carbon content. On the other hand, nitrogen does not contribute to the heating value rather it pollutes the environment by releasing oxides of nitrogen [34-35]. From the results (Table 4.7) it can be said that the tree species under investigation may not create significant problem of NOx pollution during their burning.

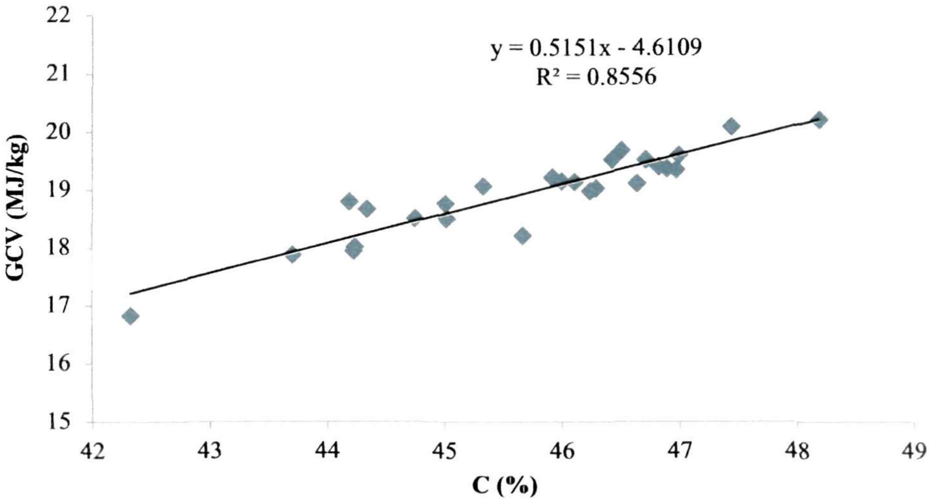


Figure 4.3: Relationship between Carbon content and GCV

4.4.2 Biochemical composition and Extractive content

The caloric content of wood is dependent on its biochemical constituents such as cellulose, hemicellulose, lignin, extractives and ash forming minerals. Fuwape [36] reported the influence of biochemical constituents on heating value of wood. Softwood of Pinus species were reported to contain relatively higher percentage of resin, wax and lignin which are responsible for their high heat of combustion [37-41]. The process of combustion involves the thermal degradation of the fuel and subsequent oxidation of the products. Cellulose and hemicellulose which are composed entirely of sugar units have a relatively low heat content because of their high level of oxidation while lignin and extractives have a lower degree of oxidation and a considerably higher heat of combustion [42]. It has been reported that the quality of woody feedstock may have an impact on the efficiency of some energy conversion systems [43]. Wood with high holocellulose content and low proportion of bark content is preferred for bioconversion processes, while wood with high lignin content is desirable for thermochemical processes [44]. Generally, softwoods typically contain 40 - 44 % cellulose, 26 – 32% hemicelluloses, and 25 – 35 % lignin. Hardwoods generally contain about 40 – 44 % cellulose, 15 – 35% hemicelluloses, and 18 – 25% lignin [45].

In this part of the study, biochemical constituents such as cellulose, hemicellulose, lignin, Organic extractives content (OEC), Hot water extractives content (HEC) and Total extractives content (TEC) of the wood samples of each of the tree species were determined and their effects on the heating values of the woods are discussed. The results of the biochemical constituents of the samples are presented in Table 4.8.

From Table 4.8, it is seen that cellulose content in fuelwood species varied from 43.51 to 53.37%. Cellulose content was highest in *A. nepalensis* (53.37%) whereas lowest in *Q. leucotrichophora* (43.51%). Hemicelluloses content varied from 21.52 - 31.74% and was highest in *Q. leucotrichophora* (31.74%) whereas, lowest in *A. nepalensis* (21.52 %). Likewise, lignin content varied from 21.09 -27.34 % and was highest in *Q. lanata* (27.34%) whereas, lowest in *B. variegata* (21.09 %). In the present investigation, it is seen from the Table 4.2 and Table 4.8 that GCVs of fuelwood species increased with the increase in lignin content. *Q. lanata* with higher lignin content of 27.34% corresponded to higher GCV of 20.22 MJ/kg whereas, *B. variegata* with lower lignin content of 21.09 % corresponded to the lower GCV of 16.83 MJ/kg. This can be attributed to the fact that lignin is rich in carbon and hydrogen (which are the main heat producing elements) and hence lignin content undeniably influences the GCV of fuelwood more than that of holocellulose [29, 46]. Moreover, lignin with its lower degree of oxidation has higher heat of combustion in comparison to cellulose and hemicelluloses [47]. Demirbus [48] and Jenkins *et al.* [49] reported that holocellulose (cellulose and hemicelluloses) has a GCV of ~ 18.60 MJ/kg whereas, lignin has a higher GCV of 23.26 – 26.58 MJ/kg. A positive relation between lignin content and GCV of fuelwood species can be observed from Figure 4.4, which was also in accordance with the findings of White [50].On the other hand, no relationship was observed between HHV and holocellulose of the fuelwood species, which is in agreement with the findings of Vargas-Moreno [51] and Demirbas [52].

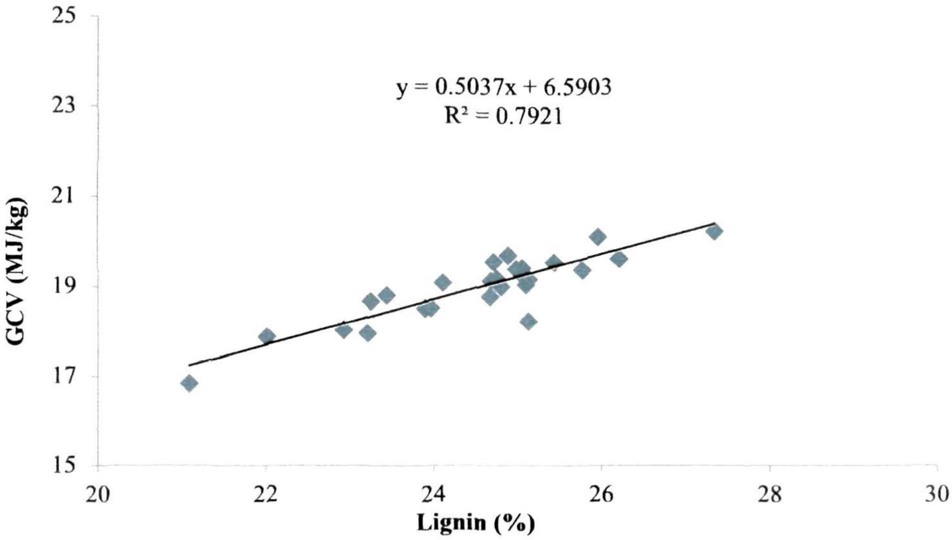


Figure 4.4: Relationship between lignin content and GCV

Extractives contribute to higher heating value in fuelwood [36, 42]. Extractives in fuelwood are non-structural aromatic compounds, which possess one or more phenolic hydroxyl group. In wood extractives include terpenes, tannins, resins, sugars, starches, fats, oils, proteins and organic acids, most of which are soluble in organic solvents. Boiling distilled water dissolves the inorganic salts, some organic acids and the carbohydrate components including starch and simple sugars [53-54]

In the present study (from Table 4.8), TEC of fuelwood species varied from 6.56 – 12.65% and was highest in *M. elengi* (12.65%) and lowest in *B. variegata* (6.56%). On the other hand, OEC was highest in *R. arboreum* (4.98%) and lowest in *B.*

variegata (1.77%). HEC was highest in *T. myriocarpa* (10.18%) and lowest in *L. polyantha* (2.84%)

Table 4.8: Biochemical constituents and Extractive contents of fuelwood species

Name of the species	Biochemical constituents (Oven dry wt.)			Extractive content (Oven dry wt.)		
	Cellulose (%)	Lignin (%)	Hemicelluloses (%)	OEC (%)	HEC (%)	TEC (%)
C. indica	51.25 ± 0.33	23.90 ± 0.97	24.85 ± 0.69	3.47	07.50	10.97
M. pustulata	45.10 ± 0.90	25.10 ± 0.72	29.80 ± 1.31	4.25	05.24	9.49
D. binectariferum	48.51 ± 1.73	24.72 ± 1.46	26.77 ± 0.34	3.82	06.89	10.71
B. retusa	50.29 ± 2.21	25.06 ± 1.16	24.65 ± 0.45	4.37	07.06	11.43
M. semiserrata	47.48 ± 0.52	23.25 ± 0.71	29.27 ± 1.21	3.61	06.33	9.94
C. australis	52.54 ± 0.31	24.80 ± 1.31	22.49 ± 0.95	4.05	05.29	9.34
D. procerum	48.55 ± 0.92	25.96 ± 2.20	25.49 ± 0.22	3.45	03.51	6.96
T. myriocarpa	53.21 ± 0.23	23.21 ± 0.76	23.58 ± 1.75	2.15	10.18	12.33
S. cerasoids	47.25 ± 1.18	25.44 ± 0.72	27.31 ± 0.84	4.31	05.96	10.27
K. calcyna	45.27 ± 0.88	24.89 ± 1.78	29.84 ± 0.21	4.72	02.98	7.70
M. phillipensis	52.38 ±1.49	22.01 ± 0.55	25.61 ± 0.55	2.91	05.37	8.28
A. odoratissima	46.52 ± 1.24	24.11 ± 0.74	29.37 ± 1.11	4.23	06.40	10.63
L. polyantha	47.20 ± 0.75	25.77 ± 1.26	27.03 ± 0.33	3.95	02.84	6.79
M. elengi	49.26 ± 0.48	24.68 ± 0.42	26.06± 0.62	3.66	08.99	12.65
B. variegata	47.36 ± 2.01	21.09 ± 0.77	31.55 ± 0.87	1.77	04.79	6.56
P. integrifolia	50.69 ± 0.98	22.93 ± 0.53	26.38 ± 0.38	3.68	06.95	10.63
T. hodgsonii	49.62 ± 0.14	25.06 ± 0.55	25.32 ± 1.24	3.80	07.75	11.55
P. acerifolium	46.59 ± 1.11	23.97 ± 0.50	29.44 ± 0.71	3.52	04.78	8.30
V. altissima	51.93 ± 0.29	25.13 ± 0.35	22.94 ± 0.26	4.12	04.67	8.79
S. wallichii	45.22± 0.68	24.67 ± 0.44	30.11 ± 0.39	3.50	03.17	6.67
A. nepalensis	53.37 ± 0.93	25.13 ± 0.94	21.52 ± 1.31	3.20	03.81	7.01
Q. lanata	49.48 ±1.47	27.34 ± 0.73	23.18 ± 0.26	4.89	03.71	8.60
Q. leucotrichophora	43.51 ± 0.67	24.75 ± 0.27	31.74 ± 0.54	2.18	05.34	7.52
R. arboreum	46.41± 1.78	26.21 ± 0.65	27.38 ± 0.41	4.98	05.48	10.46
M. esculenta	52.45 ± 0.43	23.44 ± 0.22	24.11 ± 0.84	3.75	05.85	9.60
E. acuminata	44.93 ±1.21	24.99 ± 1.37	30.08 ± 1.16	4.25	03.66	7.91

OEC- Organic extractive content, HEC- Hot water extractive content ,TEC- Total extractive content (OEC+ HEC)

In the present investigation, a positive relationship was observed between GCV and OEC whereas, the relationship between GCV and TEC as well as between HEC and GCV were obscured. Similar results were also reported by Nasser *et al.* [27] and Howard [40]. A positive relationship between OEC and GCV is shown in the Figure 4.5. There are many different types of extractives and their GCVs probably vary widely. Terpenes and resin are the two classes of extractives that significantly affect the GCV of fuelwood [40, 50].

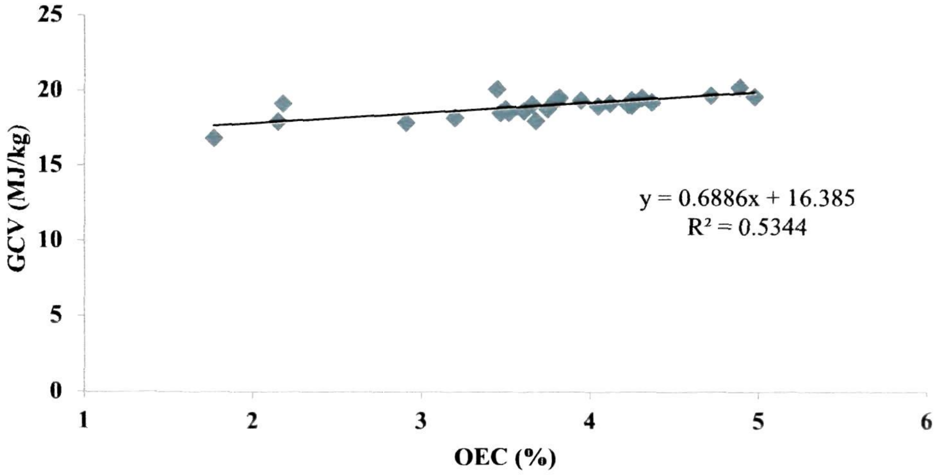


Figure 4.5: Relationship between OEC and GCV

4.5 Statistical Analysis of data

Pearson correlations for various parameters like GCV, carbon content (C), lignin content, ash content of the fuelwood species are shown in Table 4.9. Statistical analysis was carried out using SPSS software. This analysis aided in identifying the pairs of attributes with strong relationships.

