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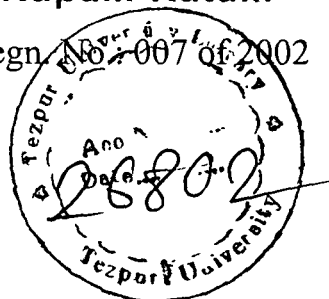# STUDIES ON CARBONIZATION OF SOME INDIGENOUS TREE SPECIES OF NORTH-EAST INDIA

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

by

Rupam Kataki

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IN

The School of Energy, Environment & Natural Resources
DEPARTMENT OF ENERGY
Tezpur University
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CERTIFICATE BY THE SUPERVISOR

This is to certify that the matter embodied in the thesis entitled *'Studies on carbonization of some indigenous tree species of north-east India'* submitted by Sri Rupam Kataki for the award of degree of Doctor of Philosophy of Tezpur University is a record of bonafied research work carried out by him under my supervision and guidance. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Date: June 30, 2005

(D. Konwer)

Acknowledgement

Date: (Rupam Kataki)

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Chapter I

INTRODUCTION

Chapter I

Introduction

Energy is considered as an essential input for industrial and economic development and for improving the quality of life. The positive relationship between energy use and gross domestic production (GDP) is very much inherent in economic expansion plans for the developing countries. Even the commercial energy consumption is expected to rise more rapidly than the growth of national economies of developing countries (OTA, 1992). In case of India, future projection shows that the commercial energy demand for the year 2009-10 will be 600 Mtoe, which is much higher as compared to the consumption level of 200 Mtoe in the year 1990 (TERI, 1992).

Majority of developing countries including India import oil to meet their energy requirement and for doing so, a major share of national budget of each of these countries is required to meet the cost of the imported oil. Moreover, this type of commercial energy-oriented development through ever-increasing consumption of electricity and oil has resulted in inequalities, external debt and

environmental degradation (Ravindranath & Hall, 1995). Therefore, time has come for developing countries, which are highly dependent on imported oil, to rethink about desirability and sustainability of such dependence for development. Reddy *et al.* (1991) have viewed that the conventional paradigm of development characterized by commercial energy-oriented policies is non-sustainable. They have suggested that it may be useful for developing countries to redefine their energy strategy so as to include the criteria of sustainability, promotion of equity and self-reliance in their long-term energy plan.

During the last two or three decades, renewable energy sources have emerged as the alternatives to the conventional fossil fuels. A gradual shift from the use of fossil fuels towards the use of renewable sources of energy has become necessary for long-term sustainable development in all countries, particularly in the developing world. Renewable sources of energy cover mainly the solar energy, biomass energy, wind energy, hydro-electric power, ocean thermal energy, tidal energy, etc. which are more equitably distributed over the earth surface as compared to fossil fuels [Goldemberg *et al.* (1988)].

Development benefits associated with the use of renewable energy include the generation of rural jobs, urban and rural public health improvement, isolation from international price fluctuation etc. In addition, renewable sources of energy are not associated in the same manner with environmental pollution as in the case with fossil fuels [Hustad & S_nju (1992)].

Renewable energy technologies have evolved markedly over the past two or three decades and the cost of all renewable energy systems and devices have

declined significantly and are projected to decline even further (WB, 2002). Various projections made by individual researchers and world bodies on future contributions of renewable energy have once again established the importance of use of renewable energy. WEC (1993) in their conservative projection for renewables reveals that with minimum possible scenario, renewable sources of energy would meet 3-4 % of total energy amounting to 539 Mtoe while under maximum possible scenario with major policy initiatives, renewable sources of energy could provide 8-12 % of total energy by 2020. In this regard, a recent International Energy Agency (IEA) publication (IEA, 2003) reveals that in 2001, world Total Primary Energy Supply (TPES) was 10,038 Mtoe, of which 13.5 % or 1,352 Mtoe, was produced from renewable energy sources. Thus, renewable sources of energy offer considerable potential for replacing conventional energy sources and in some cases are already competitive with them (IEA, 2003).

Biomass is a renewable fuel used in nearly every corner of the developing world as a source of heat, particularly for cooking and heating in the domestic sector. World wide, solid biomass is by far the largest renewable energy source, representing 77.4 % of global renewable energy supply as compared to 16.4 % from hydropower, 3.2 % from geothermal energy, 0.3 % from solar and tidal energy and 0.2 % from wind energy (IEA, 2003). Thus, solid biomass is by far the most important among all renewable sources of energy.
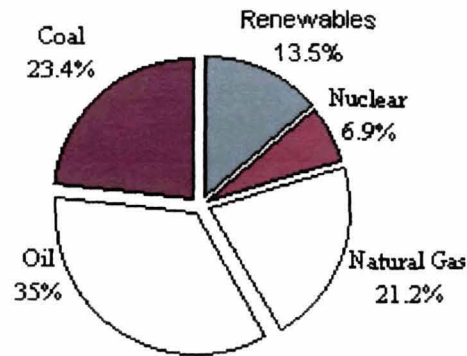
Fig. 1: Fuel share in world Total Primary Energy Supply (TPES) in 2001
[Source: IEA, (2003)]
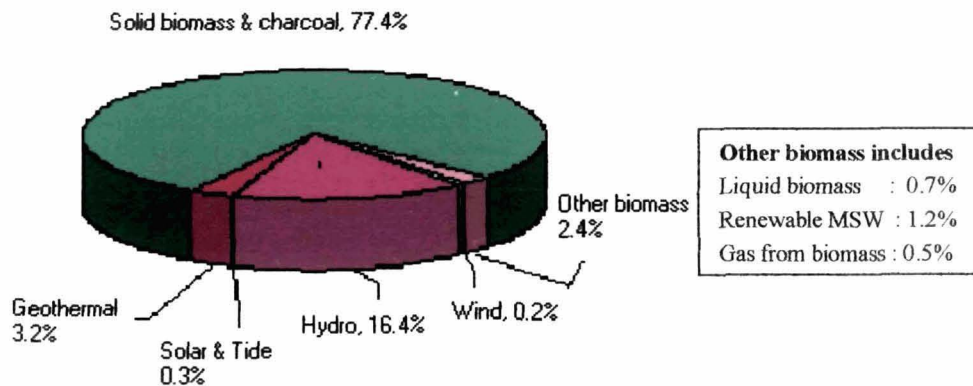
Fig 2: Products' shares in world renewable energy supply in 2001
[Source: IEA, 2003]

Out of various biomass fuel types like woodfuel, agricultural residues, cowdung, etc. woodfuels that constitute fuelwood, charcoal and other wood derived fuels are the world's most important form of non-fossil energy sources particularly in the developing countries and is evident from the fact that the share of woodfuel to the total energy supply in the developing countries (excluding China) is about 20 % [IEA (1996:II. 289-308, III.31-187)]. Production and consumption of woodfuels are concentrated in low-income

countries, with five countries – Brazil, China, India, Indonesia and Nigeria accounting for about 50 % of the total production and consumption of woodfuel world wide [FAO (1997)]. Trossero (2002) reported that woodfuel use in developing countries, where about 77 % of the worlds population lives is to the tune of 76 %. In developed countries, woodfuels represent only 2 % of their total energy consumption.

Table 1: Charcoal consumption in 1995 and estimated projection in different regions of the world

	1995	2010	2020
East Asia			
• Share of charcoal in final biomass use	5 %	7%	8%
• Charcoal production/use (Mtoe)	5.6	7.8	9.2
• Wood input in charcoal production (Mtoe)	16.5	21.7	25.1
• **Energy loss in charcoal transformation (Mtoe)**	10.8	14.0	15.9
South Asia			
• Share of charcoal in final biomass use	2%	3%	4%
• Charcoal production/use (Mtoe)	3.5	7.9	11.1
• Wood input in charcoal production (Mtoe)	12.6	28.2	39.5
• **Energy loss in charcoal transformation (Mtoe)**	9.1	20.3	28.4
Latin America			
• Share of charcoal in final biomass use	9%	9%	9%
• Charcoal production/use (Mtoe)	6.4	7.0	7.2
• Wood input in charcoal production (Mtoe)	13.2	14.5	14.9
• **Energy loss in charcoal transformation (Mtoe)**	6.8	7.5	7.7
Africa			
• Share of charcoal in final biomass use	3%	6%	8%
• Charcoal production/use (Mtoe)	6.8	19.1	30.8
• Wood input in charcoal production (Mtoe)	27.0	72.1	112.1
• **Energy loss in charcoal transformation (Mtoe)**	20.3	53.0	81.3
Total developing countries			
• Share of charcoal in final biomass use	3%	4%	5%
• Charcoal production/use (Mtoe)	22.3	41.8	58.3
• Wood input in charcoal production (Mtoe)	69.3	136.5	191.6
• **Energy loss in charcoal transformation (Mtoe)**	47.0	94.7	133.3

[Source: IEA (2003)]

Charcoal is an age old refined form of woodfuel and has been known from even before the dawn of recorded history. It is an important energy source for domestic cooking and wide range of industrial and processing applications such as manufacturing of activated carbon, calcium carbide, carbon disulfide, silicon carbide, sodium cyanide, reduction of iron-ore in the steel industry, refining of metals (eg. copper, bronze, silicon, aluminum and electro-manganese) black smithies, cloth ironing, heavy-clay soil conditioner, orchid planting medium etc. Despite its comparatively higher price than other woodfuels, wood charcoal is able to compete with fossil carbons because of its relative purity (low ash content) and high reactivity.

Charcoal is produced by a process called carbonization. Carbonization as defined by IUPAC Compendium of Chemical Technology is a process by which solid residues with increasing content of element carbon are formed from organic material usually by pyrolysis in an inert atmosphere. As with all pyrolytic reactions, carbonization is a complex process in which many reactions take place concurrently such as dehydrogenation, condensation, hydrogen transfer and isomerization.

In the process of carbonization of wood, wood pieces are heated in the absence of air to temperatures sufficiently high for them to undergo substantial thermal decomposition. This decomposition results in the evolution of large amounts of gas and vapours and the formation of a carbon-rich solid residue (charcoal). The final temperature employed in most charcoal making operations

is in the range of $400^0 - 500^0$ C; although further decomposition continues to occur at higher temperatures.

The process of carbonization of wood can be illustrated as follows:

```
                    ┌──────► Gas              ┌──────► Light gas
Wood ───────────────┼──────► Tar (Oil) ───────┤
                    └──────► Charcoal          └──────► Charcoal

         Primary reactions              Secondary reactions
         (exothermic)                   (endothermic)
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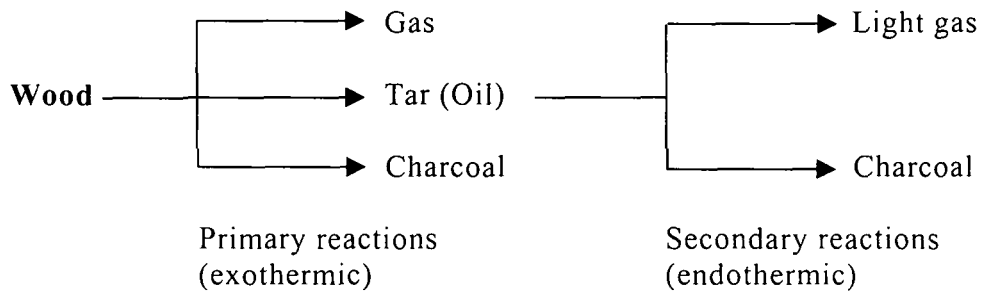
The factors affecting wood carbonization are – the nature of wood, wood chemical composition, wood structure and physical properties such as density, permeability, thermal conductivity, size and shape and various external conditions such as temperature, heating rate and pressure.

Wood properties can differ, not only from species to species but also within a given species and from point to point in the same tree. Despite of their differences, wood from a variety of sources exhibit many similarities.

Wood chemical components can be distinctly divided into two groups. The main group is the macromolecular cell wall components viz., cellulose, polyoses (hemicellulose) and lignin which are present in all woods and the minor low-molecular-weight components viz. extractives and mineral substances. The proportion and chemical composition of lignin and polyoses differ in softwoods and hardwoods, while cellulose is a uniform component of all woods.

8

The wood components can be schematically presented as below:

```
                        ┌─────────────────────┐
                        │        WOOD         │
                        └─────────────────────┘
              ⇓                              ⇓
   ┌─────────────────────┐        ┌─────────────────────┐
   │ Low-molecular-weight│        │   Macro-molecular   │
   │     substances      │        │     substances      │
   └─────────────────────┘        └─────────────────────┘
        ⇓          ⇓                   ⇓            ⇓
   ┌─────────┐ ┌──────────┐    ┌──────────────┐ ┌─────────┐
   │ Organic │ │ Inorganic│    │ Polysaccharide│ │ Lignin │
   └─────────┘ └──────────┘    └──────────────┘ └─────────┘
        ⇓          ⇓                   ⇓            ⇓
  ┌──────────┐ ┌──────┐       ┌───────────┐ ┌──────────────┐
  │Extractive│ │ Ash  │       │ Cellulose │ │ Hemicellulose│
  └──────────┘ └──────┘       └───────────┘ └──────────────┘
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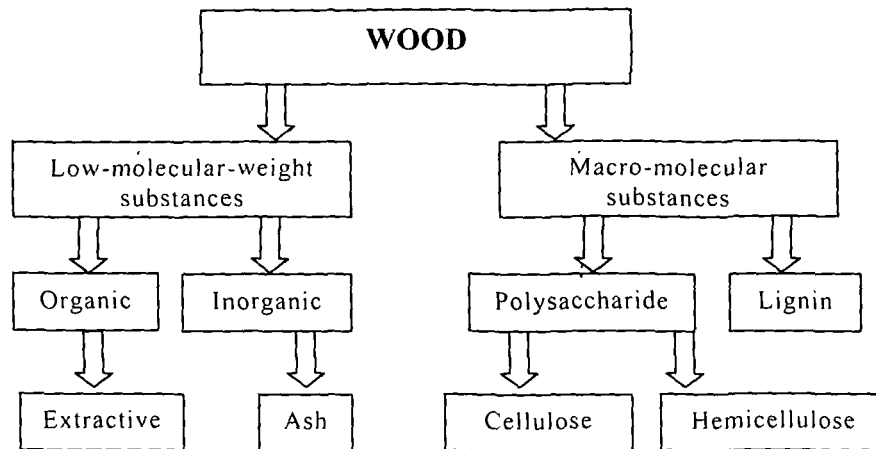
Fig. 3: General scheme of wood chemical components

Cellulose is the main component of cell wall, making up approximately one half of both softwoods and hardwoods with the elementary formula $(C_6H_{10}O_5)_n$. It is a linear polysaccharide composed of β-D-glucopyranose units connected to each other by (1,4) glucoside bonds.

During carbonization, cellulose starts decomposing at 240^0 C, but significant weight loss begins only at 275^0 C. Decomposition is complete by 350^0 C, with the bulk of the weight loss occurring rapidly in the temperature range 330^0 – 350^0 C (Hirata et al., 1991; Browne & Tang, 1962). The decomposition products are largely volatiles. Slow heating with a prolonged period in the temperature range 200^0 – 250^0 C favours char production, while rapid heating to high temperatures favours depolymerization.

Hemicellulose are a mixture of polymers based on 5-carbon monosaccharides units. On carbonization, hemicelluloses undergo preliminary softening at the temperatures in the range of 130^0-190^0 C (Goring, 1963) and

decomposition occurs between 200^0 C and 260^0 C producing mostly volatile decomposition products but still contributing more to the char yield than cellulose (Browne & Tang, 1962; Hirata *et al.*, 1991). Hardwoods contain more of hemicellulose than softwoods.

Lignins are complex macromolecules based on phenylpropane units. Lignins when heated start softening at temperatures 130^0-190^0 C (Goring, 1963) and decomposition occurs with evolution of volatiles in the temperature range of 280^0 to 500^0 C (Browne & Tang, 1962). The predominant product of lignin decomposition is char and much of the charcoal formed during wood carbonization is believed to be derived from lignin.

Low-molecular-weight substances are numerous components apart from macro cell wall components, which can simply be classified as organic and inorganic matters. The organic part is commonly called as extractives while the inorganic part is obtained as ash. Extractives of wood comprise of aliphatic, aromatic and alicyclic compounds, hydrocarbons, alcohols, ketones and various fatty acids, sterols, tannins, waxes, esters, phenolic compounds, resins, terpenes and gums (Roy *et al.*, 1990). These compounds can be extracted from wood using organic solvents singly or in combination with water.

The role of extractives in carbonization is not very clear and there are contradictory reports regarding its effect on carbonization. Roy *et al.* (1990) reported a marginal increase in charcoal yield on removal of extractives from wood.

Moisture content of wood is a most commonly used property of fuelwood. Its quantity is inversely proportional to the amount of heat that is recovered from traditional combustion where the latent heat of evaporation is lost with flue gases. Influence of moisture content on charcoal formation appears to be of physical rather than chemical nature. Wood particles with high moisture content would require a longer heating period than similar but dry particles and this may indirectly favour char forming reactions.

Ash content of wood is the measure of non-combustible inorganic minerals in it. The ash content is as such low in wood and their presence, if present in higher amount, increases the yield of char simply because of their presence in it. This reduces the net heating value of charcoal by reducing the available amount of combustible carbon in unit mass. Contrary to this, external addition of some inorganic additives can enhance char formation in carbonization of wood.

Density of wood has direct bearing on charcoal yield and quality. It may be expected that wood with high density would yield more charcoal than wood with lesser density. Though higher density may facilitate char forming reactions in the particle surface, but in the interior, the effect may be opposite. Thus there are conflicting reports regarding the effect of density on charcoal yield.

Despite the versatility of charcoal's end use, use of wood for charcoal production is often regarded as a contribution to deforestation and addition of pollutants to the environment. But Foley (1986) pointed out that charcoal making is rarely the only pressure on woodland resources. According to him the

expansion of farming land is often responsible for a far greater level of forest destruction. In parallel, there also exists charcoal making systems in which fuelwood resources are sustainable or being created on farms (Chomcharn, 1991).

In spite of this, it is still argued that promoting charcoal development will result in more fuelwood demand since the overall energy efficiency in charcoal conversion is lower than that obtained by using firewood directly. Keita (1987) made a detailed and comparative study of energy balance for fuelwood and for charcoal used as a domestic fuel. He observed that charcoal as a fuel had a higher efficiency than wood as long as the useful thermal energy yield of wood is lower than 20 %. As far as long distance transportation of fuel was concerned, charcoal was still the most economical source of energy. Moreover, under the development context, charcoal can be placed in the middle position of energy ladder followed by fuelwood, dung-cake, agricultural residues and preceded by biogas, kerosene, LPG, electric and microwave energy. Even more important in charcoal development is the associated socio-economic factors such as creation of more employment and generation of income. The system for producing, transporting and marketing of charcoal employ a large number of enterprises, and operate as a market system with limited interference from authorities (Ellegard & Nordstorm, 2003). The production of charcoal itself has become one of the major income sources for poor people in rural areas. Moreover, in areas, where charcoal have long been accepted as a marketable product, there also exits a system of woodfuel

production, flow and utilization often functioning as a informal sector activity. In those areas, the prospect of further commercialized production of charcoal may be high, depending upon the availability of the wood required for charcoal making. It is also an essential commodity to poor people in urban areas and an affordable, convenient and assessable energy source at relatively stable price.

In India, the practice of charcoal production and use has been quite old. Woodfuels are the major sources of domestic energy for the rural masses of India. In the state of Meghalaya in particular and the whole of north-east India in general, woodfuels constitute up to 80 % of the total energy consumption and over 90 % of the population of this north-eastern Himalayan region uses biomass as an important source of energy (Bhat & Sachan, 2004). Charcoal production and marketing is well established in Meghalaya. The production of charcoal is mainly concentrated in Ri-Bhoi and West Khasi Hills districts. Around 1,06,268 quintals of charcoal was produced during April 2004 to September 2004 which is the lean period due to rainy season. However, the production was found to be almost double in the main season from October 2004 to March 2005.

Charcoal production in the state of Meghalaya is practiced commonly in nearby sites of the forests using the traditional earth mound kiln. This method is characterized by low efficiency and gross variation in yield and quality of charcoal as it depends upon the experiences of the charcoal makers in building the kiln and their operational skill. Lower efficiency can also be attributed to the fact that the by-products (tar, liquid and gas) of such carbonization process
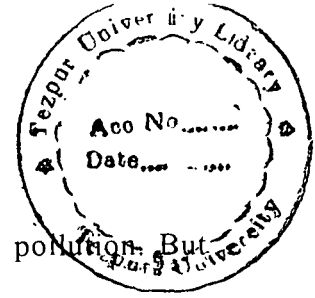
cannot be trapped and thus escape to the environment causing pollution. But even to-day, this method is quite popular among the charcoal producers because of its low investment and its versatility regarding the use of wood as raw material.

As more than 80 % of the forest land in Meghalaya is owned by individual or community, the raw material is collected free of cost. Thus, charcoal business has flourished well in the state becoming a good income source among rural masses.

In the recent years, with the ever-increasing population pressure and shifting cultivation, over dependence on forests for various needs and removal of forest trees for charcoal production, the size of the forests has reduced to a great extent. According to a recent report of the Ministry of Environment and Forests, Government of India (Anonymous, 2000), excessive deforestation has brought more than 50 % area of the north-east hill states under wastelands. In Meghalaya, 44.2 % of the total geographical area is under wastelands. Evaluation of fuelwood consumption rates and status of forest resources in the north-eastern Himalayan region has lead Bhat & Sachan (2004) to conclude that the estimated growing stock is unable to sustain the rate of fuel consumption in this region.

The reduction in forest cover has left the charcoal producers of the state with little choice about the selection of tree species for charcoal making. The absence of farm forestry or energy plantation has further aggravated the problem. In these circumstances, charcoal is produced with whatever species

available nearby and this has in turn affected both quality and quantity of charcoal. In addition, economically important tree species are also used up in charcoal production. Therefore, extensive farming of selected tree species in available wastelands could be a viable alternative to bridge the gap between demand and supply

Our survey has revealed that rural populations of Meghalaya have strong preferences for certain tree species for charcoal production. But as resources become scarce and preferred species are not sufficiently available, presently the charcoal producers are using all kinds of tree species for charcoal production. In this regard, no systematic work has been done so far to characterize these tree species from the charcoal production point of view. Ravindranath *et al.* (1991) opined that before undertaking any programme of biomass production, local tree species diversity, traditional preference of tree species for various purposes and information regarding the performance of different species in that area should be taken into consideration.

Though charcoal production has been practiced in the hilly states of north-east India, particularly in the state of Meghalaya, since the long past, no scientific study has been made so far to identify the indigenous tree species of the region, which can produce charcoal with higher yield and of better quality. Moreover, no work has been done to know the actual yield of charcoal and other by-products of carbonization of wood of these indigenous tree species such as tar, gas and liquid, which are also of great value to-day.

With this background, the present study was undertaken with the following objectives:

Objectives :

1. to survey the tree species currently used for production of charcoal along with their preference and availability and to select some preferred species for charcoal production in the state of Meghalaya;

2. to determine the wood physico-chemical characteristics, biochemical constituents and elemental compositions of the selected tree species which may have influence on yield and properties of charcoal;

3. to analyse the charcoal samples obtained from mass-balance experiments for their properties for identifying the species that produce charcoal with higher percentages of yield and of better quality.

4. to evaluate the yield and quality of charcoal in the traditional earth-mound kiln from two selected tree species and compare the results with those of the charcoal samples produced by these two species in laboratory-scale reactor.

Such a study may be useful in identifying some indigenous tree species of north-east India particularly of the state of Meghalaya from which charcoal with higher yield and better quality can be produced and such promising species may be recommended for inclusion in the farm forestry or energy forestry programme in the wastelands of the region.

Moreover the study on the mass balance of decomposition products of carbonization at various temperatures with different heating rates will provide a

quantitative picture of various other useful by-products such as gas, tar and condensable liquid apart from charcoal and from these results, the optimum carbonization conditions such as temperature and heating rate may be suggested.

This chapter is well written and it is easy to understand the context.

Some paragraphs lack references. You should try to give the source of all statements, unless it is considered as common knowledge.

The language is close to perfect, but I have indicated when there are deviations from what I consider correct expressions.

(However, English is not my mother tongue).