The Pearson correlation analysis shows (Table 4.9) that, GCV mainly depends on carbon and lignin content. GCV showed a high significant correlation with C (r = 0.925) and Lignin (r = 0.879). This means that GCV is a function of C and Lignin. On the other hand GCV had a negative correlation with ash (r = - 0.837). This signifies that wood samples with high carbon and lignin will have high GCV and low ash content. Moreover, C and lignin too showed negative correlations with ash, r = - 0.810 and -0.825, respectively. Carbon showed high positive significant correlations with lignin (r = 0.937) which means that lignin is a primary constituent that contributes to the total carbon content in the wood samples.

Table 4.9: Pearson Correlations (2-tailed, n = 26) for Gross calorific value (GCV), carbon content(C) and lignin content

	GCV	C	Lignin	Ash
GCV	1	0.925**	0.879**	-0.837**
C	0.925**	1	0.937**	-0.810**
Lignin	0.879**	0.937**	1	-0.825**
Ash	-0.837**	-0.810**	-0.825**	1

**Correlation is significant at $p < 0.01$ (2-tailed)

Chapter 4: Part-V

4.6 Ash analysis of the fuelwood species

Wood combustion produces ash, which is highly alkaline [55]. Many ash-forming inorganic elements are associated with organic compounds in wood. During combustion the organic structures are decomposed and ash-formers are released. Mainly alkali and alkaline earth metals are released. Wood ash contains only trace amounts of heavy metals. Some of the alkaline earth metals leave the combustion zone as solid particles while the alkali metals are transported in vapour forms as oxides, hydroxides and chlorides. When wood is burned with coal, the alkalis can act as absorbents for the sulphur present in coal [56-57].

Wood ashes are found to be good fertilizers and can be used as mineral nutrients for forest and agricultural soils [58-59]. Wood ash is also used as a road base, an additive in cement production, a binding agent and an alkaline material for neutralization of acidic waste. Etiegni and Campbell [60] have reported that wood ash leachate contained 92% hydroxide and 8% carbonate, which create problems for its disposal.

The elemental analysis of wood ash is essential in order to develop recycling processes, which could expand its uses. The composition of ashes varies between different plants, depends on the combustion method and on the growing conditions from where the biofuel was taken [61].

Table 4.10 Elemental analysis of wood ash

Tree spices	Ash elements (mg/kg)										
	Ca	Mg	K	Na	P	Si	Mn	Cu	Zn	Cd	Pb
C. indica	18916.0	1993.4	7110.0	815.0	978.2	1198.6	605.3	75.46	155.00	0.84	37.50
M. pustulata	3584.6	292.8	2690.5	305.8	189.0	712.4	110.3	30.00	21.22	2.76	18.97
D. binectariferum	4432.9	997.8	1803.9	1105.2	859.7	1025.1	219.5	94.51	95.71	3.49	32.01
B. retusa	5554.1	698.3	3091.4	978.3	1008.4	1467.4	502.1	113.55	49.49	5.02	40.11
M. semiserrata	8754.0	1077.9	4152.4	336.3	808.6	817.0	167.7	44.92	66.75	2.89	12.34
C. australis	3780.2	548.3	3500.8	1344.9	670.9	906.4	276.0	63.39	105.27	1.88	43.42
D. procerum	2387.6	876.9	2512.7	323.6	267.5	854.0	156.6	12.97	27.92	4.37	52.34
T. myriocarpa	12887.7	1400.0	8878.4	234.2	904.1	1510.3	433.3	75.58	118.90	2.98	23.50
S. cerasoids	8900.0	369.7	6123.5	852.7	311.6	1698.4	285.9	103.93	99.48	3.73	42.79
K. calcyna	6232.5	1342.4	3907.8	898.6	778.8	1543.5	375.6	65.97	29.56	4.49	25.72
M. phillipensis	16783.7	1887.7	8768.6	1078.4	921.6	1370.9	431.1	96.34	100.89	1.67	33.20
A. odoratissima	8426.6	663.5	5239.7	737.2	787.0	698.7	365.4	115.45	77.65	0.94	12.98
L. polyantha	2472.8	418.2	2269.9	453.5	334.9	498.4	198.0	67.21	108.44	1.12	13.34
M. elengi	9115.4	834.6	3506.7	1907.6	558.3	730.9	300.0	65.34	35.52	2.15	15.55
B. variegata	23053.5	1189.0	8593.6	2243.0	845.7	1754.6	780.8	78.90	22.48	3.34	17.44
P. integrifolia	17688.8	1282.3	7833.5	2054.6	1100.4	1640.0	506.2	48.00	110.00	2.22	11.45
T. hodgsonii	5862.5	651.5	3145.0	986.4	745.7	852.0	367.0	86.67	25.11	3.49	9.00
P. acerifolium	7735.4	415.7	4537.8	1610.0	1244.0	710.4	647.5	90.54	127.44	5.67	15.50
V. altissima	8547.9	1095.8	5082.2	2101.3	638.5	659.0	437.9	101.23	95.50	0.96	29.40
S. wallichii	6398.6	959.0	3851.9	1500.0	829.1	700.9	510.0	98.39	88.09	7.12	39.94
A. nepalensis	4820.0	1103.6	2590.1	1253.4	931.7	1123.3	620.0	120.20	147.62	8.18	20.11
Q. lanata	2952.0	702.0	2009.4	590.9	350.5	573.0	221.6	46.00	54.28	5.42	10.49
Q. leucotrichophora	4291.8	962.7	3008.7	358.0	899.0	492.8	190.4	55.70	89.24	2.93	22.84
R. arboreum	2508.0	533.5	1542.9	229.3	452.7	390.2	150.0	81.93	93.92	4.29	15.56
M. esculenta	4500.0	482.9	2840.4	490.5	679.0	451.8	280.9	104.17	111.00	1.56	16.00
E. acuminata	5550.8	930.0	3593.6	1150.4	801.3	695.0	419.4	79.89	46.78	4.89	30.44

In the present investigation, ashes obtained from the 26 tree species under investigation were analysed for inorganic elements like Ca, K, Na, P, Mg, Mn, Si, Cu, Zn, Pb, Cd and results are presented in Table 4.10. Among all the tree species under study, Ca (23053.5 - 2387.6 ppm) was the most abundant ash element followed by K (8878.4-1542.9 ppm). The wood ash of *B. variegata* showed the highest value of Ca (23053.5 ppm) content followed by *C. indica* (18916 ppm), *P. integrifolia* (17688.8 ppm) and lowest value of Ca was found in *D. procerum* (2387.6 ppm). The range of P varied from 189.0-1244 ppm whereas, the range for Mg was 292.8 - 1993.4 ppm.Ca present in wood ash is an important liming agent while K, P and Mg are relevant plant nutrients [62]. The present investigation showed that the fuelwood species such as *B. variegata, C. indica, M. phillipensis* and *T. myriocarpa* possessed higher concentration of Ca and consequently their ashes were suitable as a fertilizer especially to ameliorate the acidity in soil [63]. From the Table 4.10, it is seen that ashes of wood species such as *B. variegata, C. indica, M. phillipensis* and *T. myriocarpa* were not only rich in Ca but also abundant in other plant nutrients like K, P and Mg

The range of Na, Mn and Si found in the present study were 2243.0 - 229.3 ppm, 780.8-110.3 ppm and 1754.6 -390.2 ppm respectively (Table 4.10).

Cu and Zn are essential trace elements for plants, with negative effects only in high concentrations, while Cd and Pb are toxic elements even at low concentrations [64]. The range of Cu, Zn, Pb and Cd in the present study were 120.20 -12.97 ppm, 147.62 - 21.22 ppm, 52.34 - 9.00 ppm and 8.18 - 0.84 ppm, respectively (Table 4.10). The pollutant concentration limit for some of the heavy metals (for land application) as approved by US-EPA (40 CFR part 503.13) [65] are Cd-39 mg/kg, Cu-1500 mg/kg, Pb-300 mg/kg, Zn-2800 mg/kg. From Table 4.10, it can be inferred that the values for Cu, Zn, Pb and Cd were well below the limits as reported in US- EPA (40 CFR part 503.13) [65].

Ash is of serious concern in biomass combustion as it causes slagging, bed agglomeration, fouling and corrosion in the combustion devices, which ultimately degrades its performance and severely damages the firing equipment [66]. Ca and Mg normally increase the melting temperature of ashes, while K and Na decrease it. This can cause sintering or slag formation in the combustion chamber [67]. Table 4.10 reveals that ashes of wood species like *V. altissima, M. elengi, B. variegata* and *P. integrifolia* possessed higher Na concentration. On the other hand higher concentration of K was found in ashes of *M. phillipensis, T. myriocarpa, B. variegata, P. integrifolia* and *C. indica*

Chapter 4: Part-VI

4.7 Ranking of fuelwood species on the basis of Combustion Characteristic Factor (CCF)

4.7.1 *Thermogravimetric analysis (TGA)*

Thermogravimetric analysis (TGA) has been an extensively used technique for studying the combustion behavior/profile of fuelwood species [68]. TGA records the weight loss of a sample against time and temperature. A plot of the rate of weight loss of sample while burning, against uniformly rising temperature under oxidizing atmosphere is referred to as 'burning profile'. The information generated from the burning profile of a fuel is useful for understanding its behavior during the combustion process [68-69].

In the present study TG/DTG curves or burning profiles of 26 fuelwood species are presented in Figure 4.6 (a-z). Three major weight loss stages were observed for all the investigated fuelwood species. The initial stage of weight loss between the temperature ranges of ~ 42-120°C was due to the moisture loss. In the burning profile, second and third weight loss stages were named as volatilization and burning zone (second zone) and char burning zone (third zone), respectively [70]. Temperature range of weight loss (for both second and third weight loss stages) for the fuelwood species are listed in Table 4.11. The temperature range observed for volatilization and burning zone was 181.19 - 390.48°C while 377.23 - 506.63°C for the char burning zone.

Wood degradation temperature is related to thermal stability of its individual constituents (cellulose, hemicelluloses and lignin) [71]. During combustion, the weight loss of fuelwood species in the second zone is due to total decomposition of hemicelluloses and cellulose accompanied with partial decomposition of lignin whereas, the third stage of weight loss is due to the decomposition of the remaining lignin and combustion of char residues [72]. Kim *et al.* [73] reported that the degradation of hemicelluloses, cellulose and lignin occurs between the temperature range of 180 - 350°C, 275 - 350°C and 250 - 500°C, respectively. When compared to cellulose and lignin, hemicelluloses are thermally and chemically less stable [74]. The lower stability of hemicellulose in thermal decomposition is attributed to its chemical structure (random amorphous structure) [75-76]. In contrast, the thermal stability of cellulose is higher due to its high degree of polymerization and crystalline nature [76]. The thermal stability of lignin is very high in comparison to cellulose and hemicellulose, because it is composed of three kinds of benzene-propane units, being heavily cross-linked and having very high molecular weight [75-76].

The results of combustion parameters such as ignition temperature, peak temperature and maximum combustion rate are shown in the Table 4.11. The ignition temperature (T_i) is one of the most important parameter of a burning profile. It corresponds to the point at which the burning profiles under goes a rapid rise [77]. Ignition temperature depends on early release of volatiles during combustion of wood [78]. Holocellulose portion of wood is mainly responsible for volatile formation [31-32]. The ignition temperature was lowest in *P. acerifolium* (259.42°C) and highest in *A. nepalensis* (293.62°C) (from Table 4.11). A higher ignition temperature is related to low holocellulose content and vice versa. Consequently, a higher holocellulose content of 76.03% corresponds to the former whereas; the lower holocellulose content of 74.87% corresponds to the later.

Peak temperature and maximum combustion rate are two other significant parameters of a burning profile. The peak temperature is defined as the temperature where the rate of weight loss is maximal due to combustion and is considered as an indicator of reactivity of the fuelwood species [79]. On the other hand, the rate of weight loss at the peak temperature in the burning profile is known as maximum combustion rate [77].