Chapter II

REVIEW OF LITERATURE

Chapter II

Review of literature

It is said that charcoal burning is probably the oldest chemical process known to man. The first use of charcoal was in smelting metal, which dates back to 4000 years BC. It is believed that without it, bronze and iron ages simply would not have happened (Carew, 1999).

According to Bard (2001), biocarbons have been manufactured by men for more than 38,000 years and are still among the most important renewable fuels in use today (Mochidzuki, 2002).

In this regard, a World Bank publication (Plas, 1995) reveals that demand for charcoal is increasing which can not be reversed easily. This is partly because of gradual reduction of Government subsidy on LPG and kerosene and subsequent increase in the prices of these two common energy sources. The growing problem of rural unemployment has also added to its demand as production of charcoal is labour intensive and is estimated to create an employment of 300-350 man-days per tetrajoule as compared to only 10 and 10-20 man-days per tetrajoule for kerosene and LPG respectively

(Bhattarai, 1998). But environmental activists feel that charcoal production should be stopped altogether because of its very low production efficiency. In this backdrop, the World Bank paper has suggested that proper management of natural resources and improved transformation efficiency of charcoal producing kilns are the ways through which charcoal issue could be addressed.

Dumrongthai (1998) reported good economic returns from charcoal industry in Thailand. Economics of charcoal production was studied in one of the Thai Plywood Company's Plantation Unit where charcoal was produced from harvest waste and discarded low quality wood in brick beehive kiln. They further observed that employment generation and economic returns were found to be quite encouraging. According to Dumrongthai, charcoal had a good market in rural areas of Thailand as the prices of other energy sources had risen and also charcoal was exported outside Thailand.

Trossero (1991) evaluated the charcoal making technologies prevailing in the developing countries. The major difference was observed between systems which heat the wood by external means using wood, oil, gas etc. and systems which allow combustion on a limited scale to occur inside the carbonizer by burning part of the wood charged and using this heat to dry and carbonize the remaining wood.

Systems with external heating allowed more precise control but to transmit the heat to the charge was different and inefficient and metal retorts were almost essential. By-products could be recovered free of contamination from the products of combustion.

Systems using internal generation of heat could be further divided on the basis of their method of combustion. The three possibilities existed – earth kiln, which was lowest in cost, bricks or masonry kiln of intermediate cost and steel kiln which was the most expensive.

Trossero (1991) further stressed on the need for a national policy on woodfuel energy (fuelwood and charcoal) and emphasised that such a policy should cover the whole field of energy use, since fuelwood supply could not be expanded without corresponding inputs of liquid fuels, electricity use etc. He outlined three major aspects for consideration while drawing up such a woodfuel policy. These were – (a) present volume of woodfuel, (b) consumption and supply pattern of woodfuel and (c) potential for future improvement of wood energy.

Charcoal making in Asia as observed by Chomcharn (1991) was still away from the preferred development stage i.e. the realization of a sustainable and efficient system in supply of wood, processing, distribution and end use of charcoal. Though charcoal production and use were quite substantial in Asia, absence of clear forest policy and energy policy on charcoal due to a suspicious associated deforestation issue were major constraints in achieving a desired level of development.

He further discussed the often-disputed charcoal production and deforestation issue and refuted the claim that charcoal making was the prime cause of deforestation. In many Asian countries, there existed charcoal making systems in which supply of fuelwood resources were sustainable or being created on farms. He described five resource bases in the existing charcoal production systems viz. the production from farm and homestead

forests, mangrove forests/plantation, rubberwood, sawmill wastes and coconut shell. Various techniques were in operation and notable among them were rice husk mound, earth mound pit, mud beehive, brick beehive, sawdust mound and drum.

The normal technology oriented intervention aimed at conservation of forest trees by improving quality of charcoal and efficiency of charcoal production systems had so far met with limited success. The reason as pointed out by Chomcharn (1991) was a lack of relevant and adequate field information, particularly how the existing charcoal production systems operated and their contribution both in energy and socio-economic terms. He also emphasised on the need to tackle the overall problems of charcoal energy systems simultaneously.

The main source of primary energy in Brazil is forest biomass. With the introduction of Brazil Government's policy of granting fiscal incentives to charcoal enterprises in 1967, a vast reforestation programme was started and thereafter charcoal production from planted forests in Brazil was initiated (Magalhaes & Rezende, 1991). Since then, the forestry sector advanced greatly in technological terms – such as genetic improvement, fertilizer application, forest management and protection programme and all these had enabled an ever-increasing supply of feedstocks for charcoal production in Brazil. But subsequent withdrawal of Government subsidy and financial resources created a situation of increasing demand for charcoal and its decreasing supply. In this backdrop, they stressed on the need to establish a new policy for Brazilian forestry sector through which one would conciliate supply and demand in such a fashion as to guarantee the survival of the

industrial segment with sustainable supply of wood. They predicted that with technological improvement, a time should come when the charcoal production would be a more profitable business.

Seifritz (1993) investigated the question whether or not charcoal produced in the classical way, could be a definite sink for anthropogenic carbon dioxide (CO_2) escaping into the atmosphere. This needed production of charcoal on a large scale and in a capital-lean manner from the wood of short-rotation energy crops. He stressed on the need of a mutual strategy between the industrialized countries (being the main source of anthropogenic CO_2) and developing countries (acting as a sink for it) wherein fund flows from the former to the latter and this could be expected to exhibit favourable CO_2 avoidance costs on a least-cost basis and might be economically beneficial for both partners.

Chidumayo (1987) surveyed the availability of wood stocks for charcoal production in the miombo woodlands of Zambia. The basal area of miombo woodland stands was significantly correlated to the aridity ratio in the study area i.e. basal area increased with increase in the aridity ratio. Mean basal area of woodland stand and volume of stackwood yield per m^2 basal area at stump height did not differ significantly among study areas. Correlation and regression analysis of the data led to the development of regression models for estimating standing woodstocks and yield for charcoal production in miombo woodlands in different parts of Zambia.

Jute stick, an agricultural waste is mostly destroyed by burning into ashes. The hollow structure of the stick hinders its conversion to charcoal through carbonization. Banerjee & Mathew (1985) succeeded in designing

optimum parameters for its efficient conversion to a light-weight smokeless charcoal. The jute stick charcoal was found to be in chip form with a high fixed carbon content. The ash content of the jute stick charcoal was significantly lower and was 20-30% lighter than hardwood charcoal. They also explored the possible avenues for use of the charcoal from such agro-wastes.

Teckchandani & Dubey (1986) developed a technology with little machinery for pyrolytic conversion of dried tree leaves, agricultural wastes such as soybean stalk, pulse stalk, paddy straw, groundnut hull and municipal waste into charcoal. The charcoal prepared in this way burnt with almost the same or better efficiency as that of wood charcoal.

Yatim & Hoi (1987) evaluated the quality of charcoal from various types of wood. The analysis of charcoal for their fixed carbon, ash, volatile matter and moisture contents produced in beehive kiln from rubberwood, acacia, eucalyptus and pine and subsequent comparison of their properties with those of the charcoals from mangrove woods indicated similarity. They concluded that charcoal produced form these tree species were suitable for industrial use.

The possibility of thermo-conversion of over-matured and wilt diseased coconut palms of different age groups to charcoal was investigated by Gnanaharan et al. (1988). They used a portable type 'Tongan kiln' to produce charcoal from stem wood of these palms. Comparison of the results of proximate analysis i.e. fixed carbon, volatile matter and ash contents and yield of charcoal from these two types of palms (over-matured and wilt

diseased) showed no significant variation. They concluded that charcoal from coconut wood was of good quality and suitable for domestic use.

Conversion of waste olive wood to value added charcoal was reported by Figueiredo *et al.* (1989a). They studied the pyrolysis of olive wood to produce charcoal and fuel gas in the temperature range of 300^0 - 900^0 C, both isothermally and under temperature programming. The charcoal was characterized by proximate and elemental analyses and the gases were analysed with the help of gas chromatograph/ Their results led to the conclusion that the optimum temperature for pyrolysis was 700^0 C as charcoal obtained at temperature above 700^0 C were not significantly better in quality and quantity than the charcoal produced at 700^0 C. They remarked that the gases such as CO, CO_2, CH_4 and H_2 produced during pyrolysis could be suitable for close-coupled applications.

Figueiredo *et al.* (1989b) studied the pyrolysis of holm-oak wood sawdust to determine the characterstics of the charcoal and the nature and amounts of gases produced. Pyrolysis of holm-oak wood of varying particle sizes was carried out at a temperature ranging from 300^0 – 900^0 C. Fixed carbon content of the charcoal was found to increase with the increase of temperature upto 700^0 C and then remained essentially constant. The composition of the pyrolysis gas produced at each temperature was determined and its heating value was calculated. Considering the quality of the charcoal and the heating value of the gases produced, they concluded that the optimal pyrolysis temperature was 600^0 C.

The difficulty in selling of wood of pine plantation thinning in Brazil led Pontinha *et al.* (1992) to explore some possible ways to use these wood to

value added products. They carbonized these woods and the charcoals obtained from logs·of first and fourth thinnings of *Pinus caribaea* var. *hondurensis* and *Pinus oocarpa* were analysed for their physical and chemical properties. Similar properties were also determined for charcoal obtained from sawdust of the woods from first and fourth thinnings. Properties of charcoal made from pine wood materials and 7-yr-old *Eucaplyptus grandis* were compared. Comparison of the results revealed that though *Pinus* spp. had better chemical properties than that of *E. grandis*, the charcoal obtained from *E. grandis* had higher values of apparent density and lower values of bulk density than that of *Pinus* spp.

Maschio *et al.* (1992) reviewed the process of pyrolysis as a promising route for biomass utilization. They studied the pyrolysis process experimentally using apparatus of different scales. The influence of the main process parameters on the yield and characteristics of the products were investigated. The most attractive products of conventional pyrolysis was charcoal as the handling and use of bio-oil posed some problem due to its characteristics. The pyrolysis gas was of medium BTU gas and could be easily burnt. Fast pyrolysis gave low charcoal yield and high yield of a medium BTU gas rich in hydrogen and carbon monoxide.

Acacia and *Eucalyptus* are two fast growing exotic tree species in India. Thermo-chemical conversion of these two species were studied by Kumar *et al.* (1992). They carbonized the woods of these two tree species in the temperature range $400^0 - 1200^0$ C using two different heating-cooling cycles viz. slow and rapid. The yield of chars and their chemical compositions were found to be dependent on the carbonization temperature, heating rate,

soaking time and the nature of the wood species. The char yield gradually decreased with increase in carbonization temperature and the majority of volatilisation occurred upto 800^0 C. Slow carbonization resulted in higher char yield than rapid carbonization. The char yield from *Eucalyptus* wood samples was greater than that from *Acacia* wood. The carbon content of *Eucalyptus* wood char was found to be little higher than that of *Acacia* wood produced under similar carbonization condition, which may be due to the relatively higher lignin content of *Eucalyptus* wood.

Calahorro *et al.* (1992) investigated the possibilities of production of charcoal by carbonization of wastes generated during the olive grove (*Olea europea* L.) prunning. They aimed at studying the quality of charcoal obtained from different parts of the olive tree by pyrolysing at 600^0 C in a dynamic atmosphere of nitrogen or in an uncontrolled atmosphere of air. They also studied the influence of particle size of the raw materials on the quality of charcoal. The surface areas and helium densities of all the charcoals prepared were also determined. Greater values of pyrolysis yields were observed for processes carried out in a nitrogen atmosphere than for those obtained in air while the results of ultimate analysis and proximate analysis of charcoal samples obtained in a nitrogen atmosphere and air did not vary significantly. They also observed an increase in quality of charcoal as the size of the starting raw materials increased. They remarked that characteristics of final product of carbonization depended to a greater extent on the nature of starting material and the temperature of pyrolysis than on the kind of atmosphere in which pyrolysis was carried out.

Lim & Lim (1992) studied the carbonization of oil palm trunks at moderate temperature ranging from $400^0 - 550^0$ C with holding time of $1 - 3$ h and at two heating rates. They reported a non-dependence of holding time on quantity and quality of charcoal produced. Heating rates had little influence on yield and fixed carbon content of charcoal whereas increased terminal temperature of carbonization caused decrease in yield and increase in fixed carbon content. Calorific value and ash content of the charcoal were found to be independent of the varying parameters. From the study, they concluded that oil palm trunks are not suitable for carbonization as the charcoal produced showed low caloric content and high ash content. In another study, Lim & Vizhi (1993) carbonised cocoa tree prunnings at moderate temperature ranging from $400^0 - 550^0$ C with holding times of $1 - 3$ h and at a constant heating rate of 5^0 C/m and found that holding time had no significant effect either on the yield or on charcoal quality. Increase in terminal temperature showed a negative effect on yield and volatile matter content and a positive effect on fixed carbon content and calorific value. Ash content was however not affected by the holding time or terminal temperature. Findings of their study indicated that charcoal of acceptable quality could be produced from cocoa tree prunnings.

In another experiment, Lim (1993) carbonised the cocoa wood prunnings at higher temperature ranging from $600^0 - 800^0$ C. The proximate analysis of the charcoal thus produced and that of the raw wood revealed a clear dependence of yield, volatile matter and fixed carbon content on terminal temperature. However, no clear trend of variation in the ash content and moisture content of charcoal produced at various temperatures was

observed. He also found that there was very small incremental increase in the fixed carbon content after achieving a terminal temperature range of 650^0 – 700^0 C, and therefore he had suggested that for industrial scale charcoal production from cocoa wood, a carbonization temperature ranging from 650^0 – 700^0 C is sufficient when heating rates of few degree centigrade are employed.

Lim *et al.* (1994) further investigated the physical properties and burning characteristics of cocoa wood charcoal. They reported that the quality of cocoa wood charcoal was quite comparable to those of other commercial grade charcoals. Results of their study revealed that density of cocoa wood charcoal is lower than those of most commercial charcoals while its friability and caloric content were comparable to mangrove wood charcoal. He also observed that the time taken for ignition of cocoa wood charcoal was shorter than that of other charcoals. They opined that cocoa wood charcoals were no way inferior to other commercial grade charcoals as far as their physical properties and burning quality were concerned.

Rockrose (*Cistus ladaniferus* L.), a woody shrub was studied by Gomez-Serrano *et al.* (1993) as a potential raw material for manufacture of charcoal and activated carbon. Rockrose wood as well as its charred and activated products prepared by varying heat treatment (200^0-1000^0 C) conducted under different conditions were characterized in terms of composition, calorific value, texture and surface chemistry employing different techniques such as TGA, gas adsorption, mercury porosimetry, density measurements, SEM and FT-IR. The wood composition and calorific value were found to be similar to other woods. Production of charcoal

occurred even at 400^0 C. Above 600^0 C, the micro porous structure of the chars became partially closed. Activated carbons were prepared by gasification of charcoal (obtained at 600^0 C) in air at 600^0 C and in CO_2 and steam at 750^0 C. They observed significant differences in properties of the activated carbon depending on the activating agent. The presence of surface oxygen groups containing carbon – oxygen single bonds, which may be formed from carbon – carbon double bonds, was greater with air and steam than in CO_2.

Fuwape (1993) reported the combustion related properties viz. moisture content, specific gravity and percentages of carbon, hydrogen, oxygen, nitrogen, sulfur and ash in wood as well as in charcoal from two agro-forestry tree species *Leucaena leucocephala* and *Techtona grandis*. He reported significant differences in the moisture content, specific gravity and percentage elemental composition and ash content in wood and charcoal produced from the two species. Charcoals produced from the two species were found to have higher carbon content, ash content and average heat of combustion than their parent woods.

Effect of carbonization temperature on charcoal yield and quality produced from some tropical fast-growing and short-rotation forest tree species viz. *Gliricidia sepium, Leucaena leucocephala* and *Gmelina arborea* were evaluated by Fuwape (1996a). Out of the three species, *G. sepium* yielded the highest yield of charcoal. Yield and volatile matter content of the charcoal were found to decrease with an increase in carbonization temperature while there was an increase in the percentage of fixed carbon content.

In traditional process of charcoal production, a good amount of charcoal in the form of charcoal fines is left in the production sites because of difficulty in collection. Even small pieces of charcoal also do not fetch a good price in the market and left in the production site as waste. Fuwape (1996b) studied the possibilities of making briquette from the charcoal fines and small pieces of charcoal and found that briquettes made from these waste materials were as good as good quality charcoals. He also reported that average gross heat of combustion of briquettes made from charcoal fines was not significantly different from that of good quality marketable charcoal.

Mok *et al.* (1992) reported that very high yields of charcoal production (40 % from cellulose and 48 % from hemicellulose) could be obtained in a sealed reactor. They concluded that higher charcoal yields can be obtained when species with high lignin content and/or low hemicellulose content are used as feedstock. They employed the technique of Fourier Transform Infrared (FTIR) spectroscopy to determine if the charcoal produced in a closed retort is subsequently different from that produced in conventional charcoal kilns and found that charcoals prepared in sealed reactor were chemically the same as those prepared in conventional reactors.

In a study, Shah *et al.* (1992) aimed at understanding and upgrading the process of wood to charcoal conversion, commercial partial-combustion kiln (PCK) was used for experimental carbonization that yielded a mass efficiency of 15 –30 % (based on initial wet mass). They observed that in the present process, control of these kilns was tedious, subjective and difficult to generalise. Lower mass yield also contributed to deforestation and atmospheric pollution through smoke. Their investigation on a pilot PCK for

weight loss during carbonization, smoke characteristics and kiln temperature revealed that weight loss and smoke temperature could yield useful process parameters. Oxidation of the carbonization smoke was important in production of charcoal by PCK.

Khristova & Vergnet (1993) assessed the suitability of two unusual biomass materials viz. *Hibiscus sabdariffa* var. *sabdariffa* stem and *Calotropis procera* wood of Sudan as potential raw material for charcoal production. Physical properties and chemical constituents of these two biomass materials were determined. The carbonization trials were carried out in a laboratory scale retort under conditions close to that of field condition. Though the charcoals of *H. sabdariffa* and *C. procera* had low density and high wood-to-bark ratio by volume, the charcoal yield and quality were comparable to those obtained from other tree species. Proximate analysis of charcoals obtained from these two tree species revealed that 79 %, 86.5 %, fixed carbon content respectively with gross heating value of 30.3 MJkg^{-1} for *H. sabdariffa* and 32.4 MJkg^{-1} for *C. procera* charcoals. Low density of both the charcoals and consequently more reactivity and fast burning were the only disadvantages. *H. sabdariffa* charcoal would be good for domestic use while *C. procera* charcoal was better with respect to fixed carbon content and gross heating value. They opined that further trials would be decisive for balancing the availability and low cost of the raw materials, good yield and energy value of the charcoal against low density, porosity and friability.

Connor & Viljoen (1995) reviewed the progress made in understanding the fundamentals of wood carbonization. He emphasised on the need to improve the efficiency of the present charcoal production techniques for

increasing charcoal yield. For this, a better understanding was needed of the fundamentals of carbonization and particularly the kinetics, heat and mass transfer processes occurring within and around individual wood pieces as they carbonize. The factors affecting carbonization within particles like wood are its chemical constituents, physical properties and wood structure. They also reported that external conditions such as temperature, heating rate and pressure were also important as far as their influence on wood carbonization was concerned. They suggested for further co-ordinated and concerted research work to understand the carbonization fundamentals as the knowledge about the physical and chemical processes occurring during carbonization were not very clear.

Density and permeability are two major physical properties of wood that could be expected to influence significantly the migration rate of volatiles and thereby affecting final char yield during carbonization. Initial experiments by Connor et al. (1996) involving closely related tree species revealed a fair correlation between density of wood and charcoal yield. But further investigation with different wood species showed that co-relation between density and charcoal yield was tenuous. Early results for wood samples from several Eucalyptus species grown in Brazil confirmed the lack of relationship between density and charcoal yield but suggested a stronger link between permeability and charcoal yield. However, extension of the investigation to woods of widely varying densities and permeabilities showed that no straight forward relationship exists between density, permeability and charcoal yield.

Production of charcoal from unbroken babassu (Orbignya martiana) nut was investigated for their suitability as a potential feedstock for

steelmaking in Brazil. The physical and chemical properties of babassu nut following heat treatment upto 1000^0 C were reported by Emmerich & Lunego (1996). Comparison between some important properties for steelmaking use of babassu charcoal carbonized at 600^0 C heat treatment temperature (HTT), reference charcoal and reference metallurgical coke revealed that babassu charcoal at 600^0 C HTT were of higher density, low sulfur content and low phosphorous content. They concluded that production of babassu charcoal would be enough to supply a significant part of required feedstock for Brazil and also would lead to the preservation of babassu palm forest unlike other native charcoals where the tree is sacrificed.

Ishengoma et al. (1997) reported the quality of charcoal produced from *Leucaena leucocephala* in earth kilns in Tanzania. Though density of *L. leucocephala* charcoal was lesser but its calorific value and ash content were found to be better than those of the commercial grade charcoals.

Sadakata et al. (1997) studied the fundamental aspects of carbonization of waste wood, lignin and holocellulose. Carbonization of wood and extracted lignin and holocellulose was carried out in the temperature range of 400^0-900^0 C using a small-scale electric furnace. Mass balance of decomposition products of wood, lignin and holocellulose revealed that char yield decreased gradually from 40 % to 20 % in wood, 25 % to 10 % for holocellulose and 80 % to 45 % for lignin with an increase of temperature from 400^0 to 900^0 C. The tar yield was <1% at 700^0 C from the holocellulose and 4% from both wood and lignin. Yield of gas from holocellulose was >80 % at 900^0 C, while that from lignin was around 35 %. CO was the major product above 500^0 C in all *the cases. The largest yield of CO was given by holocellulose. CH$_4$ yield was*

more from lignin than from holocellulose. More hydrocarbons were present in the gas obtained form lignin. Calorific value of the gas produced from lignin was found to be higher than that from holocellulose. From elemental analysis of the char samples obtained from wood, lignin and holocellulose, it was observed that char from lignin contained 90 % carbon when carbonization temperature was > 800^0 C. The calorific value of the lignin char was (30.6-31.8 MJ kg^{-1}), found to be slightly higher than that of wood or holocellulose.

Wood quality and charcoal quality of nine *Eucalyptus* species were evaluated by Trugilho *et al.* (1997a) with a view to identify the highly potential genotype for use as energetic raw material. Three multivariate techniques: i) variance analysis, ii) cluster analysis and iii) canonical variable analysis were used to evaluate the quality of wood and charcoal. The multivariate variance analysis showed a significant difference between the genotypes when Roy test was used for both wood and charcoal qualities at 1% probability. *E. maculata* presented the highest distance (D^2) in comparison to other species for wood and charcoal. *E. grandis* also presented a higher dissimilarity than the other species, showing a higher breeding potential in the selection of superior genotypes. *E. cloeziana, E. pellita and E. tereticornis* were found to be more suitable species for charcoal production due to their higher lignin contents. They further studied these species to evaluate their wood quality for charcoal production (Trugilho *et al.*, 1997b). The co-relation between a group of variables related to charcoal characteristics and a group of variables related to wood quality was studied through the use of multivariate technique of canonical correlation. The canonical correlation showed that the properties of wood that are highly associates with charcoal quality were the

high basic density, low ash content, high lignin content, thickness of fiber walls and fiber wideness. Based on this observation, they suggested that these variables must always be analysed conjunctly in studies related to charcoal productions.

Supply of dry wood for charcoal production from a *Eucalyptus cloeziana* plantation in Brazil was assessed by Lopes *et al.* (1998). The biomass yield of the plantation was determined by using Bitterlich method and equations were established to predict yield of wood per hectare. Charcoal yield was 34.4 % and the mean fixed carbon content was slightly below 77 %. The rotation ages, under maximum mean increment per month and the yields per hectare in volume, wood dry weight, charcoal and fixed carbon were 84 months, 87 months, 89 months and 89 months respectively.

Efforts were made to carbonise eight species of forest and fruit bearing trees in Tunisia that have been mostly used by country men for charcoal preparation through traditional vertical stack method (Mlaouhi *et al.*, 1999). Each species was divided into three diameter classes < 10 cm, >10 cm but < 20 cm and > 20 cm for the carbonization study. The wood humidity of the species varied from 16 % to 20 % and the density was in the order of 0.8 to 1.1 gm/cc. A final temperature of $600^0 - 700^0$ C was employed during carbonization with the duration ranged from 110-130 h. The yields of charcoal from wood samples of different diameters were found to be proportional to their wood densities. Out of the three diameter classes of each of the tree species, five tree species showed the highest yield in < 10 cm diameter category, two species showed in >10 cm but < 20 cm diameter category and only one species showed the highest yield in > 20 cm diameter category.