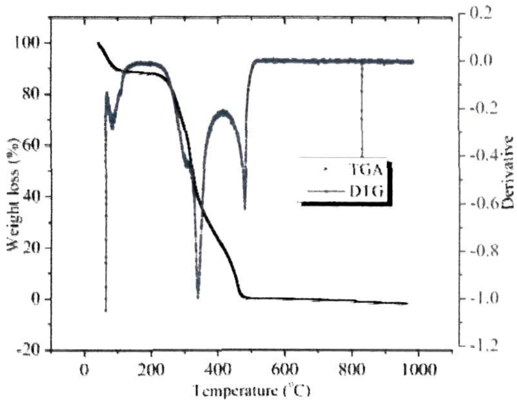


Figure 4.6 (a): TG/DTG curve of *C. indica*

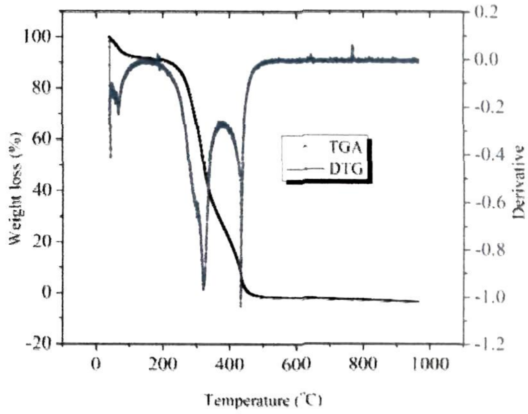


Figure 4.6 (b): TG/DTG curve of *M. pustulata*

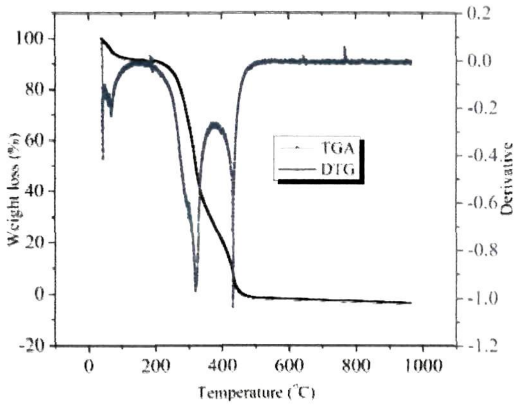


Figure 4.6 (c): TG/DTG curve of *D. binectariferum*

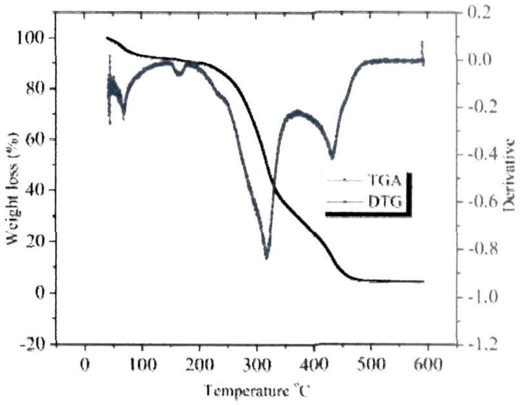


Figure 4.6(d): TG/DTG curve of *B. retusa*

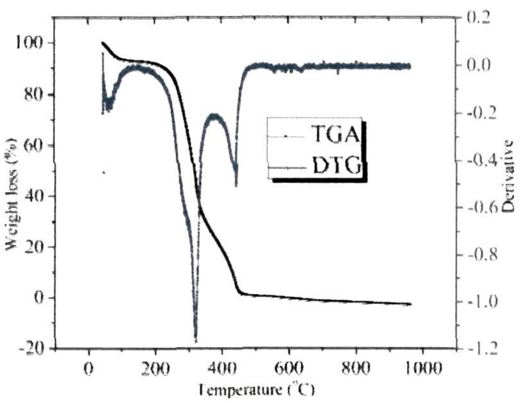


Figure 4.6 (e): TG/DTG curve of *M. semiserrata*

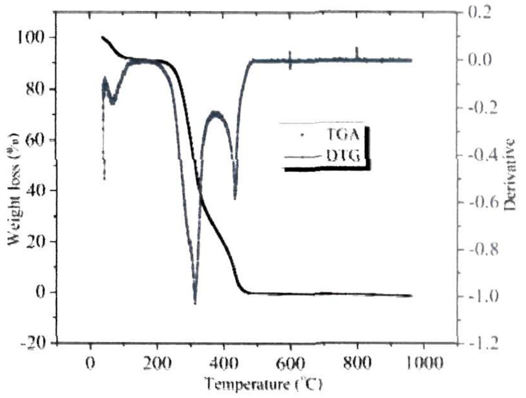


Figure 4.6 (f): TG/DTG curve of *C. australis*

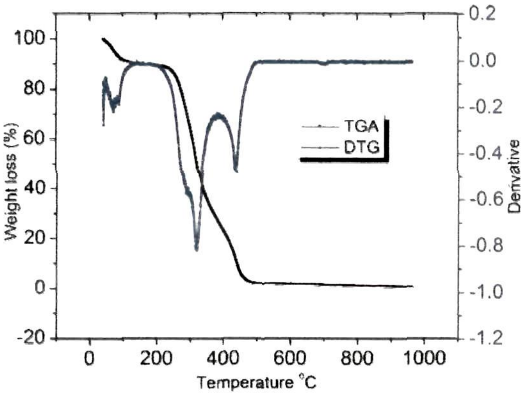


Figure 4.6 (g): TG/DTG curve of *D. procerum*

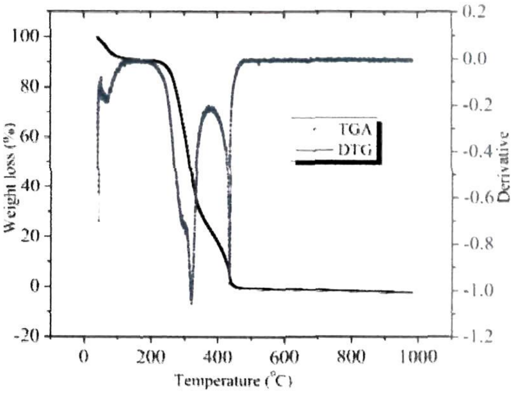


Figure 4.6 (h): TG/DTG curve of *T. myriocarpa*

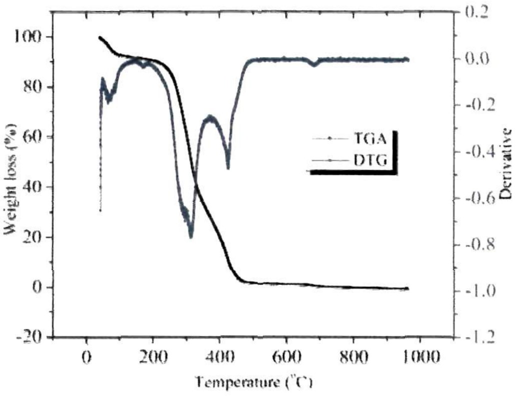


Figure 4.6 (i): TG/DTG curve of *S. cerasoids*

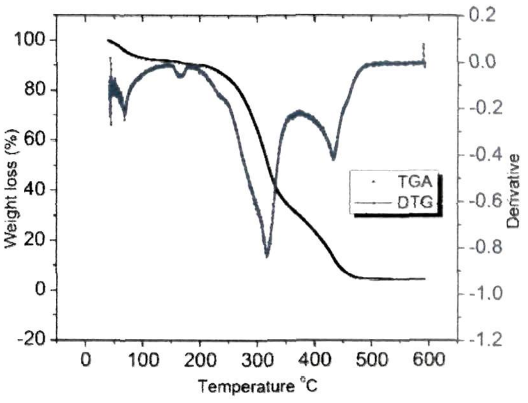


Figure 4.6(j): TG/DTG curve of *K. calcyna*

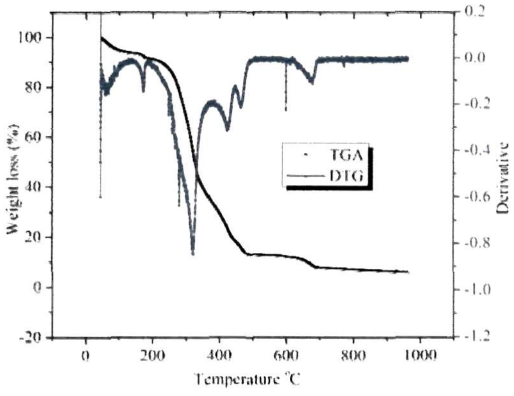


Figure 4.6 (k): TG/DTG curve of *M. phillipensis*

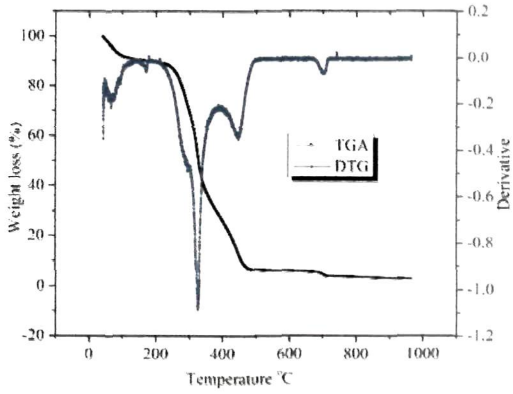


Figure 4.6(l): TG/DTG curve of *A. odoratissima*

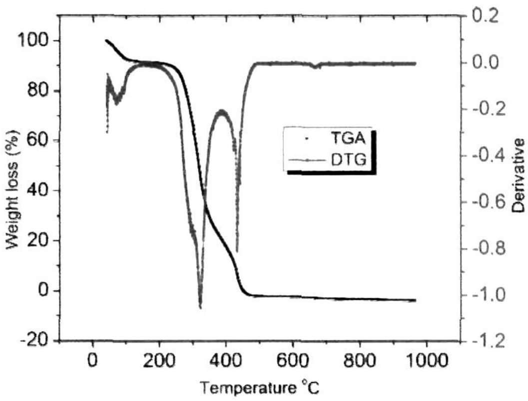


Figure 4.6 (m): TG/DTG curve of *L. polyantha*

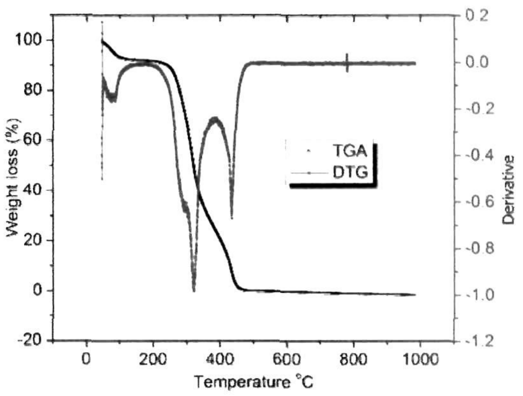


Figure 4.6 (n): TG/DTG curve of *M. elengi*

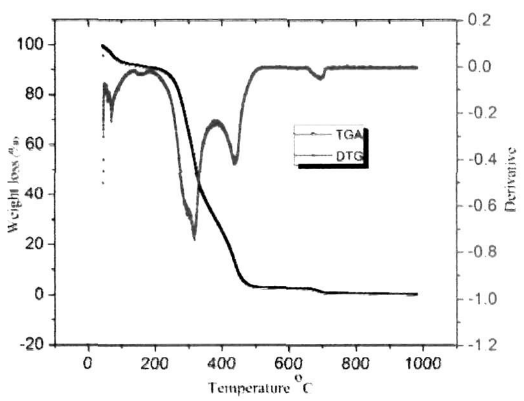


Figure 4.6 (o): TG/DTG curve of *B. variegata*

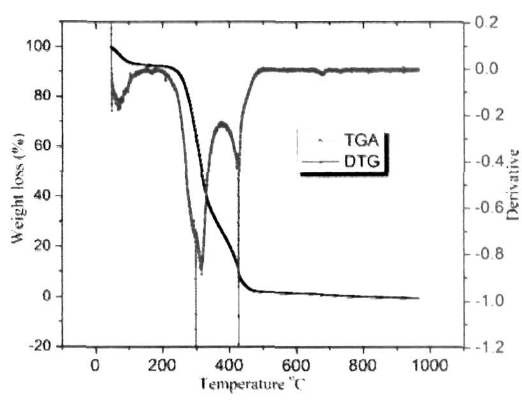


Figure 4.6 (p): TG/DTG curve of *P. integrifolia*

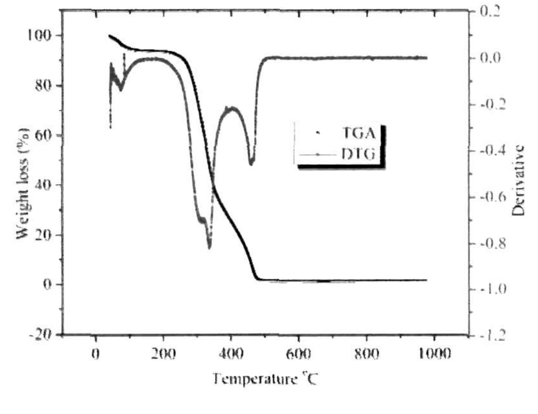


Figure 4.6 (q): TG/DTG curve of *T. hodgsonii*

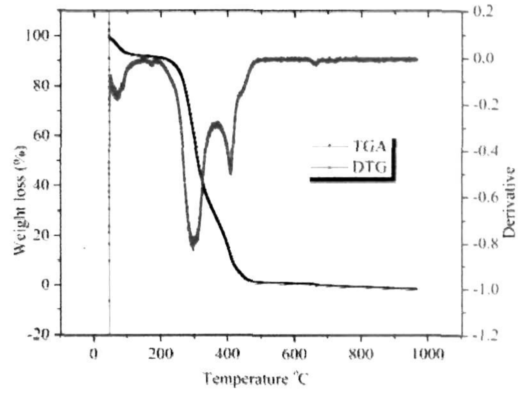


Figure 4.6 (r): TG/DTG curve of *P. acerifolium*

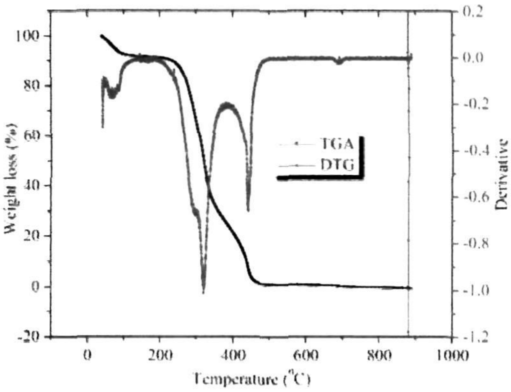


Figure 4.6 (s): TG/DTG curve of *V. altissima*

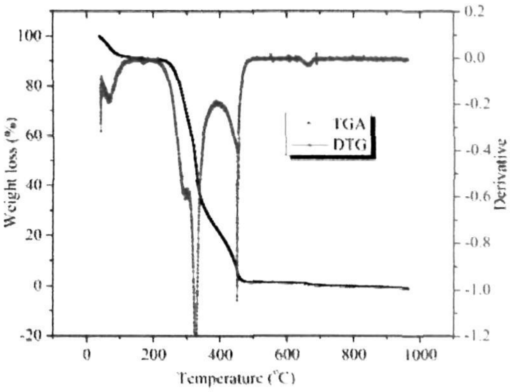


Figure 4.6 (t): TG/DTG curve of *S. wallichii*

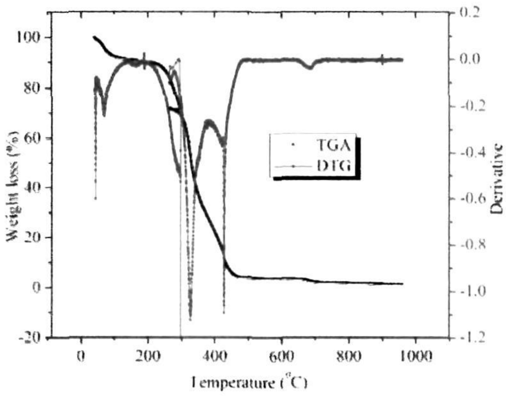


Figure 4.6 (u): TG/DTG curve of *A. nepalensı*

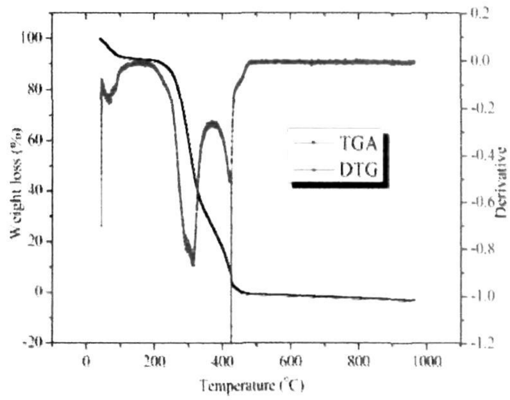


Figure 4.6 (v): TG/DTG curve of *Q. lanata*

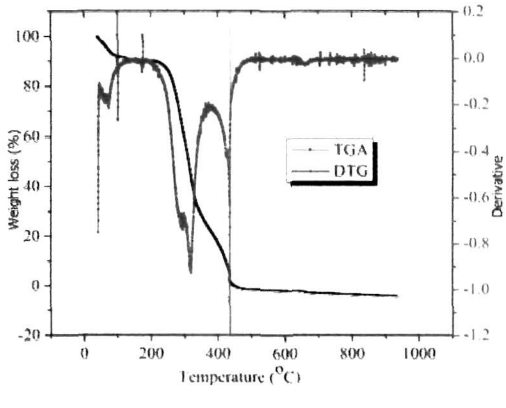


Figure 4.6 (w): TG/DTG curve of *Q. leucotrichophora*

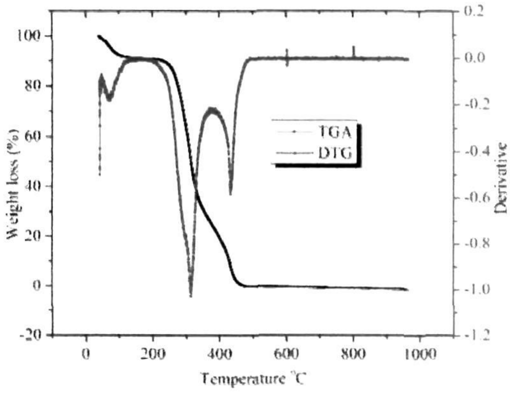


Figure 4.6 (x): TG/DTG curve of *R. arboreum*

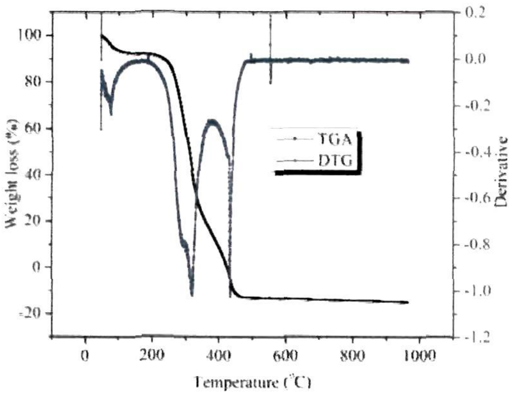


Figure 4.6 (y): TG/DTG curve of *M. esculanta*

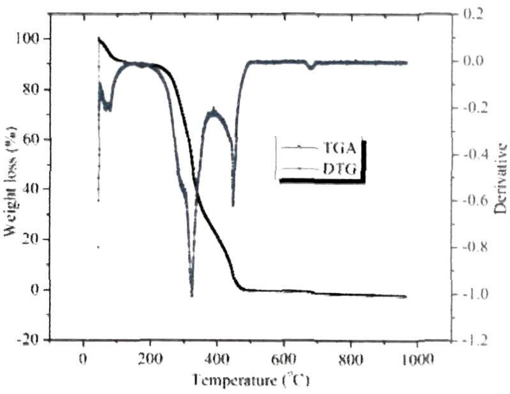


Figure 4.6 (z): TG/DTG curve of *E. acuminata*

Figure 4.6 (a-z) TG/DTG curves of fuelwood species

The peak temperatures for volatilization and burning zone, and char burning zone [Figure 4.6 (a-z) and Table 4.11] were highest in *T. hodgsonii* (327.45°C and 456.08°C, respectively), while lowest in *P. acerifolium* (296.49°C and 404.60°C, respectively). Fuelwood species having lower peak temperature shows high reactivity and vice versa. *P. acerifolium* exhibited lowest peak temperatures in volatilization and burning zone, and char burning zone, respectively and consequently was most reactive species in the respective zones. Maximum combustion rates for volatilization and burning zone, and char burning zone were highest in *S. wallichii* (14.94 % min^{-1}) and *R. arboreum* (13.20 % min^{-1}), respectively while lowest in *B. variegata* (8.52 % min^{-1}) and *M. phillipensis* (3.00% min^{-1}), respectively. The difference in the maximum combustion rates among fuelwood species can be attributed to the differences in their physico-chemical properties [80].

Table 4.11 Summary of TGA

Name of the species	Volatilization and burning zone				Char burning zone		
	Ignition temperature T_i (°C)	Peak temperature (°C)	Maximum combustion rate, $(dw/dt)_{max}$ (%min^{-1})	Temperature range (°C)	Peak temperature (°C)	Maximum combustion rate, $(dw/dt)_{max}$ (%min^{-1})	Temperature range (°C)
C. indica	288.20	316.81	11.94	216.86-377.23	455.76	05.76	408.20-490.32
M. pustulata	281.10	321.44	13.02	188.38-364.23	433.08	11.76	385.52-485.34
D. binectariferum	281.18	322.09	10.92	190.87-364.23	428.38	14.10	389.12-493.64
B. retusa	270.96	317.90	10.38	186.12-360.80	434.35	03.90	378.87-491.12
M. semiserrata	281.01	321.21	13.08	188.38-366.72	442.76	04.80	392.71-481.75
C. australis	264.06	312.76	10.74	184.26-361.88	425.99	06.18	379.86-490.39
D. procerum	277.06	321.38	14.16	189.49-367.83	435.57	09.42	389.12-478.30
T. myriocarpa	264.38	314.47	08.58	181.19-358.43	425.89	04.38	383.31-488.94
S. cerasoids	274.37	319.17	10.08	194.47-372.53	435.57	04.56	395.20-496.12
K. calcyna	290.36	323.87	13.98	200.27-377.23	447.46	05.94	401.01-506.63
M. phillipensis	279.20	324.05	08.94	195.57-360.64	424.79	03.00	391.61-495.02
A. odoratissima	290.56	326.35	12.24	197.78-373.64	444.97	03.12	399.90-492.53
L. polyantha	280.35	320.27	13.44	207.46-368.94	430.86	10.62	395.20-483.13
M. elengi	279.52	320.27	11.82	193.08-368.94	430.87	06.24	390.50-484.23
B. variegata	267.47	316.68	08.52	184.79-371.42	437.78	04.02	390.50-504.42
P. integrifolia	268.70	314.80	08.71	203.87-365.34	425.89	06.70	386.91-485.34
T. hodgsonii	276.32	327.45	11.50	196.15-390.48	456.08	07.15	408.50-500.54
P. acerifolium	259.42	296.49	09.24	195.57-353.45	404.60	04.86	377.23-475.94
V. altissima	278.17	318.96	13.56	187.16-367.11	441.12	07.68	391.95-485.73
S. wallichii	293.26	326.16	14.94	214.65-378.61	449.67	08.49	407.09-478.15
A. nepalensis	293.62	326.35	10.55	199.17-367.83	428.38	09.78	392.71-483.13
Q. lanata	267.68	309.75	09.72	217.98-355.48	427.74	11.64	382.92-470.29
Q. leucotrichophora	270.31	319.17	11.58	197.78-365.34	430.89	5.64	389.12-474.83
R. arboreum	275.58	313.08	14.34	198.06-366.72	433.08	13.20	388.01-483.13
M. esculenta	268.55	315.57	11.70	183.68-366.72	430.93	11.94	390.50-480.64
E. acuminata	282.11	319.87	12.42	197.78-375.02	447.41	06.36	397.41-485.34

Table 4.12 Calculation of CCF (S)

Name of the species	Maximum combustion rate, $(dw/dt)_{max}$ ($\%min^{-1}$)	Mean combustion rate, $(dw/dt)_{mean}$ ($\%min^{-1}$)	Ignition Temperature T_i (°C)	Burnout temperature T_{BO} (°C)	$S\times10^{-7}$	Rank
C. indica	11.94	2.93	288.20	490.32	08.59	18
M. pustulata	13.02	3.26	281.10	485.34	11.06	9
D. binectariferum	14.01	2.98	281.18	493.64	10.69	10
B. retusa	10.38	2.79	270.96	491.12	08.03	20
M. semiserrata	13.08	3.04	281.01	481.75	10.45	11
C. australis	10.74	3.13	264.06	490.39	09.83	13
D. procerum	14.16	3.19	277.06	478.03	12.39	3
T. myriocarpa	08.58	2.79	264.38	488.94	07.00	23
S. cerasoids	10.08	2.92	274.37	496.12	07.88	22
K. calcyna	13.98	2.83	290.36	503.63	09.30	16
M. phillipensis	08.94	2.68	279.20	495.02	06.20	26
A. odoratissima	12.24	2.88	290.56	492.53	08.47	19
L. polyantha	13.44	3.21	280.35	483.13	11.36	7
M. elengi	11.82	3.28	279.52	484.23	10.24	12
B. variegata	08.52	2.80	267.47	504.42	06.61	25
P. integrifolia	08.71	2.81	268.70	485.43	06.98	24
T. hodgsonii	11.50	3.22	276.32	500.54	09.68	15
P. acerifolium	09.24	3.11	259.42	475.94	08.97	17
V. altissima	13.56	3.10	278.17	485.73	11.18	8
S. wallichii	14.94	3.15	293.26	478.15	11.44	6
A. nepalensis	10.55	3.13	293.62	483.13	07.92	21
Q. lanata	11.64	3.32	267.68	470.29	11.46	5
Q. leucotrichophora	13.20	3.42	270.31	474.83	13.01	1
R. arboreum	14.34	3.15	275.58	483.13	12.31	4
M. esculenta	11.94	3.62	268.55	480.64	12.46	2
E. acuminata	12.42	3.02	282.11	485.34	09.71	14

The results for maximum combustion rate $(dw/dt)_{max}$, ignition temperature (T_i), mean combustion rate $(dw/dt)_{mean}$, burnout temperature (T_{BO}), combustion characteristics factor (CCF,S) and rank obtained by fuelwood species on the basis of CCF are presented in Table 4.12. The burnout temperature is an important combustion parameter, which indicates the completion of combustion process. It is defined as the temperature where the rate of weight loss consistently decreases to less than 1%/min [81]. In the present investigation burnout temperature was highest for *B. variegata* (504.42°C) and lowest for *Q. lanata* (470.29°C). The higher burnout temperature of *B. variegata* is attributed to the higher ash content (6.13%) in it (Table 4.2) [82]. Biomass fuel having higher burnout temperatures are more difficult to burn and require longer residence time or higher temperature to achieve complete combustion [83]. Therefore, a fuelwood having low burnout temperature (shorter burning time) exhibits better combustion performance.