Citrus aurantium gave the highest yield (27.6 %) for the category of wood having a diameter of less than 10 cm while *Olea europaea* gave the highest average charcoal yield considering all the diameter classes. They also observed that the duration of carbonization was proportional to the rate of wood humidity.

Schenkel *et al.* (1998) evaluated the performance of mound kiln carbonization process used throughout the developing world. Various indicators like mass yield, energy yield and balanced mass yield were used to assess the quantitative and qualitative efficiency of the mound kiln carbonization process and also other carbonization processes. From a comparison of various indicators of the different processes, they showed that the mound kiln carbonization process was as efficient as improved processes and was characterised by mass yields ranging from 20 % – 30 % as dry weight basis and by fixed carbon contents above 75 % as dry weight basis. The findings led them to suggest that in the present socio-economic condition of the developing countries, the mound kiln carbonization technique was quite appropriate because of its low investment, great mobility and its versatility regarding wood materials. However, the results of mound kiln carbonization technique depended mainly on the charcoal makers experience in building the kiln, operational skill and conscientiousness.

Schenkel *et al.* (1999) proposed a new indicator for the evaluation of the wood carbonization process. The present evaluation methods viz. mass yield, energy yield, and balanced mass yield – require parameters that are either dependent on final temperature or difficult to measure. The reference *mass yield (RMY) as proposed by them was based on variables that are*

commonly measured by carbonization experiments, the masses of wood and charcoal and the fixed carbon content of the charcoal. This indicator i.e. reference mass yield was independent of the carbonization temperature and hence of the charcoal quality. From the study, they concluded that RMY could be a useful tool to assess the validity of the results of a carbonization process and to verify the balance between the mass yield and the fixed carbon content.

Antal *et al.* (1996) described a practical method for manufacturing of high quality charcoal from biomass that realises near-theoretical yields of 42 % – 62 % with a reaction time of about 15 min to 2 h depending on the moisture content of the feed. The quality of charcoal so produced was comparable with the highest quality, most expensive charcoals available in the market. They reported that use of wet biomass feedstocks and application of higher pressure inside the carboniser improved the charcoal yield. This is because, an efficient heat transfer within the reactor led to the formation of a more uniform charcoal throughout the bed. In addition, the process developed by them had the additional advantage of reducing deforestation. With 45% transformation efficiency, this process would consume only 2.2 kg of biomass per kg of charcoal as against 5 kg of dry biomass per kg of charcoal produced in a conventional kiln operating at a 20 % efficiency.

Antal *et al.* (2000) further tried to increase the yield of charcoal by developing a new process where the yield of charcoal attained the theoretical value predicted to exist when thermo-chemical equilibrium is realized. They obtained high yields of fixed carbon at 1.0 MPa from a wide variety of agricultural wastes. They found higher yield of charcoal when pyrolysis was carried out in an electrically heated pressure vessel at 1.0 MPa with rapid

pyrolysis. The equivalent yield was otherwise achievable when slow pyrolysis was employed. The charcoal yields and fixed carbon content obtained from some biomass feeds such as kukui nut shell, bamboo and leucaena wood, attained the theoretical values predicted to exist when thermochemical equilibrium was realized at 1.0 MPa. In most cases, the measured fixed carbon yielded at 1.0 MPa exceed 80 % of the theoretical values. They also established a correlation between the fixed carbon contents at 1.0 MPa and the acid-insoluble lignin content of biomass feeds. They concluded that substitution of renewable carbon from biomass for coal in the metallurgical industry and elsewhere can reduce green house gas (GHG) emission while creating new jobs in the developing world and enhancing the profitability of agribusiness.

Matsui *et al.* (2000) reported the material balance of carbonization products (wood gas, wood vinegar, wood tar and charcoal) from the heartwood and sapwood of sugi (*Cryptomerica japonica* D. Don) at various temperatures. The yield of charcoal decreased because of the evolution of the wood gas with an increase in carbonization temperature. The total yield of wood vinegar and wood tar was almost constant at $500^0 - 800^0$ C. The wood vinegars obtained at temperatures over 400^0 C were found to consist of carboxylic acids such as acetic acid and propionic acid along with methanol, acetone, furans, alkylphenols, guaiacols, cyclotene and maltol. They remarked that as the constituent varieties and contents of the wood vinegars prepared at both 400^0 and 800^0 C were similar, the wood vinegars of Sugi wood was chiefly produced below 400^0 C. FTIR spectra of the charcoals showed the generation of carbonyl and olefin groups at 300^0 and 800^0 C and then the

formation of aromatic rings alongwith the disappearance of carbonyl groups below 600^0 C. The production of radical species in the charcoals carbonised at 300^0-600^0 C was observed by ESR; but, on the contrary, the charcoals carbonised below 700^0 C were inactive. The surface area and the pore volume of the charcoal of Sugi sapwood increased with an increase in carbonization temperature.

Fagbemi et al. (2001) evaluated the amounts of various pyrolysis products (charcoal, gases, tar and water) from three biomasses viz. wood, coconut shell and straw at temperatures ranging from 500^0 to 1000^0 C. The yield of charcoal regularly decreased with increase of temperature. At 900^0 C, the yield was between 21 % - 31 %, depending on the type of biomass used. At a given temperature of pyrolysis, the yield of charcoal was found to be the highest from straw followed by coconut shell and wood. Gas volume showed a sharp increase above 500^0 C and at 900^0 C, it constituted around 45 % - 50 % with respect to the weight of raw dry biomass. Straw appeared to yield more gas than other tested biomass materials which was attributed to their low thickness of the cell walls resulting in higher heat transfer favouring gas and tar production. The quantity of tar reaches a maximum value at about 500^0 C and then dropped with increase of temperature. The maximum yield of tar product seemed to be dependent greatly upon the types of biomass materials. The higher yield was found to be 35 % for wood and around 22 % for other two biomasses at 500^0 C without subsequent thermal cracking of the tar. The thermal cracking of the tar was studied and a kinetic model was proposed that quantified the tar content of gas from a wood gasifier and subsequently allowed the calculation of its heating value.

Charcoal being one of the major sources of domestic energy in most African countries, the potential of indigenous trees and shrubs for sustainable charcoal production in Laikpia, Kenya was explored by Okello *et al.* (2001). *Acacia drepanolobium* was investigated for sustainable charcoal production as it occurred in almost mono-specific stands in high densities over vast areas and it coppiced readily when harvested or top killed by fire. Suitability of *A. drepanolobium* was evaluated by developing predictive equations for standing biomass and charcoal production yield by undertaking a chrono-sequence analysis of its regrowth. Woody biomass was strongly related to stem diameter while efficiency of charcoal production from earthen kilns was in between 10 % - 18 %. Biomass in coppicing stands accumulated at a mean rate of 1.3 Mg ha^{-1} in a 14 year period yielding dry biomass of 18.26 Mg ha^{-1} useable wood that could produce a minimum of 3.0 Mg ha^{-1} of charcoal. Based on their experiments, they proposed that *A. drepanolobium* could be harvested for sustainable charcoal production over a period of 14-year cycle. They suggested that production of charcoal be commercialised using modern kilns to improve and maximize yield.

Modifications in the micro-structure of wood from *Prosopis nigra* as a function of temperature were studied by scanning electron microscopy (SEM) (Pasquali *et al.*, 2002). Some non-condensable gases obtained by isothermal pyrolysis were investigated by employing gas chromatography (GC). The results showed that the basic anatomic structure of wood remains almost uncharged in the working temperature range.

Sensoz & Can (2002) investigated the effect of temperature, heating rate and pyrolysis atmosphere on the pyrolytic product yields of turkish pine

(*Pinus brutia* Ten.) using a laboratory-scale fixed bed reactor. Pyrolysis runs were performed using reactor temperatures ranging from 300^0 to 550^0 C with a heating rates of 7^0 C min^{-1} and 40^0 C min^{-1}. The char, gas and liquid yields obtained ranged from 23 % - 36 %, 11 % - 23 % and 21 % - 30 % by weight respectively at different pyrolysis conditions. The highest liquid yield was obtained at 500^0 C with a heating rate of 40^0 Cmin^{-1}. They concluded that the significant pyrolytic conversion in the temperature interval of 450^0 - 500^0 C was due to the rapid devolatization of cellulose and hemicellulose.

Mochidzuki *et al.* (2002) showed that proper ignition and control of flash fire at 1 MPa inside a packed bed of biomass. had triggered its transformation to carbon with yields that reached the thermochemical equilibrium "limit" in less than 30 min of reaction time. The remarkable ease with which a flash fire at elevated pressure triggered the transformation of various types of biomass materials ranging from high density wood to very low density agricultural wastes reasoned well for their suggestion of expanded production of biocarbons as a substitute of coal.

Sensoz (2003) pyrolysed pine bark (*Pinus brutia* Ten.) in an externally heated fixed bed reactor and investigated the effects of temparature and haeting rate on the yield and composition of the product. Pyrolysis runs were performed using reactor temperature between 300^0-500^0 C with heating rates of 7^0 and 40^0 Cmin^{-1}. The maximum liquid (aqueous and oil phase) yield (33.25 % wt.) was obtained at a final temperature of 450^0 C. However, by increasing the pyrolysis temperature to 500^0 C, the liquid yield went down to 32.79 % wt. The char yield decreased with increase in the final temperature. At a particular temperature, lower heating rate yielded higher char yield. The

yield of gas products increased with increase in temperature. Sensoz concluded that both the temperature and heating rate had significant effects on both yields of liquid and char resulting from pyrolysis of forest biomass. Chemical fractionation of the bio-oil (pyrolytic oil) showed that it was composed almost entirely of oxygenated compounds with only low quantities of hydrocarbons.

Er Gin & Yiiriim (2003) investigated the carbonization of fir (*Abies bornmulleriana*) in an open pyrolysis system under a nitrogen atmosphere at varying temperatures to contribute to the knowledge of the artificial coalification. Bark-free samples in sawdust form were pyrolysed isothermally in the temperatures ranging from 50^0 to 300^0 C and with heating times ranging from 1 h to 50 h. Conversion of the wood took place with higher rates during the initial times and reached a steady state after approximately 35 h of heat treatment at all temperatures. The simultaneous increase in the amount of volatiles after 150^0 C can be explained by the fact that depolymerization of the network took place at higher temperatures. Evolution of a coal like pattern in the FTIR spectra of the carbonized wood could be observed by disappearance of bands due to cellulose, hemicellulose and lignin in the range of $130\sim1000$ cm^{-1} and appearance of two new bands at about 1250 cm^{-1} (asymmetric Cm- O-C stretching vibrations) and 1450 cm^{-1} (aliphatic C-H bending). The H/C ratio decreased too early before the end of the diagenetic stage and as the temperature of pyrolysis was increased, a decrease in the O/C ratio was observed which corresponded to the dehydration and decarboxylation of the original material.

Influence of some inorganic agents on catalysis or carbonization has been an area of interest for many researchers around the globe. DeGroot & Shafizadeh (1984) reported that addition of cations of calcium and potassium to wood through ion exchange had remarkable effects on the thermal decomposition of wood. Addition of calcium ions enhanced the decomposition temperature and affected the char yield slightly, whereas addition of potassium ions reduced the decomposition temperature and significantly increased the char yield. They remarked that these effects were distinct from the effects of salts of the same elements added to the wood or similar materials through absorption of a solution of the salt. Potassium carbonate absorbed on cellulose significantly increased its decomposition temperature, although it had the opposite effect when added to wood through ion exchange. They assumed that the primary sites for ion exchange were glucuronic acids in the hemicellulose fraction and it was therefore likely that the effects of exchanged cations were due primarily to their influence on the decomposition of this component. This was testified by the fact that when naturally occurring inorganic molecules were removed from wood by acid washing, the char yield was reduced and the structure of cellulose could be lost during carbonization particularly at high heating rates.

Zandersons *et al.* (1998a) reported that reasonable and effective catalysts were not only able to increase the yield of char but also to form structure appropriate for production of activated carbon. Sulphuric acid, diammonium phosphate, zinc chloride and refinery acid tar were used as catalysts and specific sized wood samples were soaked in solutions of these catalysts before carbonization at a heating rate of $3^0 - 4^0 Cmin^{-1}$ to a maximum

temperature range of 500^0-520^0 C. Charcoal yield under the influence of the above mentioned catalysts was found to be increase from 105 % to 139 % and the decrease of tar yield was approximately proportional to increase of charcoal yield. The most effective catalysts such as sulphuric acid caused radical decrease of dissolved tar yield.

Kim *et al.* (2001) used sulphuric acid as an inexpensive, nonvolatile dehydrating agent and examined the influence of its addition on pyrolysis of cellulose and wood in terms of yield, surface area and porosity. Cellulose – the most abundant organic material on earth was choosen for improvement of its carbonization yield. Charcoal and wood samples were first treated by immersing them in dilute sulphuric acid at various concentrations (1 %, 5 %, 10 %, 15 %, 20 %) for a few minutes. On carbonization of the treated as well as untreated samples, it was observed that yield of charcoal was increased significantly for treated samples at lower concentrations (up to 5 %) of the acid. Thus the presence of small amounts of sulphuric acid was found to be highly effective in improving carbon yields from cellulose and wood. Thermogravimetric analysis of original cellulose and sulphuric acid impregnated cellulose revealed that addition of sulphuric acid had lowered the onset of decomposition presumably through efficient dehydration and resulted in significantly higher char yields which reached 2-3 times of the untreated cellulose. Similar results were also obtained from thermogravimetric analysis of hardwood and softwood samples. Surface area of char obtained by heating the treated wood at 800^0 C was found to be 500-570 m^2g^{-1} while that of untreated wood char was found to be 400-430 m^2g^{-1}. Scanning electron micrograph of treated and untreated samples revealed that the untreated

samples were significantly deformed and shrunk while the morphology of the sulphuric acid treated samples was largely preserved with very small shrinkage. EDXA spectra of charcoals obtained by carbonizing the treated cellulose and wood samples at 600° C showed that the materials were nearly pure carbon with traces of oxygen and no traces of sulphur which confirmed that impregnated sulphuric acid was completely decomposed and volatilized below 600° C. They concluded that sulphuric acid impregnation could be useful for preparation of carbon materials from cellulose or wood in terms of mass yield and preservation of the original shape.

Connor & Viljoen (1998) discussed ways for improving the efficiency of charcoal production with particular reference to kilns. They pointed out that existing large-scale charcoal producers use kiln designs and operating practices that give reasonable yields and efficiencies. These designs and practices were results of largely empirical research and development procedure and very little attention being paid to fundamental aspects of wood decomposition processes and kiln behaviour. They pointed out that charcoal producers needed to acquire a better understanding of process fundamentals and to incorporate this into designs and operating procedures for further improvement in the efficiency of kiln-based charcoal production processes. According to them, the recovery of volatiles for subsequent use from kiln exhaust gases was the most promising way for making the process more energy efficient.

Muylaert *et al.* (1999) evaluated the technical feasibility of implementing a new method of charcoal production in Brazil and examined the environmental benefits of the method over the conventional muffle

furnaces. This new muffle type furnace with external combustion chamber had higher production efficiency and this would mean utilization of less amount of wet wood for production of same amount of charcoal than conventional muffle furnace methods. This in turn, had potential to save 18.7 million tons of wet wood per year and consequently, 1.4 million hectares of land would be saved from deforestation per year. The most important point was the reduction of CO_2 emission. They reported that if the new type of carbonizer was used, it could reduce the CO_2 emission by 25.7 million ton per year.

Zendersons et al. (1998b) and Zandersons & Zurins (1999) described a technology developed at the Latvian State Institute of Wood Chemistry, Latvia for lump charcoal production by small and medium sized enterprises in rural conditions. The new technology was an indirect heating equipment combined in a block with a common furnace. This was found to be more appropriate for environment friendly production of charcoal than the equipment utilizing direct heating. They demonstrated that the direct heating equipment were appropriate for processing of dry wood only, otherwise to dry wood from a moisture content of 50 % - 20 %, an extra liquid or gaseous fuel is needed that shoots up production costs substantially. Indirectly heated apparatus though expensive than partial combustion equipment, the corresponding technology was environment friendly and resulted in higher charcoal yield. They suggested that in densely populated areas and countries, charcoal producers should be encouraged to use indirectly heated equipments.

Noxious gas emission in conventional charcoal production technique using partial combustion devices can not be prevented by introducing economically viable methods. Zandersons et al. (1999), developed an

equipment which had provision for burning wood thermal degradation non-condensable gases and vapours for initial drying of wood. It was therefore considered to be more environment friendly and energetically self-sufficient once the process was started. The concentration of noxious compounds in effluent gases (CO_2, NO_x, and solid particles) did not exceed the level reached in industrial-scale firewood furnaces. Charcoal quality also conformed European standard for lump charcoal.

In an effort to explore new raw materials for sustainable charcoal production in Brazil, Zandersons *et al.* (2000a) evaluated the possibility of using sugarcane bagasse for charcoal production. The physical and chemical compositions of sugarcane bagasse were determined to examine its suitability for use as feedstock in industrial charcoal production. They suggested the use of rotary drum type apparatus for charcoal production from bagasse and recommended a two-stage process such as heating up and pyrolysis stage upto 300^0 C in three parallel rotary-drums with externally heated thermoreactors and the glowing stage with the peak temperature ranging from 475^0 to 500^0 C in a single rotary drum reactor. Material balances were drawn up and the joint potential amount of heat was calculated. They showed that the heat flow of pyroligneous vapour, formed by combustion of all the volatile biomass thermal destruction products in the furnace had exceeded the upper limit of the heat necessary to carbonize sugarcane bagasse by 1.6 to 1.8 times. Hence, the technology using sugarcane bagasse for charcoal production would be energetically self-reliant. Such a reactor, according to them would also considerably improve the emission situation as it will drastically reduce the emission of noxius gases to an environmentally acceptable limit.

In an another attempt, Zandersons *et al.* (2000b) studied the feasibility of upgrading the powdery sugarcane bagasse charcoal to usable and applicable forms for domestic and industrial use and more particularly for quartz reduction to metallic silicon. As the quartz reduction technology needs charcoal lumps of not less than 1.5 cm with good strength, the task of converting powdery charcoal to lump charcoal was done first by milling the charcoal to a granularity of less than 0.2 mm and by making use of binders. Use of 20 % molasses or 20 % - 30 % wood tar as binders provided a optimal compression strength of briquettes. The use of leaching techniques with strong mineral acids for reduction of impurities was necessary to allow its use for purification of metallurgical silicon to electronical grade silicon. They concluded that sugarcane bagasse could be effectively used as raw material for carbonization and the process would be environment friendly, energy self-dependent and a continuous-flow technology. The need for extra fuel was not necessary for carbonization if proper design and construction of the processing unit could be realised.

The impact of charcoal production on forest land has always been a matter of concern for environmental activists. Chidumayo (1993) studied the recovery of miombo woodlands following clearance of woodland for carbonization. Though charcoal production removed 50 % of the total woody biomass, clearing of successive regrowth miombo did not appear to affect productivity. However, the sites where carbonization was carried out, the soil structure, seedlings and root stocks were found to be destroyed/damaged. Fortunately, these sites covered only 2 % – 3 % of the deforested area and thereby he contradicted the popular belief that land degradation was caused by

deforestation for charcoal production in the miombo woodland region of central and southern Africa.

Monela *et al.* (1993) conducted a survey to assess the socio-ecinomic aspects of charcoal consumption and its impact on the environment along the Dar es Salam – Morogoro highway in Eastern Tanzania. Data were collected through field observation, monitoring at a selected forest products checkpoints and interviewing charcoal producers, traders and consumers, over a period of one year covering both rainy and dry seasons. Returns from charcoal production of the rural households were also calculated. They reported that a total area of 1524 km^2 was cleared for charcoal production in the last 35 years. Such heavy dependence on charcoal of rural communities either for domestic energy purpose or for earning a livelihood could be attributed to the fact that charcoal was the most affordable and efficient fuel in the study area. They concluded that heavy charcoal consumption near the growing city of Dar es Salam promoted the charcoal business with a positive impact on households but at the expense of environmental protection.

Cutting of wood for fuelwood and charcoal has been cited as a major cause of deforestation by various workers. But Openshaw (1996) contradicted this point and opined that the change of land use pattern was the major cause of deforestation. According to Openshaw, the principal reason was expanding land under arable agriculture with extending cattle farming and urbanisation were other factors. He suggested that rather than viewing the use of wood as a cause of deforestation and one of the reasons for global warming, the management of existing tree resources, the planting of trees and above all the expanded use of wood, especially wood energy could be a major strategy to

slow down and eventually reverse the production of excess green house gases. He opined that the use of trees should not be regarded as a problem, but as a solution to sustainable economic growth.

Hofstad (1997) constructed a dynamic model of deforestation around Dar es Salaam linking marginal cost and demand of charcoal. The exploited area formed a wedge, which expanded in side as net price of charcoal increased. Wood was primarily harvested at the edge of the wedge. Simulations were drawn up that showed with an increase in charcoal price, supply area had also increased along with harvest rates. Increment of woody biomass within the wedge will supply little charcoal for many years because woodland density did not affect production costs. Therefore, reduced demand for charcoal and shift to other forms of energy were the controlling factors of deforestation.

deMiranda (1999) discussed the deforestation and forest degradation by commercial harvesting for firewood and charcoal in the Pacific region of Nicaragua. He surveyed and analysed the ground situation and reported that deforestation appeared to be more associated with the changes of use of land from forest to agriculture and cattle ranching while forest degradation appeared to be directly associated with fuelwood harvesting for both household and industrial uses and charcoal production. He concluded that fuelwood harvesting for firewood and charcoal was not the main factor causing deforestation in the tropical dry forests of the Pacific region of Nicaragua.

Economics of charcoal production in miombo woodlands of eastern Tanzania was investigated by Luoga et al. (2000). They assigned monetary

values to commercial charcoal production using traditional earth kilns through cost-benefit analysis (CBA). Charcoal was found to be the most commercialised resource in the study area. The profit from charcoal production was attributable to very low capital outlays, free own labour, free raw materials and lack of concern about associated external costs and high demand for charcoal. But when the cost of labour, raw materials and opportunity costs were considered, the net present value was negative. This indicated that profit realization was accomplished at the expense of other potential uses of the woodlands. The estimated local wood consumption for charcoal was very high compared to subsistence firewood consumption. Though commercialisation of the charcoal production provided tangible monetary benefits to rural communities, the huge area cleared for charcoal production every year would lead to the resource depletion and would ultimately threaten their long-term survival. Some policy intervention in order to safeguard the resources was recommended from the study.

With the African Development Programme (AREED) enterprise development support and seed financing, one Zambian enterprise KPBS was set up to produce charcoal from sawmill waste (Usher, 2003). For this purpose, 15 Argentine Half-Orange Brick Kilns were constructed and marketing and distribution networks were established. The long-term fuel supply and land lease agreements with the local sawmills allowed KPBS to produce 2700 tons of charcoal annually. Thus, using a waste product for fuel and a process having conversion efficiency twice as traditional methods, KPBS proved that a clean energy enterprise could both solve an environmental problem and be good business as well.

The review of the literature within the field of study is excellent. However, it is obvious that the latest years up to 2005 are not included. I assume that the literature studies were performed before the actual research started.

I will wait and see if more recent literature is used in the discussions related to your own results.

Chapter III

MATERIALS AND METHODS

Chapter III

Materials and methods

3.1 Study sites

The study sites selected for the present study were the different forest areas of the state of Meghalaya. The state is located in the north-east India and it lies between 25^0 1' and 26^0 5' north latitudes and 85^0 49' and 92^0 52' east latitudes.

The total geographical area of the state is 22429 sq. km with a population of 2306069 (as per Census report of 2001). The temperatures range from approximately 2^0 C in winter to 36^0 C in summer depending upon the altitudes ranging from 300 m to 2000 m above sea level. The state is predominantly hilly in nature. It experiences the highest rainfall in the world with an annual average rainfall of about 11000 ml.

The state has a monsoon type of climate, but with wide variations depending upon altitude and physiographic differences of land mass.

The soils of Meghalaya are dark brown to dark reddish-brown in colour varying in depths from 50 – 200 cm and acidic in nature. *how acid ? pH value*

Total area of the forests in the state is around 949550 hectares out of which only 71270 hectares are under reserved forests while a total of 850300 hectares of forest lands belong to community or individuals of the state.