In the study, mean combustion rate was found to be highest for *M. esculenta* (3.62 °C) and lowest for *M. phillipensis* (2.68°C).

The combustion characteristic factor (CCF) is a parameter which is used to compare the combustion performance of fuelwood species. CCF(S) was calculated by using the method reported by Jiricek *et al.* [84] and Qing., *et al.* [85] where maximum combustion rate and mean combustion rate are considered as positive criteria whereas, square of ignition temperature and burnout temperature are considered as negative criteria. Higher the CCF value better is the combustion performance of the fuelwood. According to a previous report biomass fuels having CCF values greater than 2 shows good burning performance [70]. In the investigation, the range of CCF for fuelwood species varied from 6.20-13.01 and was found to be highest in *Q. leucotrichophora* (13.01) while lowest in *M. phillipensis* (6.20). Since in our study all the fuelwood species had CCF >2, we concluded that all of them possessed good burning performance

From Table 4.12, on the basis of CCF (S) the fuelwood species exhibited better combustion performance in descending order is as follows:

Q. leucotrichophora, M. esculenta, D. procerum, R. arboreum, Q. lanata, S. wallichii, L. polyantha, V. altissima, M. pustulata, D. binectariferum, M. semiserrata, M. elengi, C. australis, E. acuminata, T. hodgsonii, K. calcyna, P. acerifolium, C. indica, A. odoratissima, B. retusa, A. nepalensis, S. cerasoids, T. myriocarpa, P. integrifolia, B. variegata, M. phillipensis.

Chapter 4: Part-VII

4.8 Overall ranking (OR) of fuelwood species on the basis of PWC, FVI and CCF.

An overall ranking (OR) of studied fuelwood species was obtained on the basis of PWC, FVI (II) and CCF ranks as presented in Table 4.13 under column VI. The total score for individual tree species was calculated by addition of the respective

Table 4.13: Overall ranking (OR)

Fuelwoods species	Ranking as per FVI (II)	Ranking as per CCF	Ranking as per PWC	Total score	Overall * Ranking (OR)
C. indica	23	18	25	66	20
M. pustulata	4	9	6	19	6
D. binectariferum	8	10	8	26	8
B. retusa	17	20	14	51	14
M. semiserrata	16	11	18	45	13
C. australis	15	13	10	38	11
D. procerum	2	3	1	06	1
T. myriocarpa	22	23	19	64	19
S. cerasoids	18	22	20	60	18
K. calcyna	19	16	21	56	16
M. phillipensis	24	26	22	72	21
A. odoratissima	14	19	12	45	13
L. polyantha	7	7	3	17	5
M. elengi	12	12	11	35	10
B. variegata	26	25	23	74	23
P. integrifolia	25	24	24	73	22
T. hodgsonii	10	15	15	40	12
P. acerifolium	21	17	17	55	15
V. altissima	13	8	2	23	7
S. wallichii	11	6	13	30	9
A. nepalensis	20	21	16	57	17
Q. lanata	1	5	1	07	2
Q. leucotrichophora	5	1	4	10	3
R. arboreum	3	4	5	12	4
M. esculenta	6	2	9	17	5
E. acuminata	9	14	7	30	9

*Overall ranking ranges from 1 (best) (lowest total score) to 23(worst) (highest total score).

PWC, FVI and CCF ranks.

The best overall ranking was ascertained to the species with lowest total score and vice- versa. On the basis of OR, the promising fuelwood species in descending order are as follows:

D. procerum, Q. lanata, Q. leucotrichophora, R. arboreum, L. polyantha ~ M. esculenta, M. Pustulata, V. altissima, D. binectariferum, S. wallichii ~ E. acuminata, M. elengi, C. australis, T. hodgsonii, A. odoratissima ~ M. semiserrata, B. retusa, P. acerifolium, K. calcyna, A. nepalensis, S. cerasoids, T. myriocarpa, C. indica, M. phillipensis, P. integrifolia, B. variegata.

References:

1. Abbot, P., *et al.* Defining Firewood quality: A comparison of quantitative and rapid appraisal technique to evaluate firewood species from a Southern Africa Savanna, *Biomass and Bioenergy* **12**(6), 429 –437, 1997.
2. Kataki, R., & Konwer, D. Fuelwood characteristics of indigenous tree species of north-east India, *Biomass and Bioenergy* **22**, 433 – 437, 2002.
3. Purohit, A. N., & Nautiyal, A. R. Fuelwood Value Index of Indian mountain tree species, *International Tree Crops Journal* **4**, 177-182, 1987.
4. Bhatt, B., & Badoni, A. Characteristics of some mountain shrubs and trees, *Energy* **15** (11), 1069-1070, 1990.
5. Bhatt, B.P., & Todaria, N.P. Fuelwood characteristics of some Indian mountain species, *Forest Ecology and Management* **47**(1-4), 363-366, 1992.
6. Jain, R. Fuel characteristics of some tropical trees of India, *Biomass and Bioenergy* **4**, 454-461, 1993.
7. Deka, D., *et al.* Ranking of Fuelwood Species by Fuel Value Index, *Energy Sources* **29**, 1499–1506, 2007.
8. Bhatt, B.P., *et al.* Characteristics of some firewood trees and shrubs of the North Eastern Himalayan region, India, *Renewable Energy* **29**, 1401–1405, 2004.
9. Nurmi, J. Measurement and evaluation of wood fuel, *Biomass and Bioenergy* **2** (1-6), 1992.
10. Hakkila, P. Polttohakepuun kuivuminer metsassa. Summary: Forest seasoning of wood intended for fuel chips, *Communication Institutes Forestalis Fenniae* **54** (4), 82s, 1962.
11. Tietema, T.M., *et al.* Characteristics of eight firewood species of Botswana, *Biomass and Bioenergy* **I** (1), 4146, 1991.
12. Shafizadeh, F. Basic principles of direct combustion, in Biomass Conversion Processes for Energy and Fuel, Sofer, S. S. and O. R. Zaborsky, eds., Plenum Press, New York, 1981.

13. The wood database, downloaded from http://www.wood-database.com/wood-articles/wood-and-moisture/on 13/04/2014.
14. Senelwa, K., and Sims, R.E.H. Fuel characteristics of short rotation forest biomass, *Biomass and Bioenergy* **17**, 127-140, 1999.
15. Wang, S., *et al.* Qualitative evaluation of fuelwood in Florida-A summary report, *Economic Botany* **36**(4), 381-388, 1982.
16. Lyons, J. G., *et al.* A procedure for estimating the value of forest fuels, *Biomass* **8**, 283 – 300, 1985.
17. Sheng, C., & Azevedo, J. L. T. Estimating the higher heating value of biomass fuels from basic analysis data, *Biomass and Bioenergy* **28**, 499–507, 2005.
18. Garcia, R., *et al.* Characterization of Spanish biomass wastes for energy use. *Bioresource Technology* **103**, 249–258, 2012.
19. Nhuchhen, D. R., & Salam, P. A. Estimation of higher heating value of biomass from proximate analysis: A new approach, *Fuel* **99**, 55–63, 2012.
20. Joseph, A. F., & Shadrach, O. A. Biomass yield and energy value of some fast growing multipurpose trees in Nigeria, *Biomass and Bioenergy* **12**, 101–6, 1997.
21. Mingle, J. G., & Boubel, R. W. Proximate fuel analysis of some western wood and bark, *Wood Science* **1**(1), 29 – 36, 1968.
22. Singh, B., & Khanduja, S. D. Wood properties of some firewood shrubs in northern India, *Biomass* **4**, 235–8, 1984.
23. Tillman, D. A. *Wood as an energy resource*, Academic Press, New York, 1978.
24. Demirbas, T., & Demirbas, C. Fuel Properties of Wood Species, *Energy Sources* **31**, 1464–1472, 2009
25. Munalula, F., & Meincken, M. An evaluation of South African fuelwood with regards to calorific value and environmental impact, *Biomass and Bioenergy* **33**, 415 – 420, 2009.

26. Montes, C.S., *et al.* Calorific value of ***Prosopis africana*** and ***Balanites aegyptiaca*** wood: Relationships with tree growth, wood density and rainfall gradients in the West African Sahel, *Biomass and Bioenergy* **35**, 346-353, 2011.
27. Nasser, R.A., *et al.* 2014.Fuel characteristics of *Vine purings* (*Vitis vinifera* L.) as a potential source for energy, *BioResource* **9** (1), 482-496, 2014.
28. Khider, T.O., & Elsak, O.T. Heat value of Four Hardwood Species from Sudan, *Journal of forest productions & industries* **1**(2), 5-9, 2012.
29. Vos, J. The Netherlands. Biomass Energy for Heating and Hot Water Supply in Belarus, project submitted to UNGP/GEF, 2005, downloaded from http://un.by/pdf/Study%20Tour%20Biofuel%20Report%20English.pdf on 22/07/2012
30. Haykiri-Acma, H., & Yaman, S. Comparison of the combustion behaviors of agricultural wastes under dry air and oxygen, World Energy Congress 2011-Sweden, 8-13 May 2011, Linkoping, Sweden, 251-256.
31. Rowell, R.M., *et al.* Thermal Properties, in *Handbook of Wood Chemistry and Wood Composites*, R.M. Rowell, eds., CRC press, USA, 2005.
32. Kandiyoti, R., *et al. Solid fuels and heavy hydrocarbon liquids; thermal characterization and analysis*, Elsevier, Great Britain, 2006.
33. Demirbas A. Combustion of Biomass, *Energy Sources* **29**, 549–561, 2007.
34. Nirmal Kumar, J. I., *et al.* An assessment of Indian fuelwood with regards to properties and environmental impact, *Asian Journal on Energy and Environment* **10** (02), 99-107, 2009.
35. Kumar, R., *et al.* Effect of tree age on calorific value and other fuel properties of Eucalyptus hybrid, *Journal of Forestry Research* **21**(4), 514-516, 2010.
36. Fuwape, J. A. Gross heat of combustion of Gmelina (*Gmelina arborea* Roxb.) chemical components, *Biomass* **19**, 281 – 287, 1989.

37. Martin, R. E. *Thermal and other properties of bark and their relationship to fire injury of tree stems*, Ph.D. Thesis, University of Michigan, Ann Arbor, 1963.
38. Hough, W.A. Caloric value of some forest fuels of the southern United States. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, Res. Note SE-120, 1969.
39. Howard, E. T. Some observations on southern pine needles as related to utilization, Final Report FS-SO-3201-1.36 USDA Forest Service, South Forest Experiment Station, Alexandria, LA, 1971.
40. Howard, E.T. Heat of combustion of various southern pine materials, *Wood Science* **5** (3), 194-197, 1973.
41. Koch, P. Utilization of the Southern Pines, in Agriculture Handbook , No.420, Vol.1, USDA Forest Service, Washington, DC, 1972.
42. Shafizadeh, F. Basic Principles of Direct Combustion, in *Biomass conversion processes for energy and fuel*, S. S. Sofer and O. R. Zaborsky, eds., Plenum Press, New York, pp. 105 – 112, 1981.
43. Butner, R. S., *et al.* Effect of biomass feedstock chemical and physical properties on energy conversion processes-Overview, Pacific Northwest Laboratory Paper 6765, vol.1, Richland, Washington DC, 1988.
44. Kenny, W. A. Variation in some chemical characterizes in three North American species of salix, in *Improvement of feedstock quality- Proceedings of an IEA/BA Task V Workshop*, Kenny, et al., eds., Toronto, Canada, , pp. 48 – 56, 1990.
45. Shmulsky, R., & Jones, P.D. *Forest Products and Wood Science: An Introduction*, Wiley-Blackwell, UK, 2011.
46. Telmo, C., & Lousada, J. The explained variation by lignin and extractive contents on higher heating value of wood, *Biomass and Bioenergy* **35**, 1663-1667, 2011.
47. Kumar M, *et al.* Effect of carbonisation conditions on the yield and chemical composition of Acacia and Eucalyptus wood chars, *Biomass and Bioenergy* **3**, 411–4171, 992.

48. Demirbas, A. Combustion characteristics of different biomass fuels, *Progress in energy and combustion science* **30**, 219–230, 2004.
49. Jenkins, B.M., *et al.* Combustion properties of biomass, *Fuel Processing Technology* **54**, 17–46, 1998.
50. White, R.H. Effect of lignin content and extractives on the higher heating value of wood, *Wood and Fiber Science* **19** (4), 446–452, 1987.
51. Vargas-Moreno, J.M., *et al.* A review of the mathematical models for predicting the heating value of biomass materials, *Renewable and Sustainable Energy Reviews* **16**, 3065– 3083, 2012.
52. Demirbas, A. Fuelwood Characteristics of Six Indigenous Wood Species from the Eastern Black Sea Region, *Energy Sources* **25**, 309–316, 2003.
53. Sjöström, E. *Wood chemistry-fundamentals and applications*, Academic press, Orlando, USA, 1993.
54. Butterfield, B. The structure of wood: Form and Function, in *Primary Wood Processing-Principles and Practice*, J. C. F Walker, eds., Springer, Dordrecht, the Netherlands, 2006.
55. Liodakis, S., *et al.* Ash properties of some dominant Greek forest species, *Thermochimica Acta* **437**,158–167, 2005.
56. Someswar, A. R., & Jain, A. K. Sulphur captures in combination bark boiler, *Tappi J*ournal **76** (7), 179-184, 1993.
57. Claussen, J. C., &. Rasmussen, J (1993). Co-firing of coal and straw in large boilers. IEE Conf. Publ. 385 (Renewable Energy Clean power 2001), pp. 43 – 48, 1993.
58. Naylor, M. L., & Schmidt, E. J. Agricultural use of wood ash as fertilizer and liming material, *Tappi* **69** (10), 114-119, 1986.
59. Lerner, ·R. B., & Utzinger, J. D. Wood ash as soil liming material, *HortScience* **21**(1), 76 – 78, 1986
60. Etiegni, L., & Campbell, A. G. (1991). Physical and chemical characteristics of wood ash, *Bioresource Technology* **37**, 173 – 178, 1991.

61. Sutcliffe, J. F., & Baker, D. A. *Plants and Mineral Salts*, 2nd ed., Institute of Biology Studies in Biology Series, No. 48, London, Edward Arnold., 1981.
62. Saajak, V.L., & Koppejan, J. (ed.). *The Handbook of Biomass Combustion and Co-firing*, Earthscan, London, U.K., 2008.
63. Demeyer, A., *et al.* characteristics of wood ash and influence on soil properties and nutrient uptake: An overview, *Bioresource Technology* **77**, 287–295, 2001.
64. Adriano, D. C. *Trace Elements in the Terrestrial Environment*, Springer-Verlag, New York, pp. 533, 1986.
65. US- EPA (Environmental Protection Agency), CFR, 40-protection of environment (Part 425 to 699), office of the federal register-national archives and records administration, Washington DC, 2003.
66. Werkelin, J., *et al.* Chemical forms of ash-forming elements in woody biomass fuels, *Fuel* **89**, 481–493, 2010.
67. Obernberger, I., *et al.* Chemical properties of solid biofuels—significance and impact, *Biomass and Bioenergy* **30**, 973–982, 2006.
68. Kumar, R., *et al.* Fuel properties and combustion characteristics of *Lantana camara* and *Eupatorium spp.*, *Current Science* **97**(6), 2009.
69. Saidur, R., *et al.* A review on biomass as a fuel for boilers, *Renewable and Sustainable Energy Reviews* **15**, 2262–2289, 2011.
70. Wang, C., *et al.* Thermogravimetric studies of the behavior of wheat straw with added coal during combustion, *Biomass and Bioenergy* **33**, 50– 56, 2009.
71. Poletto, M., *et al.* Materials Produced from Plant Biomass. Part I: Evaluation of Thermal Stability and Pyrolysis of Wood, *Materials Research* **13** (3), 375-379, 2010.
72. Safi, M. J., *et al.* Global degradation kinetics of pine needles in air, *Thermochimica Acta* **412**, 155–162, 2004.
73. Kim, H. S., *et al.* Thermal properties of bio-flour-filled polyolefin composites with different compatibilizing agent type and content, *Thermochimmica Acta* **451**, 181–188, 2006.

74. Brown, R. C. *Biorenwable Resources: Engineering New Products from Agriculture*, Iowa State Press, Ames 2003.
75. John, M. J., & Thomas, S. Biofibres and biocomposites, *Carbohydrate Polymers* **71**, 343–364, 2008.
76. Yang, H., *et al.* In-depth investigation of biomass pyrolysis based on three major components: hemicellulose, cellulose and lignin, *Energy Fuels* **20**, 388–393, 2006.
77. Demirbus, A. Fuel and Combustion Properties of Bio-wastes, *Energy Sources* 27, 451–462, 2005.
78. Vamvuka, D., & Sfakiotakis, S. Combustion behaviour of biomass fuels and their blends with lignite, *Thermochimica Acta* **526** (1-2), 192– 199, 2011.
79. Gudka, B. A. Combustion Characteristics of some Imported Feedstocks and Short Rotation Coppice (SRC) Willow for UK Power Stations, Thesis, The University of Leeds, 2012.
80. Haykiri-Acma, H. Combustion characteristics of different biomass materials, *Energy Conversion and Management* **44**, 155–162, 2003.
81. Wilson, L., et al. Thermal characterization of tropical biomass feedstocks, *Energy Conversion and Management* **52**, 191–198, 2011.
82. Kok, M. V., & Özgür, E. Thermal analysis and kinetics of biomass samples, *Fuel Processing Technology* **106**, 739-743, 2013.
83. Kastanaki, E., &, Vamvuka, D. A comparative reactivity and kinetic study on the combustion of coal–biomass char blends, *Fuel* **85**, 1186–1193, 2006.
84. Jiricek, I., *et al.* A thermogravimetric study of the behavior of biomass blends during combustion, *Acta Polytechnica* **52**(3), 2012.
85. QING, W., *et al.* Thermogravimetric analysis of the combustion characteristics of oil shale semi-coke/biomass blends, *Oil Shale* **28** (2), 284–295, 2011.

Chapter 5

Summary and conclusion

Chapter 5

Summary and Conclusion

The state of Arunachal Pradesh is located in the North Eastern frontier of India with significant plant diversity owing to its unique climatic and typographical profile. The state is home to countless varieties of woody plants which have served and catered to the primary energy demands of its peoples since time immemorial. But however, till date, no systematic study was undertaken to study the potential fuelwood species of the region for futuristic energy plantation point of view. The present investigation was undertaken to identify some potential indigenous fuelwood species of Arunachal Pradesh based on local users knowledge. The tree species selected for the present investigation were *Castanopsis indica, Macaranga pustulata, Dysoxylum binectariferum, Bridelia retusa, Myrsine semiserrata, Celtis australis, Dysoxylum procerum, Terminalia myriocarpa, Syzygium cerasoides, Kydia calycina, Mallotus phillipensis, Albizia odoratissima, Litsea polyantha, Mimusops elengi, Bauhinia variegata, Premna integrifolia, Talauma hodgsonii, Pterospermum acerifolium, Vitex altissima, Schima wallichii, Alnus nepalensis, Qurcus lanata, Qurcus leucotrichophora, Rhododendron arboreum, Myrica esculenta* and *Ehretia acuminata*

The important fuelwood quality criteria considered by the local users of Arunachal Pradesh for selection of suitable fuelwood species were identified with the help of key informers and a ranking matrix was drawn from the pair-wise comparison (PWC) of these fuelwood species. The PWC ranking of fuelwood species was further compared with that obtained from Fuel value index (FVI) and Combustion characteristic factor (CCF). Finally, Overall ranking (OR) of studied fuelwood species was obtained on the basis of PWC, FVI and CCF ranking.

From the ranking matrix (PWC ranking) of these 26 tree species using 10 quality criteria (fast drying, hot flame, ember production, flame not smoky, easily flammable, non-sparking, weight when dry, easiness of splitting, low moisture when fresh cut and insect/termite resistance) *Q. lanata* and *D. procerum* (with same ranking value) were found to be the best and *C. indica* the least favorable.

According to PWC ranking, fuelwood species having the fastest drying rate were *R. arboreum, A. nepalensis* and *L. polyantha*. *Q. leucotrichophora*, *V. altissima*, and *D. procerum* produced maximum hot flame during burning. The suitable species found for ember production as preferred by the respondents were *Q. lanata*, *V. altissima*, and *D. procerum*. Fuelwood species such as *C. indica*, *B. variegata*, *P. integrifolia* and *S. cerasoids* were found to produce comparatively more smoke during combustion in comparison to the other species. *V. altissima, D. procerum, L. polyantha* and *Q. lanata* were found to be easily flammable as identified by the local users. With the exception of *C. indica*, *B. variegata*, *P. integrifolia* and *S. cerasoids* other studied fuelwood species displayed low sparking behavior. Fuelwood species such as *Q. lanata, V. altissima, M. elengi, D. procerum, R. arboreum, L. polyantha* and *E. acuminata* retained considerable weight after drying for a certain time frame in comparison to others. Fuelwood species which split easily were *A. nepalensis*, *L. polyantha*, *Q. lanata*, *C. australis, M. pustulata* and *M. phillipensis*. Low moisture when fresh cut is important from the quick utilization point of view as it eases the burning process. Fuelwood species suitable for this quality criterion were *V. altissima, Q. leucotrichophora, D. procerum, M. pustulata, D. binectariferum, M. esculenta* and *R. arboreum*. According to the respondents, *K. calcyna, P. integrifolia, A. nepalensis, V. altissima, P. acerifolium, B. variegata, M. phillipensis, M. semiserrata, B. retusa* and *C. indica* were less resistant to insect/termite attacks in comparison to the others.

FVI-I (= calorific value× density/moisture content × ash) was highest for *Q. lanata* among all the species under investigation followed by *D. procerum*, *Q. leucotrichophora*, *R. arboreum*, *D. binectariferum*, *M. esculenta*, *M. pustulata* etc. and lowest for *B. variegata*.

FVI-II (= calorific value × density/ ash) was highest for *Q. lanata* followed by *D. procerum*, *R. arboreum*, *M. pustulata*, *Q. leucotrichophora*, *M. esculenta*, *L. polyantha*, *D. binectariferum*, *E. acuminata*, *T. hodgsonii* etc. and lowest for *B. variegata*.

FVI-III (= calorific value × density/ moisture) was highest for *Q. leucotrichophora* followed by *M. elengi*, *Q. lanata*, *V. altissima*, *D. binectariferum*, *S. wallichii*, *A. odoratissima*, *M. semiserrata*, *C. indica*, *M. phillipensis* etc. and lowest for *A. nepalensis*.

Considerable similarity was observed for FVI-I & FVI-II ranking. Similarly, the FVI-I & FVI-II ranking were also in close proximity with the PWC ranking. However no similarity was observed for the aforesaid rankings with FVI-III ranking. In the study, much similarity was observed between laboratory analysis (FVI ranking) and local user's knowledge (PWC ranking) for selection of suitable fuelwood species.

In the investigation, GCV of wood species varied from 16.83 to 20.22 MJ/kg. Wood density ranged from 0.34 to 0.86 g/cm^3; green moisture 34.34 to 54.58%; ash content 0.70 to 6.13%; volatile matter 72.07 to 77.70%; fixed carbon 16.17 to 26.98%; carbon content 42.33 to 48.19%; hydrogen 5.32 to 6.53%; lignin 21.09 to 27.34% and total extractive content 6.56 to 12.65%.