3.2   Species selection

In the beginning of the study, a survey was made to identify the commonly used indigenous tree species for charcoal production by the rural people of the state of Meghalaya. For this we made visits to various charcoal producing localities of the state and interviewed about 50 nos. of local charcoal producers. Finally, a total of 41 indigenous tree species were identified which have been used for charcoal production.

To know about the preferences given on these tree species for charcoal production and also about their availability in the state, we selected 10 key informants of charcoal producers who were having 10 to 15 years of experiences in charcoal production. They were asked about the level of preferences for these 41 tree species for charcoal production and also about their availability in the state, especially in the charcoal producing areas. The level of preferences given on each of the tree species were: highly preferred (HP), moderately preferred (MP) and less preferred (LP). Similarly, information on availability of these 41 species was also classified into three levels: highly available (HA), moderately available (MA) and less available (LA). For a tree species preference level given

by the highest number of informants was considered as the correct information. Similarly, regarding the availability level of any species, if the highest number of informants reported any level (out of the three levels) that was considered to be the correct information. For example, about the availability of a particular species, if 5 informants reported as highly available (HA), 3 informants reported as moderately available (MA) and 2 informants reported as less available (LA), then the species was considered as highly available.

From the information collected through the personal interview of the charcoal producers about the indigenous tree species commonly used for charcoal production and their availability and preference given on them for charcoal production, a list was prepared and reported in Table 2. The highly preferred tree species were selected for the present study. The species were *Albizzia lucida* Benth., *Beilschmiedia assamica* Meisn., *Cassia siamea* Lamk. *Castanopsis hystrix* DC., *Diospyros peregrina* (Gaertn.) Gurke., *Dysoxylum procerum* Hiern., *Elaeocarpus varuna* Ham., *Eurya acuminata* DC., *Machilus bombycina* King., *Melia azedarach* L., *Michelia champaca* L., *Quercus dealbata* Hook. f. & Th., *Quercus griffithii* Hook. f. & Thomson ex. Miq., *Schima wallichii* Choisy. and *Terminalia catappa* L.

3.3 Characteristics of the tree species

Characteristics of the selected tree species in terms of their botanical description, wood quality, availability etc. have been described elsewhere (Gupta, 1981; Dutta, 1985; Dutta, 1989; Kanjilal *et al.*, 1997 and Haridasan & Rao, 1987).

3.3.1   **Botanical Name**   : *Albizzia lucida* **Benth.**

Vernacular name   : Dieng-tilpot (Khasi), Moj (Assamese)

Family   : Leguminosae
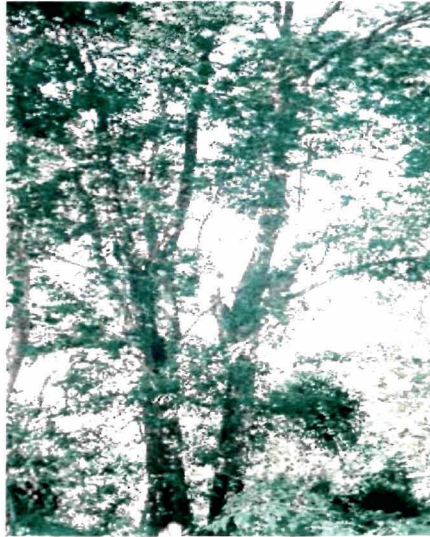
Fig. 4: *Albizzia lucida*

Middle sized tree up to 20 m high; crown oval or elongated, branches arcuate, spreading; bark grey or dary grey, smooth or nearly so, horizontally wrinkled and lenticellate; common rachis 2–4 cm long with a prominent gland, usually little above the middle, pinnae rachis 2.5–7 cm long, often with a gland near the tip; leaflets 4–14 cm × 2–5 cm, basal smaller, ovate to oblong-lenceolate, heads in subumbellate corymbose panicles, dull white, up to 2.5 cm across; corolla *ca.* 0.5 cm long, pale yellow, filaments dull white or pale yellow; pods 10–25 cm × 2.5–3 cm, shining, deep brown, 4–8 seeded.

Heartwood is hard and durable, good for house building and cart wheel and firewood. Mainly distributed in Indo-Malaya region, Assam, Nagaland and Meghalaya.

3.3.2 Botanical name : *Beilschmiedia assamica* **Meisn.**

Vernacular name : Dieng-khalang (Khasi), Amchoi (Assamese)

Family : Lauraceae

Fig. 5: *Beilschmiedia assamica*

Evergreen large trees 15-25 m high, bark pale gray to brown, horizontally wrinkled or nearly smooth; quite glabrous, leaves opposite elliptic-ovate or lanceolate, obtusely acuminate, shining and reticulated on both surfaces, fruit 7–8 cm long, very shortly pedicelled elliptic or ovoid-oblong, tip rounded, pericarp thick. Leaves 6-20 × 3-8 cm, elliptic, oblong-elliptic or lanceolate, coriaceous, palebrown when dry, base cuneate; nerves about 10 pairs, very slender, equally prominent on both surfaces; petiole 3 cm long, slender. Stamens 9 or more, perianth 5, fruits 2.5-5 cm long, ellipsoid, ovoid, ellipsoid, black when ripe.

Wood is very good for making charcoal. Widely distributed in north-east India and Myanmar.

3.3.3   **Botanical name**   : *Cassia siamea* **Lamk.**

Vernacular name   : Bon-sirish, Pahari-sirish (Assamese)

Family   : Caesalpiniaceae

Fig. 6: *Cassia siamea*

A middle sized tree. Leaves are compound with pinnate or stipules absent. The flowers are zygomorphic. Calyx is free or the 2 upper sepals may be united; the aestivation is imbricate, Corolla is ascending imbricate. Stamens are 10 or few, free or united in one or two bundles. Inflorescence: Racemose.

Wood is not too hard and yellow in colour after fresh cut. Found in all over Assam (mostly in upper Assam), areas of lower elevations in Meghalaya and planted as roadside tree.

3.3.4 **Botanical name** : *Castanopsis hystrix* DC.

Vernacular name : Dieng-sohstap (Khasi), Bor hingori (Assamese)

Family : Fagaceae

Fig. 7: *Castanopsis hystrix*

Large evergreen tree, young parts pubescent, wood hard grayish white, bark grayish-cinnamon brown, horizontally wrinkled, branches globrous or nearly so, leaves petioled, middle oppressed tomentose pubescent or puberulous beneath, nerve 10–12 pairs. Leaves 7-18 × 2-5 cm, very coriaceous oblong-lanceolate, lanceolate-elliptic, acuminate, base cuneate or rounded, sparingly toothed towards the tip; tomentose when young, spikes panicled, 5-10 cm long; involucre covered by short, stout spines, 1-2 cm across; petiole 8–12 mm. Nuts obscurely 3-angled, 2–3, 1.5–2.0 cm. Flowring and fruiting is nearly throughout the year.

Mostly found in Goalpara, Lakhimpur, Sibsagar, Dibrugarh of Assam, Meghalaya, Nagaland and Arunachal Pradesh.

3.3.5   **Botanical Name :** *Diospyros peregrina* **(Gaertn.) Gurke.**

Vernacular name : Kendu Goch (Assamese)

Family   : Ebenaceae

Fig. 8: *Diospyros peregrina*

A middle sized handsome evergreen tree with a spreading crown. Bark-blackish with numerous white blotches. Leaves - distichous, 10–20 cm × 3.5–6.5 cm, oblong or narrowly oblong, glossy green, smooth, glabrous, base rounded; petiole often twisted, 0.75–1.25 cm long. Flowers - tetramerous, white or cream coloured, scented. Male flowers in short pedunculate rusty pubescent cymes of 2–7 flowers. Calyx – 0.6 cm long, silky pubescent; segments 4. Stamens - many in pairs at the base of the corolla; anthers linear. Female flowers usually solitary, subsessile; peduncles pubescent, ovary 8-celled; style 4-lobed at the tips. Fruit - globose, 3.5–6.5 cm across.

Wood is moderately hard, used for building construction and as firewood. Found in different parts of north-east India.

3.3.6 **Botanical name** : *Dysoxylum procerum* **Hiern.**

Vernacular name : Dieng-narang (Khasi), Bandordima (Assamese)

Family : Meliaceae
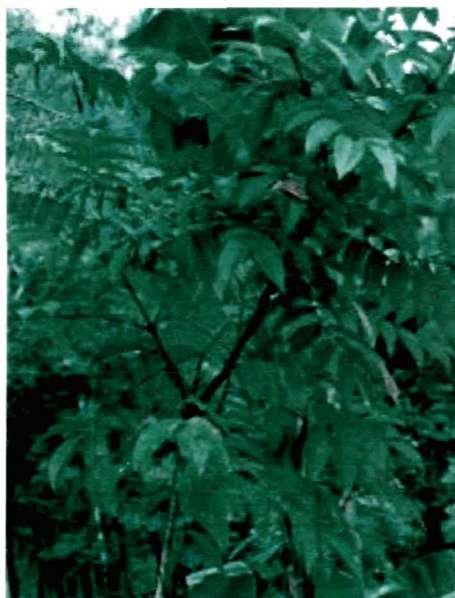
Fig. 9: *Dysoxylum procerum*

A fairly large tree up to 25 m high; bark greenish-grey, grayish-brown, smooth or scaly when mature; crown dense, oval; leaves 30–60 cm long, leaflets 5–13 in nos., 10–25 cm × 7–10 cm, ovate, ovate-oblong, base rounded, obtuse, cuneate, entire, glabrous, panicles 30-50 cm long; flowers 0.7–1 cm across, creamy white, fragrant; calyx shortly lobed; petals oblong; disc elongated; capsules 3–4 celled, pyriform, 5–6 cm in diameter; seeds black with orange aril. Time of flowering and fruiting - December – August.

Distributed nearly throughout India, common in Meghalaya in lower elevations.

3.3.7   Botanical name   : *Elaeocarpus varuna* **Ham.**

Vernacular name   : Dieng-sohkhyllam (Khasi), Pahari-varun (Assamese)

Family   : Elaeocarpaceae
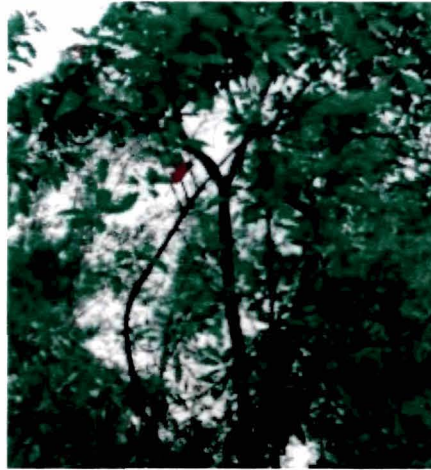
Fig. 10: *Elaeocarpus varuna*

A fairly large tree up to 25 m in height and 2 m in girth with a large spreading crown. Bark grey or brownish-grey, nearly smooth, usualy lenticellate, often with stilt roots at base, branchlets silky tomentose; leaves 13–20 cm × 4.5–8 cm, broadly oblong-lanceolate, oblong-elliptic, acuminate, rounded at base, cuspidately crenate serrate, chartaceous or thinly coriaceous, grayish-silky when young, dark green, glabrescent when mature, deep red at senescence, petiole 3.5–7 cm long, tomentose at first, racemes densely crowded, silky pubescent; flowers 1.2–1.5 cm across, buds silky, lanceolate, obscurely angled, stamens numerous, anthers shortly awned, disk red or orange red, lobed, drupe 1.5–2 cm long.

Distributed in South-Asian countries like Nepal, India, Myanmar, mostly confined to eastern region of India including Meghalaya, occasional in mixed deciduous forests along low altitude.

3.3.8. **Botanical name**   : *Eurya acuminata* DC.

Vernacular name   : Dieng-shit (Khasi), Murmura (Assamese)

Family   : Theaceae
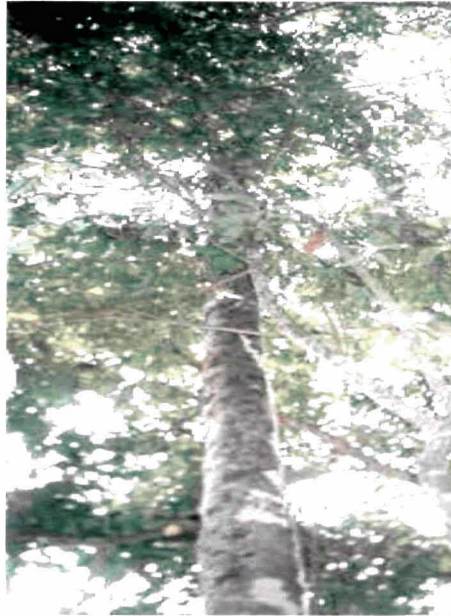
Fig. 11: *Eurya acuminata*

A small to middle sized evergreen tree, sometimes up to 12 m in height. Bark–dark-brown and fairly smooth outside, reddish inside and thin. Leaves 4–9 cm × 1–2 cm, oblong-lanceolate or linear-elliptic- lanceolate, acuminate, base cuneate, rounded or obtuse, crenate, glabrous, pale beneath, midrib channeled above, hairy beneath; flowers axillary or on fallen leaf axils, fascicled, fragment, yellow, 2-4 mm across, sepals ovate, outer smaller, petals yellow, ovate; stamens yellow, many, ovary pubescent; styles united above ½ the length; capsules up to 5 mm across, crowned by the persistent style. Time of flowering and fruiting – July to February. Wood is locally used as fuel.

Distributed in Indo-Malaya region extending to Fiji Islands, very common in varied types of forests nearly throughout Meghalaya.

3.3.9   Botanical name   : *Machilus bombycina* **King.**

　　　　Vernacular name   : Chom Goch (Assamese)

　　　　Family　　　　　 : Lauraceae

Fig. 12: *Machilus bombycina*

A middle to big sized tree up to 20 m in height with spreading crown. Bark–light dark–grey, rather rough. Blaze–mucilaginous, reddish or pinkish-brown. Inflorescence-silky. Leaves 6–13 cm × 2–4.5 cm, elliptic-lanceolate to obovate-lanceolate, oblong-lanceolate, acuminate or sub-acuminate; coriaceous, glabrous above, addressed silky beneath when young, minutely silky or puberulous with age; base cuneate or acute; lateral nerves 6–8 on either half, slender. Petiole - 0.7–1.7 cm long. Panicles-sub-terminal 4–10 cm long, branches spreading; Flowers 0.4-0.6 cm across, greenish-yellow, fruits 0.5-0.8 cm across, globose.

Wood is hard and used as ordinary timber. It is good for firewood and charcoal preparation. Muga silk worms are mainly reared on the leaves of this tree. Found through out Assam, lower Meghalaya and lower Naglanad.

3.3.10 **Botanical name** : *Melia azedarach* **L.**

Vernacular name : Dieng-jahrasang (Khasi), Ghora neem (Assamese)

Family   : Meliaceae

Fig. 13: *Melia azedarach*

Middle sized trees, crown lax, sub-oval; bark gray, grayish-brown, smooth at first, rectangular scaly in old trees; leaves bi or tri pinnate, 30–90 cm long; leaflets 2.5–5 cm × 1– 2.5 cm, ovate-lanceolate, base cuneate, oblique, serrate to entire, stellate tomentose when young; flowers 1–1.5 cm across, purple; calyx minute; petals deflexed, white, *ca.* 0.7 cm long; staminal tube purple; drupe fleshy, yellow when ripe. 1- seeded. Time of flowering and fruiting – June to December.

A very quick growing tree, distributed in Indo-Malaya region, usually cultivated in Meghalaya

3.3.11 Botanical name   : *Michelia champaca* L.

    Vernacular name   : Shap (Khasi), Tita sopa (Assamese)

    Family   : Magnoliaceae
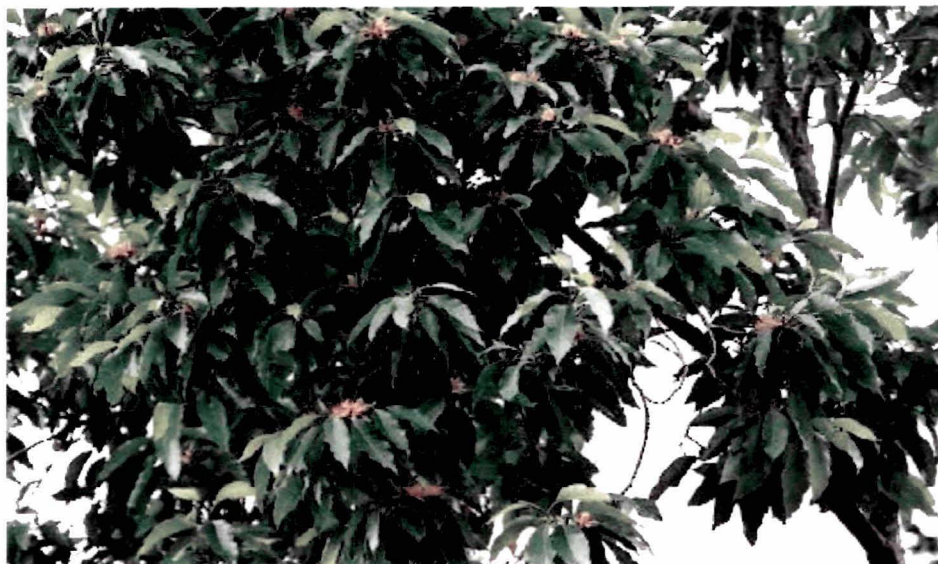
Fig. 14: *Michelia champaca*

Usually a middle sized evergreen tree up to about 22 m in height. Bark ashy-grey or brownish. Leaves 10–25 cm × 4-7 cm, lanceolate, sometimes ovate, finely acuminate, thinly coriaceous, glabrous, lateral nerves about 16 on either side of the midrib with often a few intermediate ones, slender but conspicuous. Petiole 1.7–3 cm long, slightly channeled, leaf-buds lanceolate, ferruginous-pubescent. Flowers axillary, rarely terminal, solitary 3-4 cm long, pale yellow, very fragrant; buds ovoid. Sepals petaloid, inner ones narrower, oblanceolate; fruits 7-15 cm long, cone-like, drooping; ripe carpels ovoid or ellipsoid, generally sessile.

Wood is durable, used in furniture, building works and also gives good quality charcoal. Distributed in Indo-Malaya region, usually cultivated for their fragrant flowers, cultivated as well as wild in foothills of Meghalaya.

3.3.12   Botanical name   : *Quercus dealbata* Hook. f. & Th

   Vernacular name : Dieng-sohot (Khasi), Chalsi (Assamese)

   Family   : Fagaceae

Fig. 15: *Quercus dealbata*

A small tree or shrub. Bark ashy-grey. Leaves 7.5–2 0 cm × 2.5–5.5 cm, lanceolate, usually acuminate, entire glabrous above when adult, lateral nerves 8-14 on either half; tertiaries parallel and traneverse. Inflorescence terminal, the spikes in panicles. Male flower sessile in clusters of 3; bracteoles unequal; perianth segments 5; stamens about 10. Female flowers in clusters of 3, confluent at base; styles 3; linear. Cupule sessile, woody, enclosing almost the whle of the glan; scales pubescent, connate with a free apex forming tubercles. Glans turbinate or pyriform, 1.25–1.75 cm in diameter. Ripe fruit crowded on a stout long rachis of 1–3 together.

Wood is durable and gives good quality charcoal. Common in high altitude areas of Meghalaya.

3.3.13 Botanical name   : *Quercus griffithii* **Hook. f. & Thoms. ex. Miq**

       Vernacular name   : Dieng-wah (Khasi), Shin oak (Assamese)

       Family   : Fagaceae

Fig. 16: *Quercus griffithii*

Trees up to 15 m high; crown lax, bark ash grey, fissured, warty and rough; leaves (crowded at branch tips) 10–22 cm × 3.5–12 cm, oblanceolate-elliptic, obovate-elliptic, acuminate, base narrowed, cuneate or rounded, sharply distantly serrate, glaucous tomentose beneath; male spikes slender, drooping, many together, yellow, 5-12 cm long; female clustered at tip; acorns 1–1.5 cm across; cupule adpresses scaly, covering ¼ the acrid nut.

Distributed across eastern Himalayan region, common in Meghalaya at higher elevations.

3.3.14 Botanical name   : *Schima wallichii* Choisy.

          Vernacular name   : Dieng-nganbuit (Khasi), Makorisal (Assamese)

          Family   : Ternstroemiaceae (Theaceae)

Fig. 17: *Schima wallichii*

A large tree, 15–50 m high; bark reddish-brown, warty or blotched; crown ovoid, dense, young tips silky tomentose; leaves 8–16 cm × 2.5–6 cm, elliptic-lanceolate, oblong-elliptic, oblanceolate, acute, base cuneate, margin entire, deciduously bulbous hairy beneath, glabrous above; flowers axillary, solitary or paired, white, 3–4 cm across; sepals rounded, ciliate, glabrescent; petals, ovoid up to 1.8 cm long, glabrescent; stamens yellow, nearly free, adanate to base of corolla; ovary hairy at base; style cylindric; fruits gray-pilose, up to 2 cm across, depressed globose. Time of flowering and fruiting – February to April and January to February.

Wood is commonly used as plywood, distributed in Indo-Myanmar, Nepal, Bhutan, Bangladesh, Eastern Himalayas, N.E. India and throughout Meghalaya in all types of forests.

3.3.15. Botanical name : *Terminalia catappa* **L.**

    Vernacular name   : Soh-handru-diengartaki (Khasi)

    Family   : Combretaceae

Fig. 18: *Terminalia catappa*

A tall tree with rough bark, stem often buttressed. Leaves 15–22 cm × 9–12.5 cm, obovate or obovate-oblong from a narrow cordate base; midrib sometimes with 2 depressions near the base on the under side; petiole 1.25–2 cm long, short, stout, channeled. Flowers white; spikes axillary, upper flower male and shortly pedicelled, lower bisexual. Calyx glabrous outside. Drupe 2.5–5 cm long, glabrous, ellipsoid, slightly compressed.

Distributed across Indo-Malaya region, nearly throughout India, common in Meghalaya in deciduous and tropical evergreen forest at lower elevations.

3.4 Field sampling for laboratory experiments

For each of the tree species, wood samples were collected from four different randomly selected trees of the age group 10-15 years and grown in their

natural habitats in the state of Meghalaya during March to April 2001. Size of the wood samples collected were 10 cm in length with diameter classes ranging from 10-15 cm, 15-20 cm and 20-25 cm outside the bark. Freshly cut wood samples of each of the tree species were put in polythene bags and sealed to avoid loss of moisture from it. They were labeled and brought to the laboratory for experimental works.

3.5   Analytical methods

Dry wood samples were first ground to fine powder form. This was then passed through a 40-mesh (0.4 mm) sieve and the resultant particles of size less then 0.4 mm were taken for analysis.

The wood samples thus obtained were further prepared according to TAPPI method (T 264 om-88). This includes i) fractionation of very fine materials that may clog fine filters or pass through coarse filters producing erroneous results, ii) extraction with ethanol-benzene except where the extraction process and subsequent washing could interfere with certain chemical analysis.

3.5.1 Determination of moisture content

Moisture content (MC) of the wood samples was determined according to the TAPPI method (T 258 om–89). For this, a 10 g of sample was weighed immediately after sampling and then air-dried. This air-dried sample was taken in an aluminum box and kept in an oven at 105 ± 3^0 C until constant weight was

attained. The difference of green weight and the oven dry weight was considered as moisture content.

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

3.5.2 Determination of ash content

Ash content of wood samples was determined according to TAPPI method (T 211 om–85).

At first, the silica crucible was heated in a muffle furnace at 575 $\pm 25^0$ C for 15 min., placed in a desicator for 45 min. and weighed to nearest 0.1 mg. Test sample was then placed in the crucible and weighed accurately. It was then kept in a muffle furnace. The furnace temperature was gradually raised to 575$\pm 25^0$ C so that the material was carbonized without flaming. The sample was allowed to stay at that temperature for 3'h or longer to burn away all the carbon, completion of which was indicated by absence of black particles. The crucible was then taken out of the furnace, cooled in a desicator and weighed to the nearest 0.1 mg.

$$\text{Ash \%} = \frac{\text{Weight of ash}}{\text{Weight of the sample}} \times 100$$

For each of the wood samples, the test was conducted thrice and the mean value was reported.

3.5.3 Determination of density

Air-dry density and oven-dry density were determined according to TAPPI method (T 258 om–89). Air-dry density was obtained by dividing the air-dry weight by air-dry volume while oven-dry density was obtained by dividing oven-dry weight by oven-dry volume. Volume of the wood samples was determined by water displacement method following treatment of the samples in a solution of paraffin wax in carbon tetrachloride.

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

3.5.4 Determination of calorific value

The calorific values of the wood samples were determined with the help of a Bomb Calorimeter as per the method recommended by the Indian Standard Institution (IS: 1359-1955) (Bureau of Indian Standards, 1960). The protocol for determination of calorific value was as follows:

Protocol for calorific value measurement (Gupta et al., 1996)

Calorific value as determined with a bomb calorimeter is defined as the number of heat units liberated by a unit mass of the substance when burnt in a sealed enclosure of constant volume in an atmosphere of pure oxygen gas.

At first, the bomb calorimeter was standardized by burning pure and dry benzoic acid to give the effective heat capacity of the system. About 1 g of completely dried sample was weighed accurately. The sample was then compressed to make a pellet and its weight was taken. Nichrome firing wire was

stretched across the electrodes within the bomb and a cotton thread was tied around the wire and arranged the loose ends of the thread so that they were in proper contact with the sample pellet in the crucible and then the bomb was reassembled The bomb was filled with pure oxygen at a pressure of 18 atmospheres. 2.0 kg of water was transferred to the calorimeter vessel. Oxygen filled bomb was kept inside calorimeter vessel. After adjusting the stirrer and covers in proper position, the main supply and stirrer mechanism was switched on. After an interval of not less than ten minutes, temperature to 0.01^0 C was recorded continuously for each one-minute interval. Reading was taken continuously till rate of change of temperature was found less than 0.0072^0 C/min. After that, the ignition circuit was closed and temperature variation was recorded. Bomb and thermometer were removed from the calorimeter and bomb was opened after releasing the pressure. The length of the nichrome wire left unused was measured for correction.

Calculation

Weight of fuel pellet (g)   = W

Thread correction (cal)   = Weight of cotton thread (mg) × calorific

                                    value of cotton thread (cal/mg)

                          = x

Firing wire correction (cal)   = Length of firing wire consumed (cm) ×

                                    mass/length of wire (mg/cm) × Calorific

                                    value of Nichrome wire (cal/mg)

                          = y

Temperature rise (t^{0}C)	= Final temperature-initial temperature
Apparent heat capacity of system (cal/^{0} C)	= z
Total heat liberated (cal)	= z × t
	= p
Subtract thread correction (cal)	= p − x
Subtract wire correction (cal)	= (p- x) − y
	= q
Heat liberated from W g of fuel (cal)	= q
Hence heat liberated from 1 g of fuel (cal)	= q/W
Therefore, calorific value of the fuel (cal/g)	= q/W

3.5.5 Determination of cellulose, hemicellulose and lignin

Cellulose, hemicellulose and lignin contents of the wood samples were determined by using the FiberTech I & M systems. The determination is based on the principle that fiber is an inhomogeneous mixture of various macromolecules i.e. structural polysaccharides (eg. cellulose, hemicellulose and pectins) and also non-carbohydrates like the aromatic lignin. Different chemical analytical technique yields neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL). All of these methods are based on subsequent steps of chemical treatments to solubilize "non-fiber" components and final determination of the residue content.

NDF is defined to be the residue after treatment with a neutral detergent solution (Sodium lauryl sulphate and EDTA). The residue content is cellulose (100 %), hemicellulose (100 %), lignin (100 %).

ADF is defined to be the residue after treatment with acid-detergent solution (CTAB in sulphuric acid solution). The residue content is cellulose (100 %) and lignin (100 %).

ADL is defined to be the residue after initial treatment by the ADF method followed by removal of the cellulose fraction through extraction using 72 per cent sulphuric acid.

Subtraction of the value of ADF from NDF gave us the value of hemicellulose content while subtraction of ADL from ADF yielded cellulose content and ADL is the measure of lignin.

Samples for this purpose was milled to pass through a 1.0 mm sieve as recommended. Samples were also defated with acetone three times with 25 ml portions/g sample in the Fibertech cold extraction unit prior to extraction in the hot extraction unit.

3.5.6 Determination of extractive content

Extractive content of the wood samples was determined according to TAPPI method (T 204 om–88). Extraction was done with ethanol-benzene as solvent (one volume of 95 % ethanol and two volumes of benzene) in a Soxhlet apparatus for 5-6 h. The materials removed as extractives was reported as percentage of oven-dry alcohol-benzene soluble material.

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

3.5.7 Laboratory-scale carbonization experiment

For laboratory-scale carbonization of wood samples of the tree species, the reactor used was a quartz tube (25 cm long and 5 cm inner diameter) heated electrically by a cylindrical electric furnace. The temperature of the reactor was controlled with a PID controller. Wood pieces of approximately $2 \times 2 \times 2$ cm^3 sizes were initially oven-dried at 105^0 C until they attained constant weight. Dried wood pieces of known weight of above mentioned sizes were placed inside the quartz tube and temperature of the reactor was raised gradually with a constant heating rate of 3^0 C/min. As soon as the temperature of the reactor attained the desired terminal temperature, it was held at that temperature for 1 h and then the furnace was turned off. When the furnace temperature attained the room temperature, the char was removed from the quartz tube and weighed. The gaseous products, produced during carbonization were allowed to pass through a glass liner placed in a cold trap maintained at 0^0 C, where condensable materials and tar were collected. These comprised of an aqueous phase (pyrolignious acids) and an oily phase (pyrolytic oil or tar), which were separated and weighed. The gas portion escaped the collector, passed through a U – tube filled with $CaCl_2$ and then measured by displacing a liquid of known specific gravity.

The products of carbonization of the wood of different tree species at various terminal temperatures viz. 300^0 C, 400^0 C, 500^0 C, 600^0 C, 700^0 C and 800^0 C were

collected separately and weighed. From the weight of the wood pieces charged to the reactor and the weights of char and other decomposition products viz. gas, tar and condensed liquid, their yields were calculated.

Similarly, wood of the tree species were carbonized separately at 300^0 C, 400^0 C, 500^0 C, 600^0 C, 700^0 C and 800^0 C with a heating rate of 20^0 C/min. For each terminal temperature, char and other decomposition products were collected separately and weighed. From the weight of the wood pieces charged to the reactor and the weight of char and other decomposition products, their yields were calculated.

For wood of each of the tree species, at various terminal temperatures and at a particular heating rate, the experiment was conducted thrice and the average value was reported.

3.5.8 Determination of moisture, volatile matter and ash content of charcoal

Moisture, ash and volatile matter contents of charcoal samples were determined according to the method ASTM D 3173, D3174, D3175 (ASTM 1988a, b, c).

Moisture content of charcoal samples were determined first by weighing a porcelain crucible preheated in a muffle furnace at 750^0 C and then approximately 1 g of the ground sample was placed in it. The crucible was then kept in an oven at 105^0 C till constant weight was attained. Dried charcoal sample was then cooled in a desicator for 1 h and weighed.

Difference in weight divided by the air-dry weight gives the moisture content.

For determination of ash content, a crucible with sample was put in a muffle furnace at 750 ^{0}C for 6 h. It was then cooled in a desicator for 1 h and weighed. The weight of residue divided by the initial weight gave the ash content.

For determination of volatile matter, a muffle furnace was heated to 950 ^{0}C. A crucible containing the sample was placed first for 2 min on the outer edge of the furnace keeping the furnace door open and then for 3 min on the edge of the furnace and finally the crucible was placed in the rear of the furnace for 6 min with the muffle door closed. Sample was then cooled by placing in a desicator for 1 h and then weighed. Difference in the initial weight and final weight divided by the initial weight gave the volatile matter content.

Fixed carbon was calculated by difference.

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

3.5.9 Determination of density of charcoal

The density of charcoal was determined by the same method as described for the determination of density of wood.

3.5.10 Field level carbonization experiments

The field level carbonization experiments with two tree species included among the 15 tree species of the present study were carried

out in traditional earth mound kilns separately. The size of the kiln was of 3 m in length, 1 m in breath and 2 m in height, which is the most common size of kiln used by the charcoal producers in Meghalaya.

Initially, tree species viz. *C. hystrix* and *S. wallichii* of varying girth (10-30 cm) were felled and cross-cut into logs of 1 m. The logs of the two species were left separately to dry for about 2-4 weeks.

For each kiln, a relatively flat area was selected and the wind direction was noted. Three stringers were laid on the ground against the direction of the wind. Edge markers were dug-in near the ends of the stringers and then wood was laid cross-wise on the stringers until a height of 2m was attained. While cross laying the wood the site from which lighting was to be done was carefully laid with smaller dry sticks and grass and chosen to be in the oncoming or leeward direction of the wind. To make the pile surface even, gaps between logs were filled with branches and smaller pieces of wood. The kiln is then covered with earth-turf. To facilitate ignition, a kindling was placed at the ignition point and the fire was started by using matches. When the fire had caught, the opening was also covered by earth-turf. Carbonization proceeded from the windward to leeward (or vice-versa) of the kiln. Subsidence of the kiln to about 2/3rds of the original volume and combustion of the kindling on the kiln top signaled completion of combustion.

The unloading of the kiln was done with the help of a spade with long handle. The charcoal was covered by soil immediately upon removal from the kiln to prevent spontaneous ignition and burning the charcoal to ashes. Having

cooled, the charcoal was packed in to bags and weighed. From the weight of the logs used in the pile and of the charcoal produced, the yield of charcoal was calculated.

The moisture content, density, ash content, volatile matter and fixed carbon content of the charcoal thus produced were determined by using the same standard methods as used in the case of charcoal samples produced in the laboratory-scale carbonizer.

3.6 Statistical analysis

The standard error was calculated and mentioned as ± S.E. One way anova was carried out and reported.

Variables tested ?

Also this chapter is very well written, and gives the reader enough information for interpretation of the results

Chapter IV

RESULTS AND DISCUSSION

Chapter IV

Results and discussion

Analysis of energy scenarios by world bodies like FAO and IEA (FAO, 1997; IEA 2003) has indicated that demand for woodfuel (fuelwood and charcoal) will remain high for many years to come. In recent decades, economic growth in the developing countries has indeed caused fossil fuel use to increase and the relative share of energy consumption accounted for biomass has declined. But absolute biomass energy consumption has continued to rise (Matthews *et al.*, 2000).

In India, where more than 70 per cent of the population lives in rural areas, and utilizes biomass energy traditionally for daily use, meeting their energy requirement continues to be a major challenge for the country. Moreover, rapid extraction and use of biomass resources for energy use will lead to deforestation, soil erosion and loss of biodiversity.

To meet the present and projected future demand of biofuels in the country, it is highly essential to go for large-scale energy plantation on waste

lands and unused lands. However, while identifying the tree species for energy plantation, special attention should be given to the indigenous tree species and also local people's choice and preference for tree species. Several studies have emphasized the importance of establishing energy plantation with species that are found locally and traditionally preferred for fuel (Ravindranath *et al.*, 1991; Kataki & Konwer, 2001, 2002; Deka, 2004).

Because of inherent soil fertility and heavy rainfall in north-east India, Meghalaya in particular, a large varieties of tree and shrub species grow well in this region. But there is a conspicuous lack of knowledge regarding their suitability for charcoal production.

The results of the present study are presented and discussed in the following parts:

Part 1: First of all a survey was made in the state of Meghalaya to identify the tree species grown in their natural habitats and that are currently in use for charcoal production by traditional process i.e. earth mound kiln method. From a list of 41 identified tree species, 15 species were selected on the basis of their availability and preference given by the local charcoal producers for further study.

Part 2: The selected fifteen species were analysed for their physico-chemical properties, biochemical and elemental compositions.

Part 3: The species were carbonized in a laboratory-scale reactor within the temperature range of 300^0- 800^0 C at two different heating rates viz. 3^0 C/min and

20^0 C/min and the mass balance of the decomposition products of each of the species at different terminal temperatures were determined.

Part 4: With a view to evaluate the properties of the charcoal samples produced from each of the tree species at different terminal·temperatures these were analyzed for their moisture content, density, ash content, volatile matter content and fixed carbon content.

Part 5: At the end, we conducted field experiments for charcoal production in earth mound kiln with one superior and one inferior quality tree species selected on the basis of their yield and quality of charcoal in the laboratory-scale study. Each species was put in the kiln separately with a view to compare the yield and quality of charcoal produced in the traditional earth mound kiln with those of charcoal samples produced in the laboratory-scale reactor.

$\left(\begin{array}{l}\text{In fact, in a monograph this}\\\text{approach is to be preferred.}\end{array}\right)$

$\longrightarrow$

Part 1

Selection of the tree species for detailed study

Chidumayo (1995) prepared an inventory of wood used in charcoal production in Zambia. He described around 21 tree species from 3 wood biomass classes namely forest, Miombo and Savanna woodland. The physical and chemical characteristics of wood used in charcoal production and that of their charcoal were analysed. On the basis of these results and from the charcoal consumption in Zambia, he estimated the charcoal carbon budget of Zambia.

With a view to identify the commonly used tree species grown in their natural habitats in the study sites, an initial survey was made by interviewing a cross-section of local charcoal producers regarding the type of tree species used for charcoal production, their availability and the preference given on them. Information regarding preference given on each of the tree species were collected under 3 categories: highly preferred (HP), moderately preferred (MP) and less preferred (LP). Similarly, information regarding the availability were also collected for each of the tree species under 3 categories: highly available (HA), moderately available (MA) and less available (LA). The results of the initial survey work are given in Table 2.

Alternatively in the Table head

This information is "reader friendly", but has already been given in the Method section, I think. In a scientific paper in a journal one would go directly to the results and discuss them.

From Table 2, it can be seen that out of total 41 tree species identified in the study sites, 15 species were found to be highly preferred by the local charcoal producers. However, it was observed that all these 15 tree species were not equally available in the study sites. Out of these 15 species, 4 species, namely *M. bombycina, M. azedarach, A. lucida* and *C. siamea* were found to be highly preferred and highly available in the study sites, whereas 8 other species namely *C. hystrix, Q. dealbata, E. varuna, Q. griffithii, D. procerum, S wallichii, E. acuminata* and *T. catappa* were found to be moderately available and remaining 3 species namely *B. assamica, M. champaca* and *D. peregrina* were less available. Apart from these 15 species, another 10 species (Table 2) were also preferred but they had some other competitive uses. *S. asper* and *A. diandrum* have indigenous medicinal use, *S. robusta* is an excellent timber yielding species, fruit of *S. cumini* has good market value, *C. toona, A. nepalensis, P. cerasoides and M. ferrea* are known to produce high grade timbers. *Q. glauca* and *Q. roxburghii* were not very common in the study sites. The rest 16 species were comparatively less preferred for charcoal production and used only when there is a heavy demand for charcoal in the market.

These 15 species were found to be highly preferred and therefore, selected for the detailed study. Botanical names, family and vernacular names of these tree species are presented in Table 3.

Table 2   List of tree species commonly used for charcoal production along with their availability in the study sites and preference given by local people for charcoal production

Sl. no.	Botanical name	Family	Preference	Availability
1	*Prunus cerasoides D Don*	Rosaceae	MP	MA
2	*Castanopsis hystrix A DC*	Fagaceae	**HP**	**MA**
3	*Premna latifolia Wall*	Verbanaceae	LP	MA
4	*Shorea robusta Gaertn*	Dipterocarpaceae	MP	MA
5	*Machilus bombycina King*	Lauraceae	**HP**	**HA**
6	*Cleidion spiciflorum (Burn) Merr*	Euphorbiaceae	LP	MA
7	*Croton joufra Roxb*	Euphorbiaceae	LP	LA
8	*Mesua ferrea Linn*	Clussiaceae	MP	LA
9	*Quercus dealbata Hk f & Th*	Fagaceae	**HP**	**MA**
10	*Quercus glauca Thunb*	Fageceae	MP	LA
11	*Randia longiflora Lamk*	Rubiaceae	LP	MA
12	*Wendlandia grandis Cowan*	Rubiaceae	LP	HA
13	*Quercus roxburghii Endl*	Fagaceae	MP	LA
14	*Litsea lancifolia Wall ex Hk f*	Lauraceae	LP	LA
15	*Elaeocarpus varuna Ham*	Elaeocarpaceae	**HP**	**MA**
16	*Callicarpa arborea Roxb*	Verbanaceae	LP	MA
17	*Cedrela toona Roxb ex Rottler & Willd*	Meliaceae	MP	MA
18	*Dillenia scabrella Roxb*	Dilleniaceae	LP	MA
19	*Syzygium cumini (L) Skeels*	Myrtaceae	MP	MA
20	*Macaranga denticulata (Bl) Muell Arg*	Euphorbiaceae	LP	LA
21	*Alnus nepalensis D Don*	Betulaceae	MP	MA
22	*Beilschmiedia assamica Meissn*	Lauraceae	**HP**	**LA**
23	*Litsea salicifolia Hk f*	Lauraceae	LP	MA
24	*Olea dioica Roxb*	Oleaceae	LP	LA
25	*Quercus griffithii Hook f & Th ex Miq*	Fagaceae	**HP**	**MA**
26	*Dysoxylum procerum Hiern*	Meliaceae	**HP**	MA
27	*Ficus hirta Vahl*	Moraceae	LP	MA
28	*Schima wallichii Choisy*	Theaceae	**HP**	**MA**
29	*Eyrya acuminata DC*	Theaceae	**HP**	**MA**
30	*Michelia champaca L*	Lauraceae	**HP**	**LA**
31	*Antidesma diandrum (Roxb) Roth*	Euphorbiaceae	MP	MA
32	*Mahonia pycnophylla (Fedde)*	Berberidaceae	LP	MA
33	*Terminalia catappa L*	Combretaceae	**HP**	**MA**
34	*Vitex peduncularis Wall ex Sch*	Verbenaceae	LP	LA
35	*Diospyros peregrina (Gaertn) Gurke*	Sapotaceae	**HP**	**LA**
36	*Gaultheria fragrantissima Wall*	Ericaceae	LP	LA
37	*Streblus asper Lour*	Moraceae	MP	MA
38	*Melia azedarach L*	Meliaceae	**HP**	**HA**
39	*Photinia integrefolia Lindl*	Rosaceae	LP	LA
40	*Albizzia lucida Benth*	Leguminosae	**HP**	**HA**
41	*Cassia siamea Lamk*	Leguminosae	**HP**	**HA**

Table 3: List of fifteen tree species selected for the detailed study

Sl. no.	Botanical name	Vernacular name	Family
1.	*Albizzia lucida* **Benth.**	*Dieng-Tilpot (Khasi)*	*Leguminosae*
2.	*Beilschmiedia assamica* **Meissn.**	*Dieng-khalang (Khasi)*	*Lauraceae*
3.	*Cassia siamea* **Lámk.**	*Pahari-sirish (Assamese)*	*Caesalpiniaceae*
4.	*Castanopsis hystrix* **DC.**	*Dieng-sohstap (Khasi)*	*Fagaceae*
5.	*Diospyros peregrina* **(Gaertn.) Gurke.**	*Kendugoch (Assamese)*	*Ebenaceae*
6.	*Dysoxylum procerum* **Hiern.**	*Dieng-narang (Khasi)*	*Meliaceae*
7.	*Elaeocarpus varuna* **Ham.**	*Dieng-sohkhyllam (Khasi)*	*Elaeocarpaceae*
8.	*Eurya acuminata* **DC.**	*Dieng-shit (Khasi)*	*Theaceae*
9.	*Machilus bombycina* **King.**	*Chom goch (Assamese)*	*Lauraceae*
10.	*Melia azedarach* **L.**	*Dieng-jahrasang (Khasi)*	*Meliaceae*
11.	*Michelia champaca* **L.**	*Shap (Khasi)*	*Lauraceae*
12.	*Quercus dealbata* **Hk. f. & Th.**	*Dieng-sohot (Khasi)*	*Fagaceae*
13.	*Quercus griffithii* **Hook. f. & Th. ex. Miq.**	*Dieng-wah (Khasi)*	*Fagaceae*
14.	*Schima wallichii* **Choisy.**	*Dieng-nganbuit (Khasi)*	*Theaceae*
15.	*Terminalia catappa* **L.**	*Soh-handru-diengartaki (Khasi)*	*Combretaceae*

Usually a section like this belongs
to either the introduction or the
literature review. However, as a reader
I find it convenient to be introduced
into the specific section in this way.

Part 2

Physico-chemical properties, proximate and ultimate analyses of the fifteen tree species

Wood, being one of the major raw materials for charcoal production by carbonization process, the yield and properties of charcoal invariably depend upon the properties of the wood used. The physical properties of wood such as permeability and thermal conductivity are different in longitudinal, radial and tangential directions. Given the importance of heat and mass transfer processes in determining both rates of heat transport and also rates of migration of volatile decomposition products within wood particles, wood structure and properties would be expected to have a significant influence on yield and rates of char formation (Connor *et al.*, 1996).

2.1 Moisture content

The influence of wood moisture content on charcoal formation in carbonization is very important and the nature of its influence is rather physical than chemical. It is generally expected that a wet wood (or wood with high initial moisture content) would require a longer heating period than that for a similar but dry piece of

wood. In the traditional earth-mound process of charcoal making where external heat source is not supplied, it would mean that more wood would be used up in vaporizing the initial moisture from the wood and thereby reducing the amount of wood for carbonization. This would cause a reduction in final charcoal yield. But on the other hand, wood with a high initial moisture content would require a longer heating period for vaporization of moisture present in it. This would facilitate in transferring heat to the interior of wood and this occurs when water vapour moving into the wood particles migrates inward and condenses in the cooler interior of the wood particles. This might tend to enhance the charcoal forming reactions and thus charcoal yield (Alves & Figueiredo, 1989). In view of this, it is very interesting to know how the moisture content of wood affects the charcoal yield and characteristics.