A drying profile was prepared for the studied fuelwood species. After 1st week of sundry the highest percentage of weight loss was observed in *A. nepalensis* (21.25%) and lowest in *Q. leucotrichophora* (7.71%). In the 2nd week of sundry, the highest weight loss was observed for *A. nepalensis* (29.43%) and lowest weight loss for *V. altissima* (11.12%). In the 3rd week, the highest weight loss was recorded for *A. nepalensis* (34.33%) lowest for *Q. leucotrichophora* (16.73%). Similarly in the 4th, 5th, 6th and 7th and 8th week of sundry, the highest weight loss was observed for *A. nepalensis* and lowest for *Q. leucotrichophora*. Drying profile showed that the final moisture percentage retained in the dried fuelwood species was independent of the green moisture content, besides fuelwood species exhibiting fast drying rate were almost same with those for PWC. Up to 4th week of sundry the rate of moisture loss was observed faster in the fuelwood species although with variable rates among different species. A slow decrease was evident after the 5th week of sundry. Moisture released by the fuelwood species after the 8th week of sundry was highest in *A. nepalensis* and lowest in *Q. leucotrichophora*.

The heating values (GCV, NCV and UHC) decreased with the increase in green moisture content of fuelwood species. The GCV (oven dry weight) of the studied fuelwood species varied from 16.83 MJ/kg to 20.22 MJ/kg. On the contrary, the GCV at green moisture decreased and varied from 8.27 MJ/kg to 12.57 MJ/kg. For NCV (at green moisture) this range further decreased to 6.52-10.51 MJ/kg. UHC (at green moisture) decreased to a lower range from 5.13 MJ/kg to 8.65 MJ/kg. *Q .lanata* had the highest GCV whereas *B. variegata* the lowest (at oven dry weight). On the other hand GCV, NCV and UHC values calculated at green moisture were highest for *Q. leucotrichophora* owing to low green moisture content (34.34%).

GCV of fuelwood species increased with increase in carbon, hydrogen, lignin and extractive content (extracted with ethanol-benzene) whereas, decreased with increase in ash content. Statistical analysis further revealed the same (in terms of positive correlation between GCV and carbon content; GCV and lignin content; and negative correlation between GCV and ash content).

Ash analysis of the fuelwood species revealed the predominance of Ca and K over other inorganic elements. The highest percentage of Ca and K were found in *B. variegata* and *Terminalia myriocarpa*, respectively. Wood ash of *C. indica* contained the highest percentage of Mg. The percentage Na, Si and Mn were highest in *B. variegata.* Wood ash of *P. acerifolium* contained the highest percentage of P. Highest percentage of Cu and Cd were found in *A. nepalensis*. Similarly, wood ash of *C. indica* and *D. procerum* contained the highest percentage of Zn and Pb, respectively. The study showed that the concentration range of heavy metals such as Cu, Zn, Pb and Cd were well below the pollution concentration limit as approved by US-EPA (40 CFR part 503.13).

TG analysis revealed three major weight loss stages for all the investigated fuelwood species. The temperature range observed for volatilization and burning zone was 181.19 - 390.48°C while 377.23 - 506.63°C for the char burning zone. Ignition temperature and burnout temperature were lowest for *P. acerifolium* and *Q. lanata* respectively. Maximum combustion rates for volatilization and burning, zone and char burning zone were highest for *S. wallichii* (14.94% min^{-1}) and *R. arboreum* (13.20%

min^{-1}), respectively. The peak temperatures for volatilization and burning zone, and char burning zone were highest in *T. hodgsonii*, while lowest in *P. acerifolium*. The range of CCF for fuelwood species varied from 6.20 to 13.01 and was highest in *Q. leucotrichophora* while lowest in *M. phillipensis*. On the basis of CCF, the most suitable fuelwood species was *Q. leucotrichophora* followed by *M. esculenta, D. procerum, R. arboreum, Q. lanata, S. wallichii, L. polyantha, V. altissima, M. pustulata, D. binectariferum* etc.

In the present investigation on the basis of OR, the potential fuelwood species in descending order were: *D. procerum, Q. lanata, Q. leucotrichophora, R. arboreum, L. polyantha ~ M. esculenta, M. Pustulata, V. altissima, D. binectariferum, S. wallichii ~ E. acuminata, M. elengi, C. australis, T. hodgsonii, A. odoratissima ~ M. semiserrata, B. retusa, P. acerifolium, K. calcyna, A. nepalensis, S. cerasoids, T. myriocarpa, C. indica, M. phillipensis, P. integrifolia, B. variegata.*

The following conclusions were drawn from the present study:

- Considerable similarity was observed for FVI-I & FVI-II ranking. Similarly, the FVI-I & FVI-II ranking were also in close proximity with the pair-wise comparison (PWC) values.
- No similarity was observed for FVI-I & FVI-II rankings with FVI-III ranking.
- Much similarity was observed between the laboratory analysis (FVI ranking) and local user's knowledge (PWC ranking) for selection of the suitable fuelwood species.
- The final moisture percentage retained in the dried fuelwood species was independent of the green moisture content, besides fuelwood species exhibiting fast drying rate were almost same with those for PWC ranking.
- GCV, NCV and UHC decreased with the increase in green moisture content of the fuelwood species. It signifies that tree species with low green moisture content are more desirable as firewood for getting effective and usable heat.

- GCV of fuelwood species increased with the increase in carbon content, hydrogen content, lignin content and OEC (extracted with ethanol-benzene) while decreased with increase in ash content.
- A positive correlation was observed between GCV and carbon content; GCV and lignin content whereas, negative correlation between GCV and ash content.
- Among all the investigated fuelwood species Ca was found to be the most abundant ash element followed by K. The range of heavy metals such as Cu, Zn, Pb and Cd were well below the pollution concentration limit.
- On the basis of PWC ranking, the most preferred fuelwood species were *Q. lanata* and *D. procerum.*
- On the basis of FVI-I and FVI-II, the most potential fuelwood species was *Q. lanata* whereas, in FVI-III, the most potential fuelwood species was *Q. leucotrichophora.*
- On the basis of CCF the most suitable fuelwood species was *Q. leucotrichophora.*
- On the basis of OR the ten most promising fuelwood species were *D. procerum, Q. lanata, Q. leucotrichophora, R. arboreum, L. polyantha* ~ *M. esculenta, M. Pustulata, V. altissima, D. binectariferum, S. wallichii.*

Future works and recommendation

The promising fuelwood species identified in the present study can be used for energy plantation in wasteland, degraded land and existing forests. Energy plantation will contribute towards proper fuelwood management, reduce pressure on existing forests and recuperate fuelwood crisis. However, prior to large scale energy plantation, their growth rates, biomass productivity, nutrient uptake behavior and optimum period of harvesting should be investigated. Additionally, fine chemicals, value added products, bio-alcohols, etc. can be obtained from the investigated fuelwood species by application of the integrated bio-refinery approach.

ANNEXURE

Annexure-I

1. Location and Extent

Arunachal Pradesh is situated in North-Eastern India
Longitude: Between $910^0\ 30'$ and $970^0\ 30'$ E
Latitude: Between $260^0\ 28'$ and $290^0\ 30'$ N

2. Bordering States/ Countries

East:	Myanmar and Nagaland
West:	Bhutan
North:	China and Tibet
South:	Assam

3. Area

Total geographical area (in sq. Km.):	83,743
Area under forest (in sq. Km.):	51,540
% of forest cover:	61.5

4. Physiography

Arunachal Pradesh can be broadly divided into four physiographic regions. These are the greater Himalayas, the lower Himalayan range, the sub Himalayan belt and the plains of the eastern continuity of Assam.

4.1. The greater Himalayas:

The greater Himalayas encompass snow-capped mountains rising up to 5500 m above mean sea level (amsl) and covering the northern part of the districts Lohit, Dibang valley, East and West Siang, Lower and Upper Subanshri, East and West Kameng and Twang.. The area is characterized by its very rugged topography with very steep and highly dissected hill slopes. Major rivers, such as the Tenga, Bichom, Subanshri, Kamala, Siyam, Siang and Lohit, originate in the greater Himalayas and flow into the plains of the Assam valley through the central and lower Himalayan ranges

4.2. The lower Himalayan range:

The lower and central Himalayas rising up to 3500 m above mean sea level (amsl) include the ranges between the greater Himalayas and the sub Himalayan range (Siwalik range). In the Lohit and Dibang valley districts, the ranges (up to 3000 m elevation) are densely forested. The relief of the areas is extremely rugged and the side slopes of the hills are moderately steep to steep. Some areas are severely eroded.

4.3. The sub Himalayan belt:

The sub Himalayan belt, embracing the Siwalik hills and rising up to an elevation of about 1500 m above mean sea level (amsl) includes the southern part of the hill ranges along the Kameng, Subanshri and West Siang districts. The relief is extremely rugged in steep hill ranges and it is normal in the foothills.

4.4. The plains of the eastern continuity of Assam:

The plains areas (eastern continuity of the Assam plains) include the plains of the Lohit, Tirap, Dibang and Siang rivers. The northern part is gently sloping to undulating and during the rainy season receives heavy stream loads through feeder streams. The southern part, adjacent to the Assam plains, is nearly level to very gently sloping. Elevation in the region varies from 80 to 210 m above mean sea level (amsl). The various areas are drained by the Siang, Lohit, Dibang, Kamlong, Nao-Dihing, Tirap, Namchik and Manphuk (Buridihing), Dirak and Namsing rivers.

Source: Maji. A. K., et al. Soil information system of Arunachal Pradesh in a GIS environment for land use planning, *JAG* 3 (1), 69-77, 2001.

5. Climate

The climate of Arunachal Pradesh is humid to perhumid subtropical, characterized by the high rainfall and high humidity of the sub-Himalayan belt. However, a temperate climate prevails in the lower Himalayan region and the greater Himalayan region is perpetually covered with snow. The average annual rainfall varies from 1380 to 5000 mm. The minimum temperature is around 0°C in winter months in the Bomdila and Twang areas, while it rises to 35°C during summer months in the Namsai and Tezu areas of Lohit district. The mean annual air temperature is 23.8 °C in the plains and 16.2 °C in the hilly regions.

Source: Maji. A. K., et al. Soil information system of Arunachal Pradesh in a GIS environment for land use planning, *JAG* 3 (1), 69-77, 2001.

6. Land Utilization

Sl. No.	Category	Area ('000 ha)	Percentage of TGA
1.	Total geographical area	8374	---
2	Reported area for land utilization	5659	67.57
3	Unreported area	2715	32.42
4	Forest	5154	61.54
5	Land not available for cultivation	64	0.76
6	Permanent pastures and other grazing lands	19	0.22
7	Land under misc. tree crops	37	0.44
8	Cultivable wasteland	65	0.77
9	Fallow lands other than current fallows	70	0.83
10	Current fallows	40	0.47
11	Net area sown	211	2.51

Source: Land and statistics, Ministry of Agriculture, GOI, 2008-09.

7. Soils of Arunachal Pradesh

Different kinds of soils are present in Arunachal Pradesh, due to a wide variability in factors such as climate, physiography, geology and vegetation that influence the ecosystems.

86 soil family associations are spread over the state and four soil orders viz. Inceptisols, Entisols, Ultisols and Alfisols predominate the soil. The soil contributes by different order to the total geographical area can be shown as follows

Soil order	% distribution to the Total Geographical Area(TGA)
Lnceptisols:	37.0
Entisols:	35.0
Ultisols:	14.0
Alfisols:	0.5

Source: Maji. A. K., et al. Soil information system of Arunachal Pradesh in a GIS environment for land use planning, *JAG* 3 (1), 69-77, 2001.