The physical properties of the wood of fifteen tree species are presented in Table 4. Moisture content in the species was found to vary from the lowest of 39.73 % ± 0.73 in *C. hystrix* to the highest of 59.79 % ± 0.66 in *M. azedarach*. Analysis of the results (Table 4) shows that variation in moisture content among different species are significant (5%) except for *B. assamica* and *S. wallichii; D. procerum* and *M. champaca; E. varuna, E. acuminata* and *T. catappa;* and *Q. dealbata* and *Q. griffithii.* Hakkila (1984) observed that moisture content varied from even one tree part to another tree part. Among all the species, *M. azedarach, C. siamea,* and *A. lucida* were found to have higher percentages of moisture content while *C. hystrix, Q. griffithii* and *Q. dealbata* were found to have quite low moisture contents. Apart from physiological differences, that might cause variation in moisture content in different plant parts, seasonal changes and geographic location also contribute towards the difference in

Table 4. Physico-chemical properties, Fuel Value Index (FVI) and biochemical compositions of wood of fifteen selected tree species

Species	Moisture content (wt. %)	Density (g/cc)	Ash content (oven dry wt. %)	Calorific value (KJ g^{-1})	FVI	Cellulose (oven dry wt. %)	Hemi cellulose (oven dry wt. %)	Lignin (oven dry wt. %)	Extractive content (oven dry wt. %)
A lucida	50 61 ± 0 97 c	0 511 ± 0 08 gh	2 43 ± 0 05 abc	17 30 ± 0 85 i	3 637	46 17 ± 0 32 b	26 11 ± 0 20 hi	21 21 ± 0 35 h	5 26 ± 0 13 c
B assamica	48 75 ± 0 59 e	0 631 ± 0 07 e	2 29 ± 0 09 bcd	18 20 ± 0 66 fg	5 014	44 54 ± 0 20 d	30 82 ± 0 21 a	22 39 ± 0 27 fg	2 99 ± 0 07 i
C siamea	57 36 ± 1 04 b	0 485 ± 0 08 gh	2 49 ± 0 06 ab	17 20 ± 0 67 i	3 35	46 44 ± 0 33 ab	27 72 ± 0 26 f	21 02 ± 0 37 hi	5 17 ± 0 03 cd
C hystrix	39 73 ± 0 73 i	0 870 ± 0 07 a	1 06 ± 0 07 i	20 71 ± 0 84 b	17	46 23 ± 0 27 b	24 89 ± 0 19 i	26 09 ± 0 09 a	2 67 ± 0 06 i
D peregrina	49 56 ± 0 41 d	0 710 ± 0 04 d	1 92 ± 0 04 fg	18 45 ± 0 72 f	6 82	44 17 ± 0 24 de	28 40 ± 0 25 d	22 89 ± 0 21 ef	5 77 ± 0 06 b
D procerum	46 10 ± 0 83 f	0 584 ± 0 06 ef	2 42 ± 0 09 abc	17 87 ± 0 93 gh	4 31	45 16 ± 0 25 c	30 12 ± 0 30 b	22 10 ± 0 24 g	3 87 ± 0 04 g
E varuna	42 66 ± 0 87 h	0 821 ± 0 05 ab	1 73 ± 0 07 g	20 11 ± 0 45 cd	9 54	42 88 ± 0 22 gh	28 19 ± 0 31 de	24 83 ± 0 07 c	3 25 ± 0 11 h
E acuminata	42 24 ± 0 65 h	0 879 ± 0 08 a	1 12 ± 0 10 i	21 07 ± 0 63 a	16 54	44 18 ± 0 33 de	26 73 ± 0 21 g	26 22 ± 0 15 a	3 83 ± 0 04 g
M bombycina	43 93 ± 1 11 g	0 870 ± 0 085 a	1 14 ± 0 09 i	21 33 ± 0 78 a	16 28	43 71 ± 0 29 ef	25 81 ± 0 14 i	26 45 ± 0 13 a	4 66 ± 0 09 ef
M azedarach	59 79 ± 0 66 a	0 477 ± 0 09 h	2 65 ± 0 06 a	17 09 ± 0 90 i	3 08	46 93 ± 0 34 a	27 93 ± 0 22 ef	20 65 ± 0 30 i	4 77 ± 0 09 ef
M champaca	45 46 ± 0 77 f	0 753 ± 0 07 cd	1 99 ± 0 07 ef	19 79 ± 0 80 d	7 49	43 37 ± 0 25 fg	28 24 ± 0 28 de	23 54 ± 0 09 d	3 87 ± 0 04 g
Q dealbata	40 71 ± 0 94 i	0 848 ± 0 07 ab	1 44 ± 0 07 h	20 37 ± 0 48 bc	12	42 74 ± 0 19 h	26 45 ± 0 17 gh	25 29 ± 0 21 bc	4 58 ± 0 08 f
Q griffithii	40 95 ± 0 90 i	0 802 ± 0 06 bc	1 69 ± 0 08 g	20 66 ± 0 54 b	9 80	42 65 ± 0 17 h	26 13 ± 0 15 hi	25 37 ± 0 14 b	4 93 ± 0 12 de
S wallichii	48 07 ± 0 85 e	0 536 ± 0 05 fg	2 23 ± 0 095 cde	17 64 ± 0 81 h	4 24	45 62 ± 0 31 c	26 16 ± 0 19 hi	22 01 ± 0 24 g	5 06 ± 0 10 cd
T catappa	42 04 ± 0 57 h	0 768 ± 0 08 c	2 08 ± 0 11 def	19 32 ± 0 77 e	7 13	41 67 ± 0 31 i	29 15 ± 0 24 c	23 30 ± 0 11 de	6 74 ± 0 07 a
LSD$_{0.05}$	0 69	0 5	0 23	0 34		0 50	0 37	0 51	0 26

Mean values followed by the same letter shown in subscript are not significantly different

moisture content among different species (Diaz & Golueke, 1981). The moisture content presented in Table 4 agrees with those reported by Konwer *et al.* (2001), Kataki & Konwer (2001, 2002) for some other indigenous tree species of north-east India.

2.2 Density

Denser species with low moisture content have always been preferred as fuel because of their high energy content per unit volume and slow burning rates (Abbot *et al.*, 1997; Fuwape & Akindele, 1997). Effect of variation of density in species on charcoal yield has been a matter of investigation for many researchers (Britto & Barrichelo, 1977; Cutter & Mc Ginnes, 1981; Hirata *et al.*, 1991; Connor *et al.*, 1994; Connor *et al.*, 1996). Higher density means higher thermal conductivity and therefore heat transfer into the interior of wood particles would be facilitated during carbonization. In spite of some degree of counteraction by higher thermal capacity towards heat transfer to the interior of wood, a slower rise in surface temperature still appears likely to result. The primary char forming reactions would be favoured near the particle surface where the rate of temperature increase is slowed with reversed result in the interior as a result of rapid heating. Secondary carbon-forming reactions should be increased as higher density would lengthen the period of retention time for volatiles within the wood matrix and therefore larger amount of carbon would be laid down.

There have been conflicting results in the literature about the influence exerted by wood density on char formation (Cutter & McGinnes, 1981; Britto & Barrichelo,

1977; Connor *et al.,* 1996). In the present study, density of the species varied from the highest of 0.879 ± 0.085 (*E. acuminata*) to the lowest of 0.477 ± 0.09 (*M. azedarach*). There were significant variations in density among some species as can be seen from Table 4 The variations in the density of wood among the tree species may be attributed to their anatomical differences. Fuwape (1996) observed that dense biomass materials produced dense charcoal. Buekens & Schoeters (1987) have also observed similar findings. The density of wood of tree species in the present study is in conformity with the density values reported for some species from Nigeria (Fuwape, 1996) and for rockrose wood (Gomez-Serrano, 1993).

2.3   Ash content

The ash content of wood is a measure of non-combustible material present in it. The influence of amount of inherent ash on charcoal yield and quality is still not known. In general, biomass with higher ash content increases the char yield simply by their presence in it. Many investigators have clearly showed that various inorganic additives could enhance char formation in pyrolysis of wood. While evaluating fuelwood characteristics, high ash content is always considered to be a negative character (Goel & Behl, 1996). The ash content of the species under study varied from 1.06 % ± 0.07 (*C. hystrix*) to 2.65 % ± 0.06 (*M. azedarach*). Ash content among the species under study was found to vary significantly in some species (Table 4). The values of ash content of the species under the present study agree well with those of some forest species of Nigeria (Fuwape, 1996), Spain (Gomez-Serrano, 1993) and species of indigenous tree species of north-east India (Kataki & Konwer; 2001, 2002).

2.4 Biochemical constituents

Fuel value of wood is greatly dependent on its caloric content and is generally believed to be one of the parameters to compare one fuel with another. Caloric content of wood, in turn is dependent on its major biochemical constituents namely cellulose, hemicellulose, lignin, extractives and ash forming minerals. The process of combustion of a fuel involves its thermal degradation and subsequent oxidation of the degradation products. Cellulose and hemicellulose (together known as holocellulose) 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 (Shafizadeh, 1981). The caloric content varies from one plant part to another part and also from species to species largely due to differences in biochemical constituents (Kataki & Konwer, 2001). The calorific value of the species under study varied from the highest of 21.33 ± 0.78 KJ g^{-1} in *M. bombycina* to a lowest of 17.09 ± 0.9 KJ g^{-1} in *M. azedarach*. There were significant differences of calorific values among some species while variations between some species were not significant. The calorific value of most of the species were found to be quite comparable to those of other tree species reported by various workers (Kataki & Konwer, 2001; Konwer *et al.*, 2001; Jain & Singh, 1999; Bhatt & Todaria, 1992; Goel & Behl, 1996; Jain, 1994; Neeman & Steinback, 1979).

As far as the carbonization is concerned, it is the biochemical constituents that undergo different chemical reactions in the form of primary and secondary reactions.

It leads to the formation of charcoal and various other products such as gas, pyroligneous acid and tar.

Hemicellulose is a mixture of polymers based on 5 – carbon monosaccharide units. On heating, at about 130^0 – 190^0 C, softening of hemicellulose occurs. The decomposition of hemicellulose at temperature between 200^0 - 260^0 C, yields mostly volatile primary decomposition products and less char. But the percentage of char formation is still greater than that of cellulose (Hirata *et al.*, 1991). Hemicellulose is the component of wood that on carbonization decomposes first and this was further confirmed by TGA data analysis for 5 – carbon monosaccharides residues in pyrolyzed wood (Connor & Salazar, 1988; Hirata *et al.*, 1991).

The hemicellulose content (oven dry weight %) of 15 different tree species is presented in Table 4. The highest hemicellulose content was found in *B. assamica* (30.82 % ± 0.21) and the lowest was found in *C. hystrix* (24.89 % ± 0.19). There were significant variations in hemicellulose content only among some species.

Cellulose is the most dominant constituent of wood and is much more stable than either hemicellulose or lignin and starts softening at temperature around 240° C (Goring, 1963). While decomposition of cellulose starts at 240° C, but bulk of weight loss occurs rapidly in the range of 330^0-350^0 C. Though the major degradation products of cellulose are volatiles but the yield from cellulose at a given temperature is also dependent on the heating rate. Antal *et al.*, (1980) described that the initial step on cellulose heating is a decrease in its degree of polymerization to about 200 without any associated weight loss. These lower degradation products may then undergo dehydration to form anhydro-cellulose which further decomposes to form char and

some volatiles. Alternatively, cellulose may undergo a series of depolymerization reactions leading to production of tar dominated by levoglucosan. Depending upon experimental condition, this tar may degrade to char and some volatiles or yield almost entirely volatile products. These different reaction pathways are favoured by different heating rates. Slow heating with a prolonged holding period in the temperature range 220^0 - 250^0 C favours char production. On the other hand, rapid heating of small samples to higher temperature favours depolymerization reaction and little formation of char.

Among all the tree species, wood of *M. azedarach* contained the highest percentage of cellulose (46.93 % ± 0.34) while the wood of *T. catappa* contained the lowest percentage of it (41.67 % ± 0.31). Only some species out of the fifteen were found to vary significantly in cellulose content.

During carbonization lignin decomposition is a gradual process. On heating, though marked softening occurs at temperature 130^0 - 190^0 C, the decomposition with associated weight loss and evolution of volatiles occurs primarily in the range of 280^0 - 550^0 C (Connor & Viljoen, 1995). From TGA analysis, Hirata *at al.* (1991) confirmed that more or less steady decline occurs in lignin weight between 200^0- 500^0C. The predominant product of lignin decomposition is char and much of the charcoal formed during wood carbonization is believed to be derived from lignin. It might therefore be expected that woods with higher lignin content would give higher charcoal yield.

From the results (Table 4), it is seen that lignin content of wood of the tree species varied significantly only among some species. The highest lignin content was

observed in *M. bombycina* (26.45 % ± 0.13) and the lowest being observed in *M. azedarach* (20.65 % ± 0.30). Lignin contents of the species under study agree well with those of the species of north-east India reported by earlier workers (Deka, 2004; Kataki & Konwer, 2001).

Extractives in wood are non-structural aromatic compounds, which possess one or more phenolic hydroxyl groups. Wood extractives includes terpenes, tannins, resins, degraded sugars, starches, fats, oils, proteins and organic acids, most of which are soluble in organic solvents. But no single solvent can extract all the components from wood.

The extents to which the extractives influence charcoal yield remains uncertain. Roy *et al.* (1990) found a marginal increase in the charcoal yield on removal of extractives. However, other researchers have reported that extractives increase, not decrease charcoal yield.

In the present study, the highest extractive content was observed in *T. catappa* (6.74 % ± 0.74), while the lowest was observed in *C. hystrix* (2.67 % ± 0.06). The differences in extractive content was significant only among some of the species and not all.

2.5 Elemental composition

Elemental compositions of wood of fifteen tree species are presented in Table 5. The carbon content of the wood samples of the species varied from 42.68 % (*S. wallichii*) to 46.98 % (*M. bombycina*) whereas hydrogen content varied from 4.93 % (*M. azedarach*) to 6.02 % (*Q. griffithii*). Similarly, oxygen content varied from

49.24% (*M. azedarach*) to 45.32 % (*C. hystrix*). Nitrogen of all the species ranged from 0.2 % to 0.4 % only. The results of the nitrogen content of the tree species under the present study are almost similar to that of other tree species of north-east India reported by Deka (2004).

2.6 Fuel Value Index (FVI)

Although the fuel value index of a tree species does not have any direct bearing on yield and quality of the charcoal produced by carbonization, it invariably gives a picture about the quality and heat content of the species. Therefore, as a matter of interest, we calculated the FVI of the tree species which are presented in Table 4. In the present study, it is seen that *C. hystrix* had the highest FVI (17), followed closely by *E. acuminata* (16.54) and *M. bombycina* (16.28). The lowest FVI was recorded for the species *M. azedarach* (3.08), followed by *C. siamea* (3.35) and *A. lucida* (3.63).

Table 5: Elemental composition of wood of fifteen tree species

Species	C (wt. %)	H (wt. %)	O (wt. %)	N (wt. %)
A. lucida	43.86	5.93	48.01	0.2
B. assamica	45.05	5.91	47.11	0.2
C. siamea	44.77	5.98	46.30	0.3
C. hystrix	46.95	4.98	45.32	0.2
D. peregrina	44.60	5.87	47.43	0.2
D. procerum	45.14	5.79	47.00	0.2
E. varuna	46.93	5.12	45.46	0.2
E. acuminata	46.59	4.95	46.17	0.3
M. bombycina	46.98	5.49	45.33	0.2
M. azedarach	42.94	4.93	49.24	0.4
M. champaca	44.21	5.51	49.02	0.2
Q. dealbata	46.88	5.06	45.56	0.2
Q. griffithii	46.68	6.02	45.66	0.2
S. wallichii	42.68	5.86	49.03	0.2
T. catappa	43.10	5.90	48.38	0.2

Part 2

OK, Results well presented

Discussion informative

Part 3

Mass balance of pyrolytic decomposition products of fifteen tree species at various terminal temperatures with two different heating rates

Thermo-chemical conversion of biomass is one of the most common and convenient routes for conversion of biomass materials to useable energy. This includes the processes like direct combustion, gasification, liquefaction and pyrolysis. Among all the thermochemical conversion processes, pyrolysis plays a key role in the reaction kinetics of thermal degradation of biomass and hence in reactor designing and determining the decomposition products distribution and also their composition and properties (Raveendran *et al.*, 1995, 1996). Pyrolysis is a simple process and inexpensive to construct suitable small-scale plants in locations near the raw materials source. The pyrolysis of biomass materials for the production of liquid and solid fuels is a promising technology. In the pyrolysis process, the organic part of the material decomposes to low molecular weight products, liquid or gases which can be used as fuel or chemical feedstock (Torres *et al.*, 2000).

The pyrolysis of lignocellulosic materisls has been widely studied by a large number of researchers using different techniques: fixed bed reactor (Rocha et al., 1997), vacuum pyrolysis reactor (Darmstadt et al., 2000), fluidized bed reactors (Hastaoglu & Hassam, 1995), DTA and TGA (Ahuja et al., 1996). Static batch reactors are the simplest configurations to study the pyrolysis of biomass.

The products of pyrolysis are char, gas and condensed liquid. The condensed liquid consists of pyroligneous acid, which is an aqueous acidic layer and the other heavier layer is wood tar. The wood tar contains at least 50 identified phenolic compounds, which account for upto 60 % of the tar. It also contains higher acids, aldehydes, ketones, esters, furans and hydrocarbons (Goldstein, 1992). The gaseous fraction of biomass pyrolysis consists of CO, CO_2, H_2, CH_4, C_2H_4 etc. (Fagbemi et al , 2001).

The traditional carbonization process in earth mound kiln concerns only about the final charcoal yield and does not take into account the recoverable condensed liquid fraction and the gaseous fraction and are generally released to the environment which cause pollution (Tzanakia et al., 2001; Pennise et al, 2001; Smith et al., 1999) The energy yield of this process thus is very low.

In view of the above, we carbonized the wood samples of fifteen tree species in the temperature range of 300^0 – 800^0 C with two different heating rates viz. 3^0 C/min and 20^0 C/min and the pyrolytic decomposition products yield at different terminal temperatures viz. 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C were determined. The results of the experiments are presented in Tables 6 & 7.

3.1 Gas production

From the results of the mass balance of decomposition products of the tree species (Tables 6 & 7 and Figs. 19 & 20), it can be seen that with the increase of carbonization temperature the gas yields increased in both the heating rates (3^0 C/min and 20^0 C/min). Sadakata *et al.* (1997), Sensöz & Angin (2001) and Demirbas (2001) also observed increased gas production with the increase of temperature from some other wood species and biomass materials.

With a heating rate of 3^0 C/min, at 300^0 C, gas production varied from 8.4% to 12.4%. *D. procerum* yielded the highest percentage of gas (12.4 %) whereas *M. bombycina* yielded the lowest of it (8.4 %). Within the temperature range of 300^0-400^0 C, the gas yield from all the species increased slowly as seen in Figs. 19 & 20. At this temperature range (300^0 – 400^0 C), the rate of change in gas yield varied from 3.6 % to 9.3 %. At 400^0 C also, *D. procerum* yielded the highest percentage of gas (21.0 %) while *D. peregrina* yielded the lowest percentage of it (15.3 %). At 500^0 C terminal temperature again *D. procerum* produced the highest percentage of gas (36.0 %) and *D. peregrina* produced the lowest percentage of it (27.8 %). Within 400^0 – 500^0 C, the rate of gas production was found to be the highest in *E. acuminata* (17.3 %) and the lowest was in *T. catappa* (11.4 %). At 600^0 C, *B. assamica*, yielded the highest percentage of gas (47.5 %) and *M. champaca* yielded the lowest percentage of it (40.1 %). Within 500^0 – 600^0 C, the rate of gas production was maximum in *D. peregrina* (15.6 %) followed by *E. varuna* (14.5 %) and *C. siamea* (14.4 %) whereas minimum rate was found in *E. acuminata* (8.6 %). At 700^0 C, again *B. assamica* yielded the

Table 6: Mass balance of decomposition products of fifteen tree species at different terminal temperatures with a heating rate of 3 ^{0}C/min

Species	Product (wt. %)	Temperature (^{0}C)					
		300	400	500	600	700	800
A. lucida	Gas	11.5	15.9	29.2	43.0	55.1	60.0
	Char	47.8	27.3	24.3	22.2	18.7	16.0
	Liquid	30.0	37.6	30.5	22.5	17.0	18.3
	Tar	12.5	15.2	16.1	9.0	5.2	1.3
	Total	101.8	96.0	100.1	96.7	96.0	95.6
B. assamica	Gas	12.4	20.1	35.0	47.5	56.1	63.0
	Char	53.1	30.1	26.4	23.2	20.7	17.8
	Liquid	30.0	38.3	28.7	25.1	24.1	22.0
	Tar	9.0	13.0	14.0	7.2	3.1	1.7
	Total	104.5	101.5	104.1	103.0	104.0	104.5
C. siamea	Gas	12.0	19.0	32.0	46.4	54.8	61.0
	Char	46.1	27.2	24.3	22.2	18.7	16.1
	Liquid	31.5	37.8	32.1	25.0	23.7	23.9
	Tar	10.9	14.7	15.2	5.9	3.1	1.0
	Total	100.5	98.7	103.6	99.5	100.3	102.0
C. hystrix	Gas	8.9	17.1	33.0	43.0	50.2	59.1
	Char	64.3	46.5	44.0	40.3	34.5	28.3
	Liquid	24.3	25.1	20.0	15.4	14.3	12.1
	Tar	5.4	7.8	8.0	6.2	4.9	3.2
	Total	102.9	96.5	105.0	104.9	103.9	102.7
D. peregrina	Gas	11.7	15.3	27.8	43.4	56.1	61.2
	Char	55.1	34.7	30.4	27.1	23.6	21.0
	Liquid	29.9	37.9	38.5	25.7	20.3	14.7
	Tar	7.2	12.8	6.3	4.2	2.0	1.1
	Total	103.9	100.7	103.0	100.4	102.0	98.0
D. procerum	Gas	12.5	21.0	36.0	47.0	55.5	62.4
	Char	52.5	29.5	27.8	23.6	19.9	17.0
	Liquid	30.8	40.3	29.0	25.2	24.0	22.2
	Tar	8.7	10.5	11.2	3.2	1.9	1.1
	Total	104.5	101.3	104.0	99.0	101.3	102.7
E. varuna	Gas	10.9	15.4	28.9	43.4	52.3	58.7
	Char	58.7	37.7	34.4	30.7	28.3	25.9
	Liquid	25.5	37.0	30.3	24.7	19.0	18.0
	Tar	8.3	8.9	10.4	6.1	3.0	1.3
	Total	103.4	99.0	104.0	104.9	102.6	103.9

	Product	Temperature (^{0}C)					
	(wt. %)	300	400	500	600	700	800
E. acuminata	Gas	9.2	15.4	32.7	41.3	48.4	57.4
	Char	62.1	45.3	42.8	39.5	34.2	27.6
	Liquid	24.9	26.4	21.0	17.5	16.3	14.0
	Tar	7.1	8.0	8.1	4.0	4.3	2.7
	Total	**103.3**	**95.1**	**104.6**	**102.3**	**103.2**	**101.7**
M. bombycina	Gas	8.4	16.9	33.0	42.4	47.3	55.2
	Char	62.1	43.2	40.5	37.1	32.2	27.7
	Liquid	22.3	28.5	22.0	17.4	15.4	15.0
	Tar	6.5	8.9	9.2	6.0	4.1	3.2
	Total	**99.3**	**97.5**	**104.7**	**102.9**	**99.0**	**101.1**
M. azedarach	Gas	12.0	20.0	32.1	41.5	50.0	60.0
	Char	45.5	26.7	23.9	22.9	19.6	16.3
	Liquid	32.0	42.5	37.0	35.6	32.8	27.0
	Tar	11.5	12.0	11.9	4.7	2.4	0.8
	Total	**101.0**	**101.2**	**104.9**	**104.7**	**104.8**	**104.1**
M. champaca	Gas	10.5	18.3	30.0	40.1	52.6	59.7
	Char	56.2	35.2	32.2	29.5	25.6	21.8
	Liquid	30.0	34.6	26.0	26.5	18.8	15.3
	Tar	8.0	10.5	10.8	7.5	2.9	2.3
	Total	**104.7**	**98.6**	**99.0**	**103.6**	**99.9**	**99.1**
Q. dealbata	Gas	9.1	15.7	30.1	42.4	49.5	54.3
	Char	59.5	41.0	40.0	36.2	30.6	26.5
	Liquid	21.8	29.1	22.2	17.5	20.0	20.1
	Tar	7.7	10.2	10.7	6.2	3.4	2.0
	Total	**98.1**	**96.0**	**103.0**	**102.3**	**103.5**	**102.9**
Q. griffithii	Gas	9.4	14.8	30.2	42.7	· 49.0	54.0
	Char	59.1	39.3	35.5	30.6	27.7	25.3
	Liquid	25.0	32.4	22.9	22.0	21.5	19.9
	Tar	7.5	10.2	10.4	5.7	3.2	1.7
	Total	**101.0**	**96.7**	**99.0**	**101.0**	**101.4**	**100.9**
S. wallichii	Gas	10.9	18.0	31.1	41.8	53.0	60.0
	Char	52.0	27.5	25.0	23.2	19.3	17.1
	Liquid	29.8	41.0	30.0	24.1	20.0	18.2
	Tar	6.2	8.7	9.0	7.5	4.0	1.3
	Total	**98.9**	**95.2**	**95.1**	**96.6**	**96.3**	**96.6**
T. catappa	Gas	10.7	20.0	30.4	41.9	49.0	57.0
	Char	55.9	35.2	33.8	30.7	26.8	22.2
	Liquid	31.3	37.8	27.0	28.0	20.0	16.0
	Tar	6.9	8.1	10.0	3.1	2.1	1.6
	Total	**104.8**	**101.1**	**101.2**	**103.7**	**97.9**	**96.8**

Table 7: Mass balance of decomposition products of fifteen tree species at different terminal temperatures with a heating rate of 20 °C/min