8. Characteristics of soils under different agro-ecological sub regions of Arunachal Pradesh

Class	Agro-ecological sub regions	Description
Sandy	Warm per-humid eastern Himalayas	Shallow, excessively drained, loamy-skeletal; with moderately deep, somewhat excessively drained, sandy-skeletal soils,sandy-skeletal Typic Udorthents
	Hot humid plains	(i) Deep, well-drained, coarse-loamy Typic Udifluvents; with moderately deep somewhat excessively drained, sandy Aquic Udipsamments (ii) Moderately shallow, somewhat excessively drained, coated Typic dipsamments
Gravelly loam	Warm per-humid Eastern Himalayas	(i) Shallow, excessively drained, loamy-skeletal Lithic Udorthents; with moderately deep, somewhat excessively drained,loamy-skeletal Typic Udorthents (ii) Deep, somewhat excessively drained, loamy-skeletal Entic Haplumbrepts; with moderately shallow, excessively drained, sandy-skeletal Typic Udorthents (iii) Shallow, excessively drained, loamy-skeletal, Lithic Udorthents (iv) Shallow, excessively drained, sandy-skeletal Lithic Udorthents; with oderately deep, excessively drained, loamy-skeletal Typic Eutrochrepts
	Warm per-humid Siwalik	(i) Deep excessively drained, loamy-skeletal Umbric Dystrochrepts; with moderately deep, excessively drained, fine-loamy Typic Dystrochrepts (ii) Very deep, well-drained, fine-loamy Typic Dystrochrepts; with deep, well-drained, loamy-skeletal Dystric Eutrochrept (iii) Deep, somewhat excessively drained, loamy-skeletal Typic Udorthents; with deep, somewhat excessively drained, fine- loamy Typic Dystrochrepts (iv) Deep, somewhat excessively drained, loamy-skeletal Typic Udorthents; with deep, well-drained, fine-loamy TypicDystrochrepts (v) Deep, somewhat excessively drained, fine-loamy Typic Haplumbrepts; with deep, well-drained, loamy-skeletal Typic Udorthents (vi) Deep, somewhat excessively drained, loamy-skeletal Typic Haplumbrepts; with very deep, well-drained, fine-loamy Umbric Dystrochrepts (vii) Deep, well-drained, coarse-loamy Typic Dystrochrepts; with moderately deep, somewhat excessively drained, loamy- skeletal Typic Dystrochrepts

Gravelly loam	Warm per-humid Purvanchal	(i) Deep, well-drained, loamy-skeletal Pachic Haplumbrepts; with deep, well-drained, fine-loamy Typic Haplumbrepts (ii) Deep, well-drained, loamy-skeletal Entic Haplumbrepts; with very deep, well-drained, fine-loamy Umbric Dystrochrepts (iii) Shallow, excessively drained, loamy-skeletal Lithic Udorthents; with moderately deep, somewhat excessively drained, loamy-skeletal Pachic Haplumbrepts
	Hot humid plains	Moderately shallow, well-drained, loamy-skeletal Typic Udorthents; with moderately deep, well-drained, coarse-loamy Entic Haplumbrepts
Clayey	Warm per-humid eastern Himalayas	(i) Shallow, excessively drained, loamy-skeletal Lithic Udorthents; with moderately deep, somewhat excessively drained,loamy-skeletal Typic Udorthents (ii)) Deep, somewhat excessively drained, loamy-skeletal Entic Haplumbrepts; with moderately shallow, excessively drained, sandy-skeletal Typic Udorthents (iii)) Shallow, excessively drained, loamy-skeletal, Lithic Udorthents (iv) Shallow, excessively drained, sandy-skeletal Lithic Udorthents; with oderately deep, excessively drained, loamy-skele-tal Typic Eutrochrepts
	Warm per-humid Purvanchal	(i) Very deep, well-drained, fine Typic Dystrochrepts; with deep, well-drained, clayey-skeletal Typic Haplohumults (ii) Very deep, well-drained, fine Fluventic Haplumbrepts; with deep, imperfectly drained, fine-loamy Aeric Haplaquents (iii) Very deep, well-drained, fine Pachic Haplumbrepts; with very deep, well-drained, fine Typic Haplumbrepts (iv) Very deep, well-drained, fine Typic Kandihumults; with very deep, well-drained, fine Pachic Haplumbrepts (v) Moderately deep, well-drained, fine Pachic Haplumbrepts; with moderately deep, well-drained, fine-loamy Typic Dystrochrepts (vi) Moderately deep, well-drained, clayey-skeletal Pachic Haplumbrepts; with deep, well-drained, fine Pachic Haplumbrepts (vii) Deep, somewhat excessively drained, clayey-skeletal Typic Dystrochrepts

Source: Maji. A. K., et al. Soil information system of Arunachal Pradesh in a GIS environment for land use planning, *JAG* 3 (1), 69-77, 2001

Annexure-II

9. Forest of Arunachal Pradesh

The vegetation of Arunachal Pradesh falls under four broad climatic categories and can be classified in five broad forest types with a sixth type of secondary forests. These are tropical semi evergreen forests, tropical wet evergreen forests, sub-tropical forests, pine forests, temperate forests and alpine forests.

9.1 Tropical semi evergreen forests: This forest type occurs all along the foothills and river banks up to an elevation of 600m.

9.2 Tropical wet evergreen forests: This type of forest occurs between altitudes 500-600m and found in Tirap, Changlang and Lohit districts.

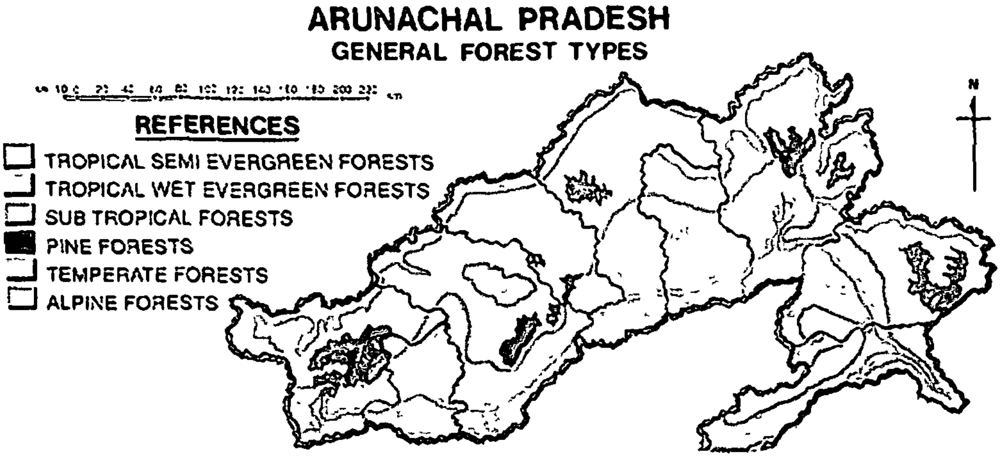
9.3 Sub-tropical forests: This type of forest occurs in all the districts between altitudes 800m to 1900m. This type of forest is essentially evergreen and dense in nature.

9.4 Pine forests: This type of forest extend both in subtropical and temperate belt in between 1000m to 1800m.

9.5 Temperate forests: This type of forest occurs in all districts as a continuous belt and extends between altitudes 1800m to 3500m

9.6 Alpine forests: This type of vegetation occurs on the peaks of higher hills above an altitude of 3500m up to 5500m. For major part of the year, the area is covered by snow and plant activity is restricted to a few months when snow melts.

10. Map of Arunachal Pradesh showing the distribution of different type of forests (Source: arunachalpradesh.gov.in/forest1htm)



11. Distribution of forests type in different districts

Type of Forests	Districts
Tropical semi evergreen	W. & E. Kameng, Papum pare, L. subanshri, W. & E. Siang, L. Dibang Valley, Lohit, Changlang and Tirap.
Tropical wet evergreen	Lohit, Changlang and Tirap.
Sub-tropical	W. & E. Kameng, Kurung kumey, Papum pare, U. & L. subanshri, W., E. & U. Siang, L. Dibang Valley, Lohit and Changlang.
Pine	Tawang, W. & E. Kameng, Papum pare, U. & L. Subanshri, W. Siang, Dibang Valley, Anjaw and Lohit.
Temperate	Tawang, W. & E. Kameng, Kurung kumey, Papum pare, U. & L. subanshri, W. & U. Siang, , Dibang Valley, L. Dibang Valley, Anjaw, Lohit, Changlang and Tirap.
Alpine	Tawang, W & E Kameng, , Kurung kumey, Papum pare, U. subanshri, W. & U. Siang, Dibang Valley, L. Dibang Valley, Anjaw and Lohit.

(**Source**. Sinha, G N Forest and Forestry in Arunachal Pradesh, SFRI information Bulletin No.27, Issued by Director, State Forest Research Institute & Mission Director, State Bamboo Mission, Arunachal Pradesh, India, 2008, arunachalpradesh gov.in/forest1htm

12. Distribution of the selected species in different forest types and districts along with vernacular names and family

Botanical name	Vernacular Name	Family	Distribution in different forest types/ Districts
C. indica	Hinguri	Fagaceae	Subtropical, Tropical semi evergreen, Temperate. In all the districts.
M. pustulata	Moralia	Euphorbiaceae	Subtropical, Tropical semi evergreen. In all the districts except Tawang, Dibang valley & Anjaw
D. binectariferum	Bandardima	Meliaceae	Subtropical, Tropical wet evergreen. In all the districts except Tawang, Dibang valley & Anjaw
B. retusa	Kuhir	Euphorbiaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap
M. semiserrata	Kalikath	Myrsinaceae	Subtropical, Temperate. . In all the districts.
C. australis	Mohita	Ulmaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap.
D. procerum	Lali	Meliaceae	Subtropical, Tropical wet evergreen. In all the districts except Tawang, Dibang valley & Anjaw
T. myriocarpa	Hollock, Jhaluka	Combretaceae	Tropical wet & semi evergreen. W. & E. Kameng, Papum pare, L.subanshri, W. & E.Siang, L.Dibang Valley, Lohit, Changlang, Tirap.
S. cerasoids	Kyamuna	Myrtaceae	Subtropical &Tropical semi evergreen. In all the districts except Tawang, Dibang valley & Anjaw
K. calcyna	Pichola	Malvaceae	Tropical semi evergreen. Tirap, Changlang, L.Dibang valley, E. &E.Siang, L.Subansiri, Papum pare, E. &W. Kameng.
M. phillipensis	Losan	Euphorbiaceae	Subtropical & Temperate. In all the districts
A. odoratissima	Jati Koroi	Leguminosae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap.
L. polyantha	Sualu	Lauraceae	Subtropical & Temperate. In all the districts.
M. elengi	Bokul	Sapotaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap.
B. variegata	Kanchon, Kurol	Leguminosae	Subtropical & Temperate. In all the districts.
P. integrifolia	Genderi	Verbenaceae	Tropical wet evergreen, Temperate. In all districts except E.Siang
T. hodgsonii	Boramthuri	Magnoliceae	Subtropical & Tropical wet evergreen. In all the districts except Tawang, Dibang valley, Anjaw
P. acerifolium	Hatipalia,	Sterculiaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap
V. altissima	Ahoi	Verbenaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap
S. wallichii	Makori sal	Ternstrcemiaceae	Subtropical & Temperate. In all the districts.
A. nepalensis	Uttis	Betulaceae	Pine & Temperate. In all the districts except E. Siang
Q. lanata	Safed Banjh	Fagaceae	Pine & Temperate. In all the districts except E. Siang
Q. leucotrichophora	Lal banjh	Fagaceae	Pine & Temperate. In all the districts except E. Siang
R. arboreum	Gurns	Ericaceae	Temperate, Alpine. In all the districts except E. Siang
M. esculenta	Kaphal	Myricaceae	Pine & Temperate. In all the districts except E. Siang
E. acuminata	Gual	Boraginaceae	Subtropical. In all the districts except Tawang, Dibang valley, Anjaw & Tirap

Source: Sinha, G.N., 2008: arunachalpradesh.gov.in/forest1htm

13. Sampling localities of the selected tree species

Tree species	**Sampling localities**
C. indica	Tippi, Seijusa, Rowta
M. pustulata	Bhalukpong, Doimara, Rowta
D. binectariferum	Riang, Tippi, Seijusa
B. retusa	Amatulla, Bhalukpong, Doimara
M. semiserrata	Tenga Valley, Kharteng
C. australis	Seppa, Riang, Shergoan
D. procerum	Riang, Tippi, Seijusa
T. myriocarpa	Tangengs, Doimara
S cerasoids	Rowta, Amatulla, Tenga Valley
K. calcyna	Baliian, Bhogapani
M. phillipensis	Tezu. Pasighat, Kharsang
A. odoratissima	Seijusa, Rowta
L. polyantha	Shergoan, Kharsang, Doimara
M. elengi	Baliian, Rowta, Seijusa
B. variegata	Tippi. Riang, Dumsa
P. integrifolia	Kharsang, Bhalukpong
T. hodgsonii	Baliian, Pasighat
P. acerifolium	Hapoli, Dumsa
V. altissima	Bomdila, Khaliang, Kharsang
S. wallichii	Tezu, Tanga Valley, Tawang
A. nepalensis	Tawang, Dumsa, Kombong
Q. lanata	Tanga Valley, Kombong, Zero
Q. leucotrichophora	Tanga Valley, Kombong, Zero
R. arboreum	Bomdila, Tawang, Barduria
M. esculenta	Tanga Valley, Tawang, Barduria
E. acuminata	Seppa, Doimara

LIST OF PUBLICATIONS

List of publications

1. Deka D., **Sedai P.** & Chutia R. S. Investigating Woods and Barks of Some Indigenous Tree Species in North-East India for Fuel Value Analysis, *Energy Sources* **36**, 1913–1920, 2014.
2. **Sedai P.**, Kalita D. & Deka D. Assessment of the fuelwood of India: A case study based on fuel characteristics of some indigenous species of Arunachal Pradesh, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (Accepted).