Species	Product (wt. %)	Temperature (°C)					
		300	400	500	600	700	800
A. lucida	Gas	15.0	21.2	32.1	46.7	56.4	61.1
	Char	42.6	24.0	23.1	21.5	18.2	16.0
	Liquid	31.9	39.0	33.3	24.8	18.4	18.3
	Tar	14.0	16.3	12.1	10.2	5.4	1.9
	Total	**103.5**	**100.5**	**100.6**	**103.2**	**98.4**	**97.3**
B. assamica	Gas	14.0	22.4	39.2	44.7	50.4	59.8
	Char	45.9	26.9	25.1	23.7	22.1	18.0
	Liquid	33.2	42.5	28.2	21.4	19.1	18.3
	Tar	10.4	13.0	8.4	5.8	5.7	1.4
	Total	**103.5**	**104.8**	**100.9**	**95.6**	**97.3**	**97.5**
C. siamea	Gas	16.2	26.1	32.5	43.8	50.1	55.6
	Char	42.1	23.7	22.6	21.0	18.1	15.2
	Liquid	32.9	38.7	32.7	26.1	24.5	24.0
	Tar	11.8	16.1	12.1	6.0	3.3	1.5
	Total	**103.0**	**104.6**	**99.9**	**96.9**	**96.0**	**96.3**
C. hystrix	Gas	10.3	18.7	33.1	46.0	48.1	53.9
	Char	57.7	37.9	34.8	28.4	26.0	24.2
	Liquid	25.7	30.7	23.0	18.1	17.1	15.3
	Tar	5.9	10.5	11.2	8.1	4.2	3.3
	Total	**99.7**	**97.7**	**102.1**	**100.6**	**95.4**	**96.7**
D. peregrina	Gas	13.0	19.8	29.3	45.7	58.4	63.1
	Char	48.7	28.3	27.0	25.4	22.8	20.7
	Liquid	31.7	40.1	38.0	26.2	20.9	16.4
	Tar	8.4	14.0	10.0	4.7	1.8	0.9
	Total	**101.8**	**102.2**	**104.3**	**102.0**	**103.9**	**101.1**
D procerum	Gas	14.7	24.9	40.3	47.4	56.1	61.9
	Char	44.7	26.0	24.8	23.6	20.0	17.0
	Liquid	31.4	40.4	30.8	25.8	24.4	22.2
	Tar	10.5	13.7	8.4	4.1	2.4	1.3
	Total	**101.3**	**105.0**	**104.3**	**100.9**	**102.9**	**102.4**
E. varuna	Gas	11.0	17.1	29.0	33.5	49 3	54.7
	Char	52.1	33.7	31.7	29.4	26.5	23.4
	Liquid	27.1	38.9	29.9	26.0	18.0	14.9
	Tar	9.0	10.4	10.9	6.9	2.4	2.0
	Total	**99.2**	**100.1**	**101.5**	**95.8**	**96.2**	**95.0**

| Species	Product (wt. %)	Temperature (°C)					
		300	400	500	600	700	800
E acuminata	Gas	12 0	21 2	35 3	42 1	51 0	54 7
	Char	57 0	37 0	34 2	28 0	26 2	24 5
	Liquid	26 1	28 3	24 6	19 9	18 9	16 3
	Tar	8 3	10 1	7 1	5 7	3 7	3 1
	Total	**103.4**	**96.6**	**101.2**	**95.7**	**99.8**	**98.6**
M bombycina	Gas	10 7	20 0	35 0	46 7	49 9	53 1
	Char	56 3	36 8	34 6	30 9	27 1	25 5
	Liquid	25	30 7	27 1	19 5	16 9	16 0
	Tar	7 9	10 3	8 1	6 1	4 7	3 0
	Total	**99.9**	**97.8**	**104.8**	**103.2**	**98.6**	**97.6**
M azedarach	Gas	16 3	25 7	32 7	44 2	51 2	56 5
	Char	41 1	23 5	21 7	19 4	17 5	15 8
	Liquid	34 1	42 6	40 7	36 1	33 0	27 5
	Tar	8 4	13 0	9 1	4 9	2 6	1 5
	Total	**99.9**	**104.8**	**104.2**	**104.6**	**104.3**	**101.3**
M champaca	Gas	11 2	20 7	30 3	41 7	55 4	59 9
	Char	50 4	31 7	30 2	27 2	24 1	21 4
	Liquid	33 0	39 1	27 8	27 1	20 0	15 0
	Tar	9 0	12 3	10 5	7 9	4 1	1 9
	Total	**103.6**	**103.8**	**98.8**	**103.9**	**103.6**	**98.2**
Q dealbata	Gas	10 9	21 0	35 7	46 7	54 3	58 1
	Char	53 4	34 2	31 1	28 2	26 4	23 7
	Liquid	24 1	31 4	24 6	20 5	21 4	21 0
	Tar	8 5	12 5	8 1	6 7	2 7	1 5
	Total	**96.9**	**99.1**	**99.5**	**102.1**	**104.8**	**104.3**
Q griffithii	Gas	10 5	22 3	35 8	47 7	55 9	60 3
	Char	52 6	34 1	32 6	29 0	26 2	23 1
	Liquid	27 3	35 7	24 0	20 5	15 0	9 7
	Tar	8 4	11 5	12 0	6 1	3 2	2 1
	Total	**98.8**	**103.6**	**104.4**	**103.1**	**100.3**	**95.2**
S wallichii	Gas	15 3	25 1	40 2	47 1	56 0	62 0
	Char	44 7	24 3	23 1	21 5	20 9	17 3
	Liquid	30 4	41 0	31 2	25 0	21 2	18 5
	Tar	10 8	14 6	10 3	8 7	4 3	2 1
	Total	**101.2**	**105.0**	**104.8**	**102.3**	**102.4**	**99.9**
T catappa	Gas	12 4	21 5	31 3	43 0	53 8	58 7
	Char	49 4	30 0	29 1	27 1	23 7	21 1
	Liquid	33 4	40 4	29 2	26 5	19 8	16 4
	Tar	7 2	9 9	13 1	5 2	2 4	1 0
	Total	**102.4**	**101.8**	**102.7**	**101.8**	**99.7**	**97.2**
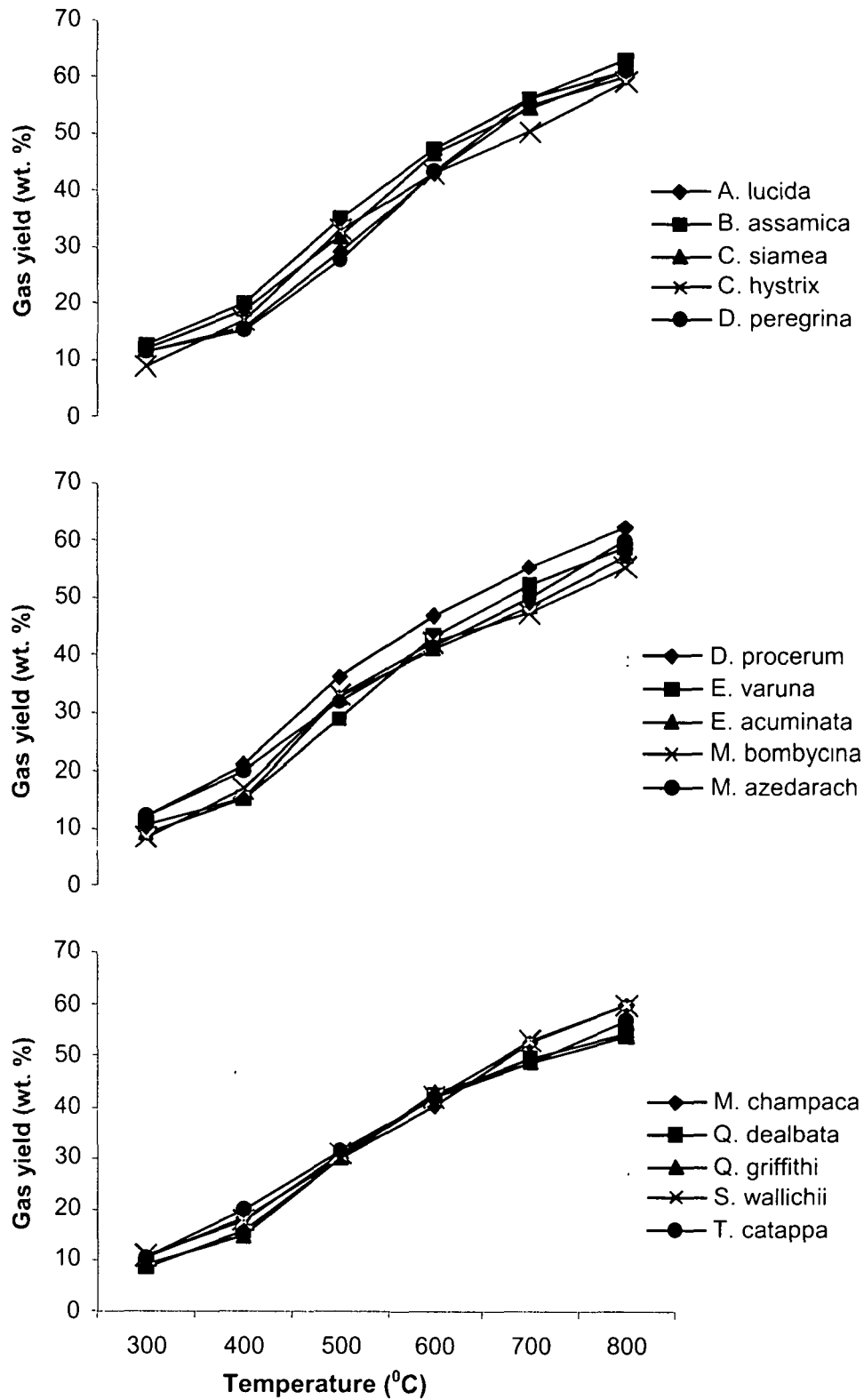
Fig. 19: Effect of carbonization temperature on gas yield (heating rate 3^0 C/min)
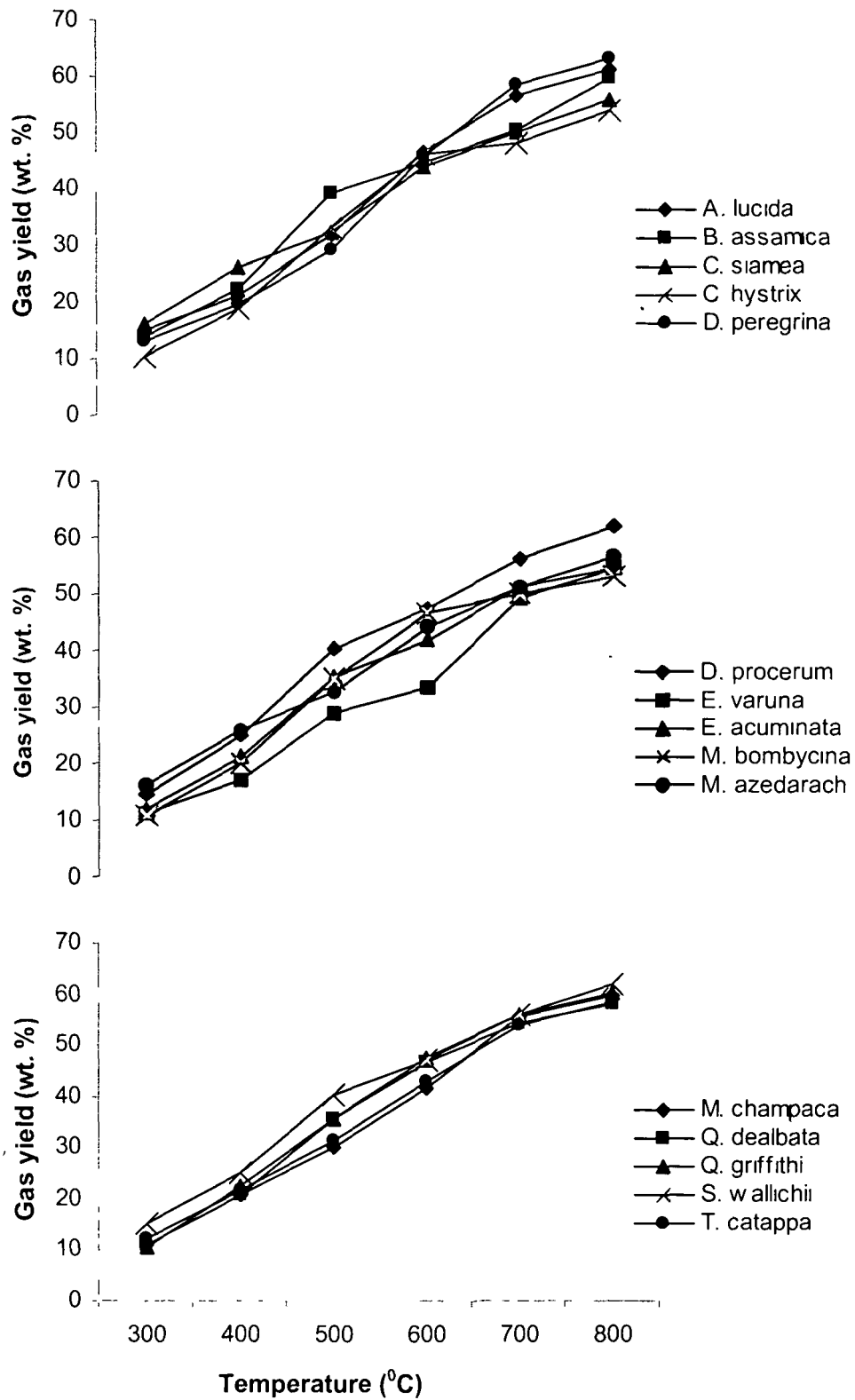
Fig. 20: Effect of carbonization temperature on gas yield (heating rate 20^0 C/min)

maximum percentage of gas (56.1 %) and *M. bombycina* yielded the lowest percentage of it (47.3 %). Within this temperature range, the rate of gas production was found to be maximum in *D. peregrina* (12.7 %) and minimum in *M. bombycina* (4.9 %). At 800^0 C terminal temperature, the highest percentage of gas production was shown by *B. assamica* (63.0 %) and the lowest was shown by *Q. griffithii* (54.0 %). In the temperature range of 700^0 – 800^0 C, the rate of gas production was maximum in *M. azedarach* (10.0 %) while the minimum rate was in *Q. dealbata* (4.8 %).

When the rate of carbonization temperature was increased to 20^0 C/min, the amounts of gas as well as rate of gas production were found to be changed markedly. With this heating rate and at 300^0 C, maximum percentage of gas was yielded by *M. azedarach* (16.3 %) and minimum was yielded by *C. hystrix* (10.3 %). Similarly at 400^0 C, *C. siamea* yielded the highest percentage of gas whereas *E. varuna* yielded the lowest of it (17.1 %). At this heating rate, the rate of gas production within 300^0 – 400^0 C, was the highest in *Q. griffithii* (11.8 %) and the lowest was in *E. varuna* (6.1 %). Again at 500^0 C, the maximum percentage of gas was produced by *D. procerum* (40.3 %) and minimum of it was produced by *E. varuna* (29.0 %). Within 400^0 – 500^0 C, the rate of gas production was shown to be the highest in *C.siamea* (6.4 %). Similarly, at 600^0 C, maximum percentage of gas was produced by *Q. griffithii* (47.7 %) and minimum was by *E. acuminata* (42.1 %). Within 500^0 – 600^0 C, the rate of gas production was found to be the highest in *D. peregrina* (16.4 %) and the lowest was in *E. varuna* (4.5%). At 700^0 C terminal temperature, *D. peregrina* yielded the highest percentage of gas

(58.4%) whereas *E. varuna* yielded the lowest percentage of it (49.3 %). Within

$600^0 - 700^0$ C, the rate of gas production was found to be maximum in *E. varuna*

(15.8 %) and minimum was in *C. hystrix* (2.1 %). At 800^0 C terminal

temperature, the highest percentage of gas was yielded by *D. peregrina* (63.1 %)

and the lowest percentage was yielded by *M. bombycina* (53.1%). Within 700^0 –

800^0 C, the rate of gas production was maximum in *B. assamica* (9.4 %) and

minimum was in *M. bombycina* (3.2 %).

At 300^0 C terminal temperature, with a heating rate of 3^0 C/min, the gas

production varied from 8.4 % to 12.5 %, whereas at the same temperature, with a

heating rate of 20^0 C/min gas production varied from 10.3 % to 16.3 %.

Similarly, at 400^0 C with a heating rate of 3^0 C/min, the total amounts of gas

production ranged from 15.3 % to 21.0 % and with a heating rate of 20^0 C/min,

the gas production varied from 17.1 % to 26.1 %. At 500^0 C, with a heating rate

of 3^0 C/min, the gas production ranged from 27.8 % to 36 %; but when the

heating rate was increased to 20^0 C/min, the gas production increased to the

range of 29.0 % to 40.3 %. Similarly, with a heating rate of 3^0 C/min, the gas

production from the species at 600^0, 700^0 and 800^0 C, ranged from 41.1 % to 47.5

%, 47.3 % to 56.1 % and 54.0 % to 63.0 % respectively while with a heating rate

of 20^0 C/min, the gas production in the corresponding terminal temperatures

ranged from 42.1 % to 47.7 %, 48.1 % to 58.4% and 53.1 % to 63.1 %

respectively. The increase of gas production from the species with the increase of

heating rate was found to be more in the carbonization temperature up to 500^0 C

as compared to those in the higher carbonization temperatures. The total amounts

of gas produced at 800^0 C were almost comparable at both the heating rates i.e. 3^0 C/min and 20^0 C/min. The increase of gas production at higher heating rate may be related to the fact that higher heating rate leads to a fast depolymerization of the solid material to primary volatiles, while at the lower heating rate dehydration of more stable anhydrocellulose is limited and very slow (Chen et al., 1997).

3.2   Char production

The char yield from the tree species was found to decrease with increase of temperature in both the heating rates. At 300^0 C, with a heating rate of 3^0 C/min, the char yield varied from 45.5 % to 64.3% whereas with a heating rate of 20^0 C/min, the char yield was found to vary from 41.1 % to 57.7 % (Tables 6 & 7). The decrease of char yield with increase of carbonization temperature was reported by various workers (Sadakata et al., 1987; Fagbemi et al., 2001; Sensöz, 2003). Sensöz & Angin (2001) reported that the decrease in char yield with increasing temperature could be due either to greater primary decomposition of the wood at higher temperatures or to secondary decomposition of the char.

When the carbonization temperature was increased, it was observed that within $300^0 - 400^0$ C, the yield of char of all the species decreased sharply and then decreased gradually up to 800^0 C at both the heating rates (Figs. 21 & 22).

At 400^0 C with a heating rate of 3^0 C/min, the char yield from all the species ranged from 26.7 % to 46.5 % whereas with a heating rate of 20^0 C/min, the char yield ranged from 23.5 % to 37.9 %. Similarly at 500^0 C terminal temperatures when the heating rate was 3^0 C/min the char yield varied from 23.9

% to 44.0 %; but when the heating rate was increased to 20^0 C/min, the char yield ranged from 21.7 % to 34.8 %.

At 600^0 C, with a heating rate of 3^0 C/min, the char yield varied from 22.2 % to 40.3 % while a with a heating rate of 20^0 C/min, the char yield varied from 19.4 % to 28.4 %. At 700^0 C, with a heating rate of 3^0 C/min, the char yield ranged from 18.7 % to 34.5 % but with a heating rate of 20^0 C/min, the char yield ranged from 17.5 % to 26.0 % only.

However at 800^0 C terminal temperature, the char yields at both the heating rates were quite comparable. At this temperature with a heating rate of 3^0 C/min, the char yield ranged from 16.0 % to 28.3 % whereas with a heating rate of 20^0 C/min, the char yield ranged from 15.2 % to 25.5 %.

From the results shown in the Tables 6 & 7, it is clear that the char yields with 20^0 C/min heating rate were lower than the yields achieved at the heating rate of 3^0 C/min. Sensöz (2003) also observed similar trend of decrease of char yield with increase of heating rate from 7^0 C/min to 40^0 C/min and he related this with the fact that rapid heating leads to a fast depolymerization of the solid material to primary volatiles, while at the lower heating rate dehydration to more stable anhydrocellulose is limited and very slow (Chen et al., 1997).

At a heating rate of 3^0 C/min, C. hystrix yielded the highest percentages of char in all the terminal temperatures. At 800^0 C terminal temperatures, it yielded 28.3 % of char. Other species producing higher percentages of char at 800^0 C were M. bombycina (27.7 %), E. acuminata (27.6 %), Q. dealbata (26.5 %), E. varuna (25.9%) and Q. griffithii (25.3 %). Species like A. lucida (16.0 %), C.

Fig. 21: Effect of carbonization temperature on char yield (heating rate 3^0 C/min)
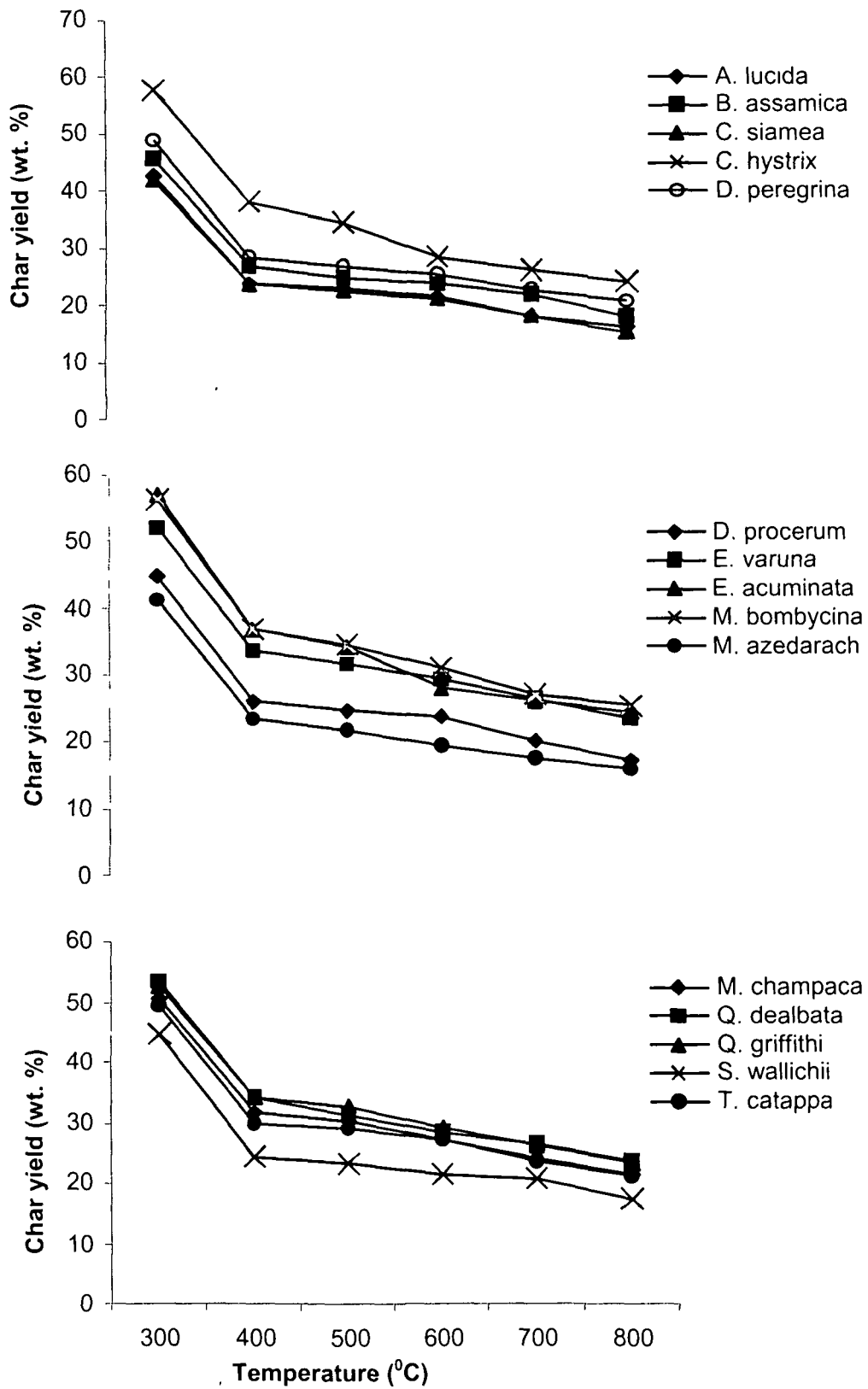
Fig. 22: Effect of carbonization temperature on char yield (heating rate 20^0 C/min)

siamea (16.1 %), *M. azedarach* (16.3 %), *D. procerum* (17.0 %) and *S. wallichii* (17.1 %) yielded much lower percentages of char. From the results of the biochemical compositions of the wood samples of the species (Table 4) and the results of their mass balance experiments (Tables 6 & 7) it is clear that the species with higher percentages of lignin contents yielded comparatively higher percentages of char. The wood samples of the above mentioned six species had much higher lignin contents as compared to other nine species.

Again at 800^0 C with a heating rate of 20^0 C/min, *M. bombycina* (25.5 %), *E. acuminata* (24.5 %), *C. hystrix* (24.2 %), *Q. dealbata* (23.7 %), *E. varuna* (23.4 %) and *Q. griffithii* (23.1 %) yielded comparatively much higher percentages of char. Our findings are in good agreement with those of Connor and Viljoen (1995) and Britto and Barrichelo (1997).

3.3 Tar production

Tar yields from all the species increased with the increase of carbonization temperature and reached a maximum at about 400^0 C or 500^0 C and then decreased as can be seen from Tables 6 & 7 and Figs. 23 & 24.

At 300^0 C, with a heating rate of 3^0 C/min, the maximum tar was yielded by *A. lucida* (12.5 %) whereas minimum of it was yielded by *C. hystrix* (5.4 %). Again, at 400^0 C, with the same heating rate, highest percentage of tar was yielded by *A lucida* (15.2%) and the lowest percentage of it was yielded by *C. hystrix* (7.8 %). Similarly at 500^0 C, *A. lucida* yielded maximum percentage of tar (16.1 %) while *D. peregrina* yielded the minimum of it (6.3 %).

At a heating rate of 3^0 C/min, among all the species, *M. azedarach* and *D. peregrina* reached the maximum of tar production at 400^0 C and then decreased gradually with the increase of temperature whereas the other thirteen species reached their maximum of tar production at about 500^0 C and then decreased sharply up to a temperature of about 600^0 C (Table 6). After this temperature the tar yielded decreased gradually. At temperatures higher then 600^0 C, secondary reactions such as tar cracking prevails and hence tar yields decreased. Kosstrin (1980) also observed the decrease of tar yield from biomass materials at higher temperatures and concluded that at temperatures above 500^0 C, secondary reactions play major role and thereby decreasing the yield of tar. Similar observations were also made by Sadakata *et al.* (1997), Scott & Piskorz (1984), Scott *et al.* (1985), Sensöz and Can (2002) and Fagbemi *et al.* (2001).

When the rate of heating was increased from 3^0 C/min to 20^0 C/min, tar yields from the tree species were found to change to some extent.

At 300^0 C, with a heating rate of 20^0 C/min, the maximum tar production was shown by *A. lucida* (14.0 %) and minimum was shown by *C. hystrix* (5.9 %). Similarly at 400^0 C, the highest percentage of tar yield was given by *A. lucida* (16.3 %) and the lowest yield was given by *T. catappa* (9.9 %). At 500^0 C, *T. catappa* yielded the maximum percentage of tar (13.1 %) whereas *E. acuminata* yielded the minimum percentage of it (7.1 %).

At the higher heating rate (i.e. 20^0 C/min) the yields of tar from most of the tree species except *C. hystrix, E. varuna, Q. griffithii* and *T. catappa* reached the maximum at about 400^0 C, while these four species reached their tar yield maximum at about 500^0 C.
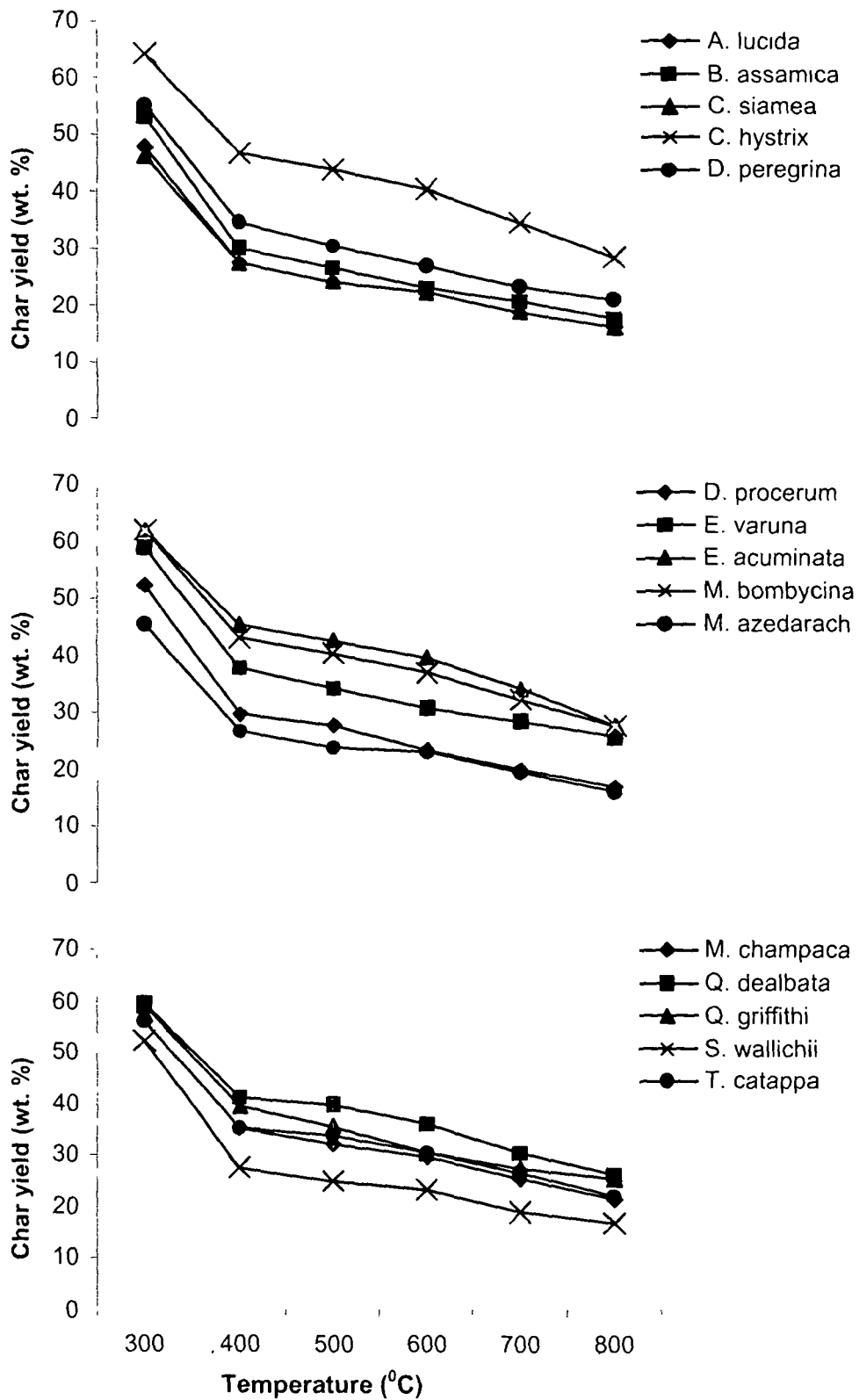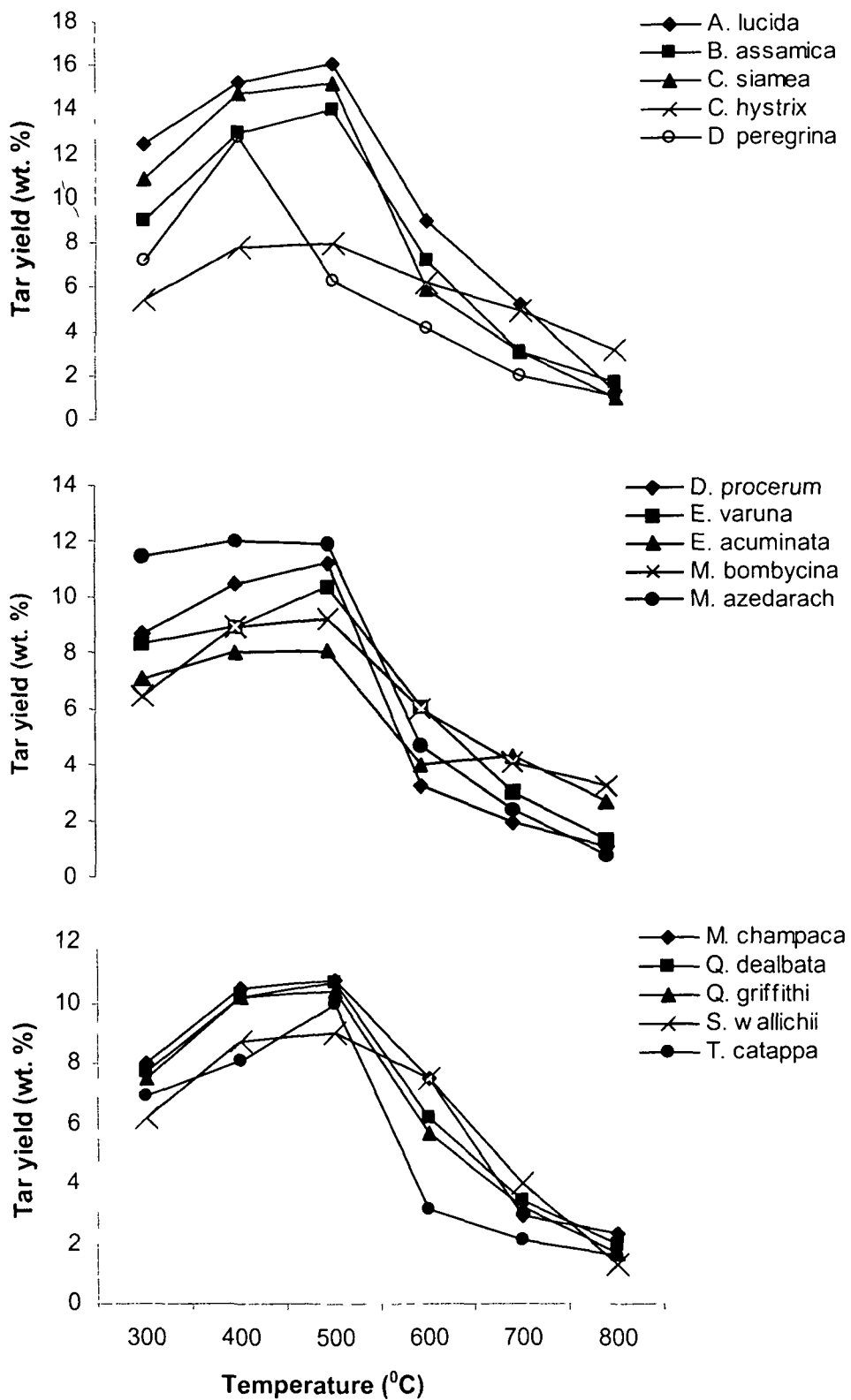
Fig. 23: Effect of carbonization temperature on tar yield (heating rate 3^0 C/min)
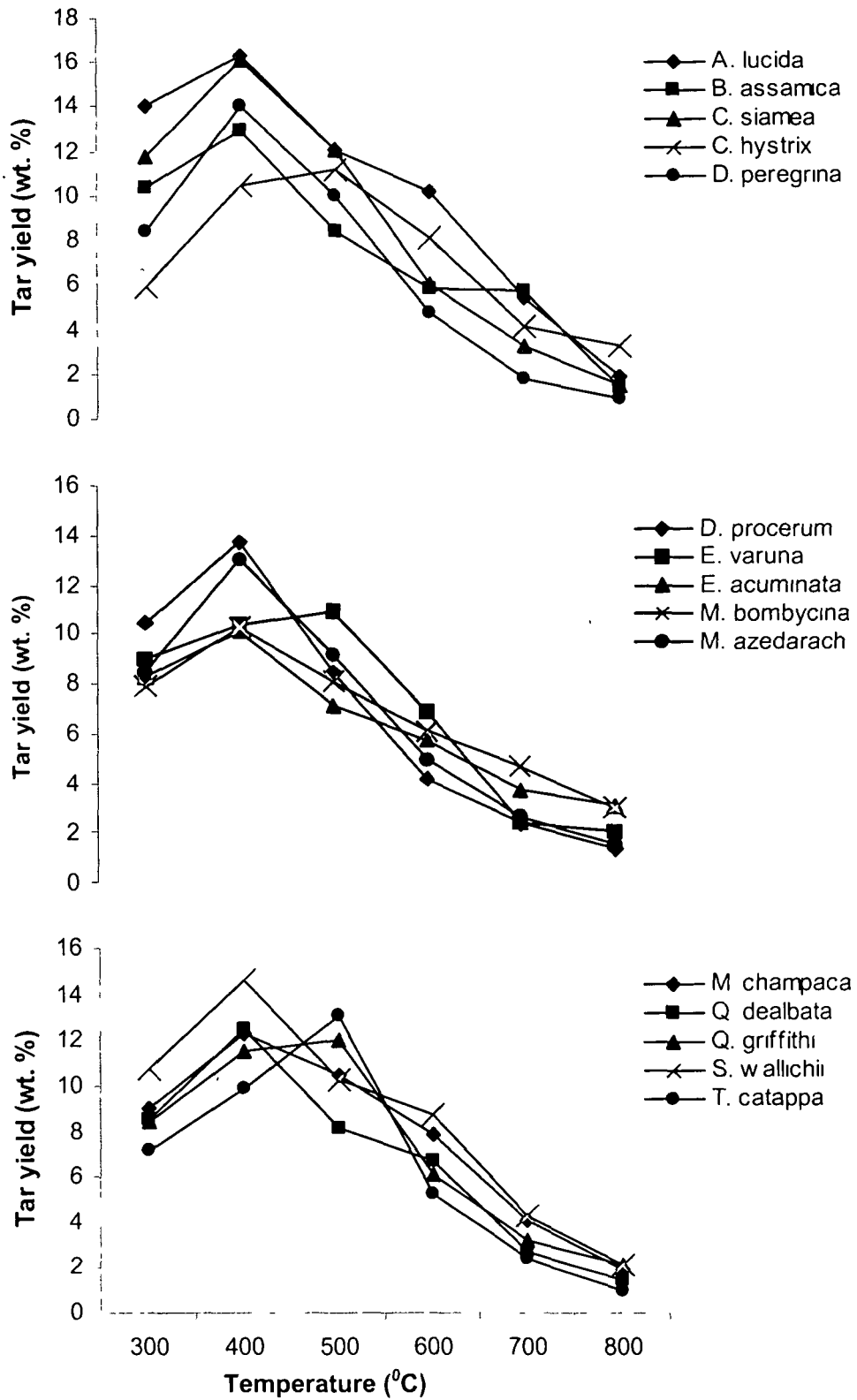
Fig. 24: Effect of carbonization temperature on tar yield (heating rate 20^0 C/min)

3.4   Condensed liquid production

From Tables 6 & 7 and Figs. 25 & 26, it can be seen that with the increase of carbonization temperature, yield of condensed liquid increased and after reaching a maximum at 400^0 C or 500^0 C, yield started decreasing. Except *D. peregrina,* all other species showed the highest yield of condensed liquid at about 400^0 C. At 300^0 C, when the heating rate applied was 3^0 C/min, the maximum percentage of condensed liquid was yielded by *M. azedarach* (32.0 %) and minimum percentage of it was yielded by *Q. dealbata* (21.8 %). Similarly, with the same heating rate at 400^0 C, *M. azedarach* again produced the highest percentage of condensed liquid (42.5 %) whereas *C. hystrix* yielded the lowest of it (25.0 %). At 800^0 C, *M. azedarach* with highest percentage of holocellulose content yielded the highest percentage of condensed liquid (25.0 %) and *C. hystrix* with highest percentage of lignin content, yielded the lowest percentage of it (12.1 %).

But when the heating rate of carbonization was increased to 20^0 C/min, at 300^0 C terminal temperature, *M. azedarach* yielded the maximum percentage of condensed liquid (41.1 %) whereas *Q. dealbata* yielded the lowest percentage of it (24.1 %). Similarly, at 400^0 C, *M. azedarach* yielded the highest percentage of condensed liquid (42.6 %) while *C. hystrix* and *M. bombycina* both yielded the lowest percentage of it (30.7 %).

At 800^0 C also, *M. azedarach* yielded the maximum percentage (27.5 %) of condensed liquid whereas the lowest percentage of it was shown by *Q. griffithii* (9.7%).
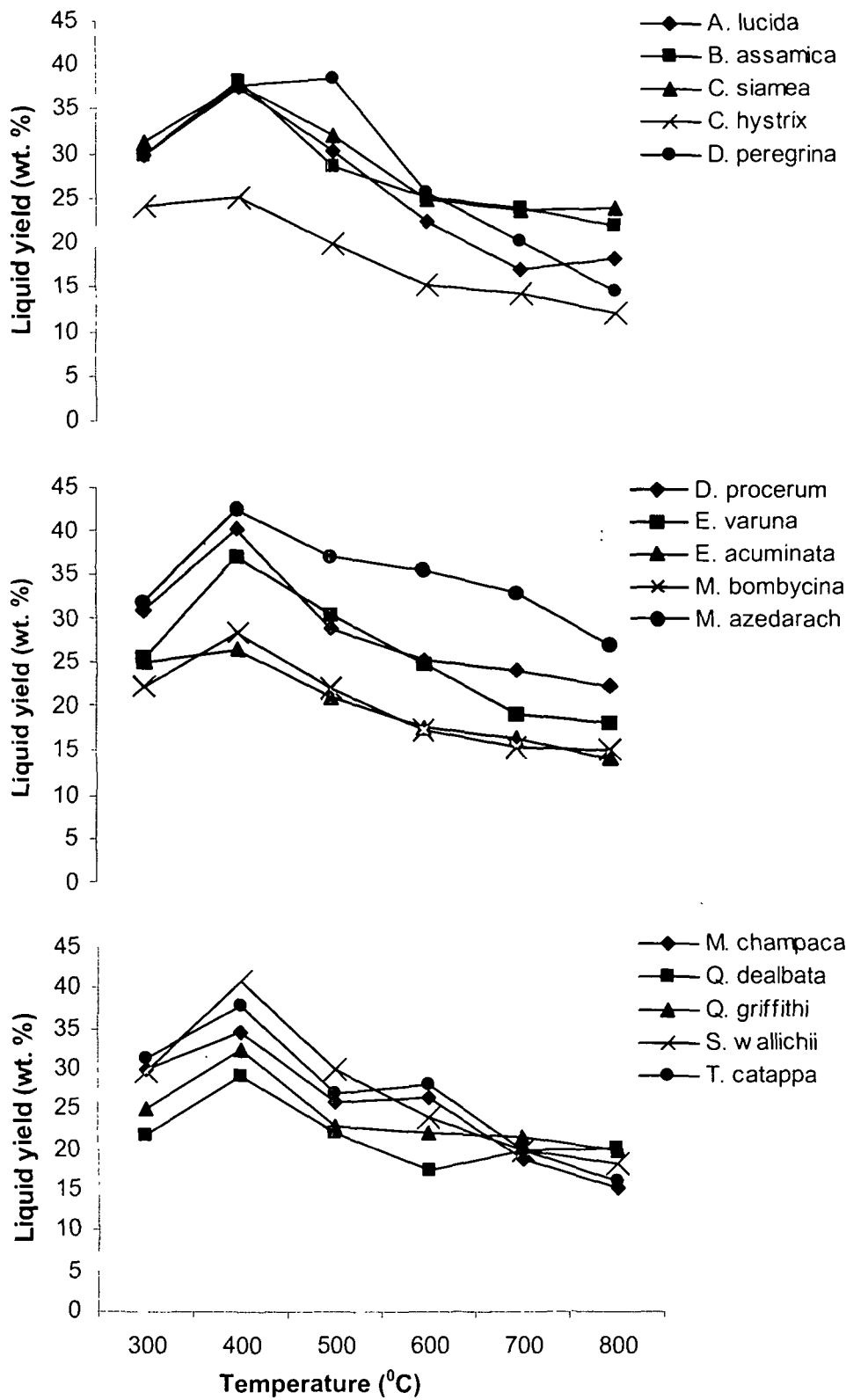
Fig. 25: Effect of carbonization temperature on condensed liquid yield (heating rate 3^0C/min)
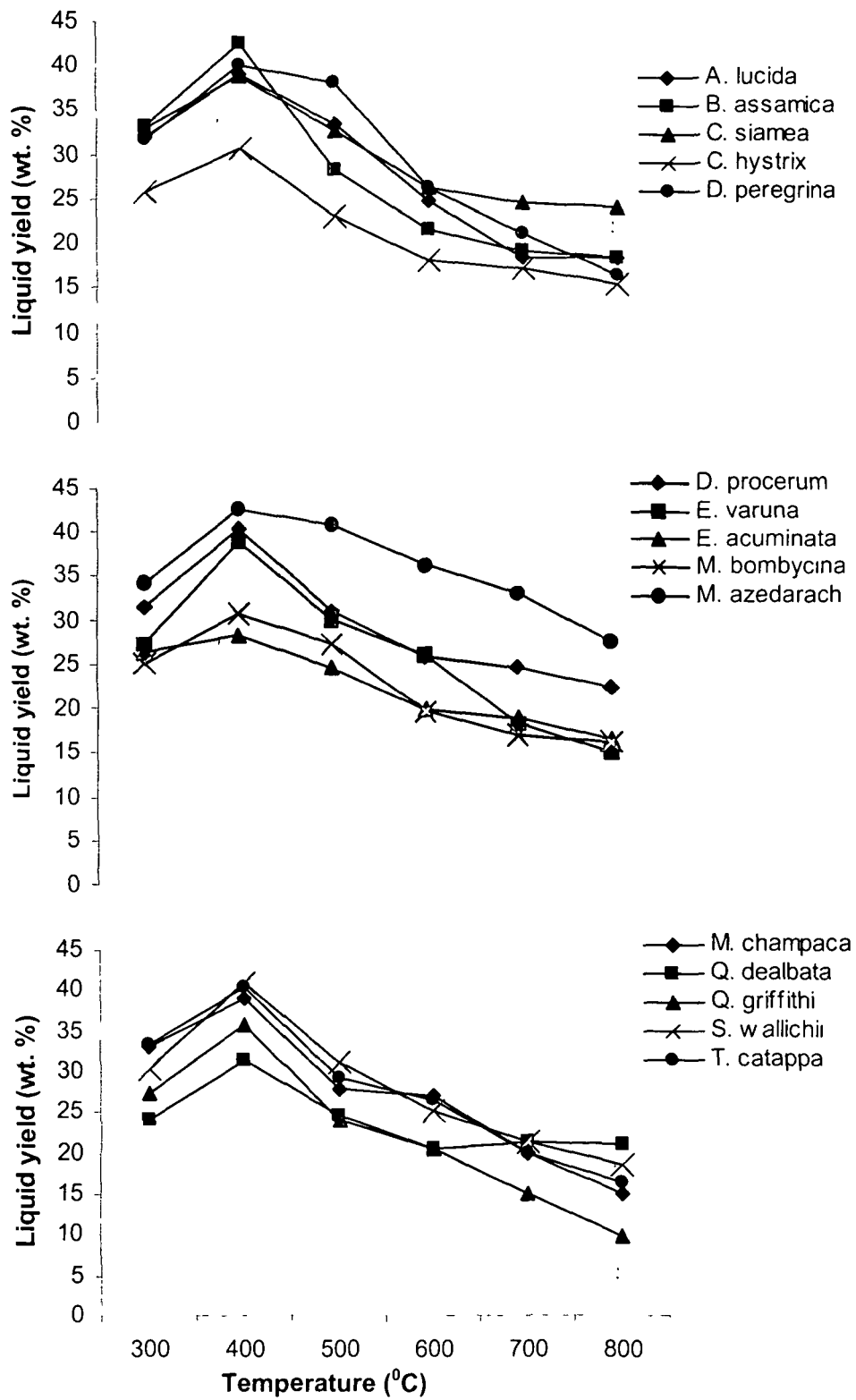
Fig. 26: Effect of carbonization temperature on condensed liquid yield (heating rate 20^0 C/min)

It can be seen from the Fig. 26, that the yields of condensed liquid from all the species reached their maximum at about 400^0 C only. It was further observed that the tree species rich in holocellulose content yielded more of condensed liquid on carbonization. In our earlier studies also we made similar observations (Konwer et al., 2005; Saikia et al., 2005). It can therefore be concluded that higher the holocellulose content in wood, higher is the yield of condensed liquid during its carbonization.

Part 3

Good

A lot of information to be
executed in this thesis and
later work in this field of
science

Part 4

Evaluation of the quality of charcoal samples produced from fifteen tree species

The quality of a charcoal is defined by various properties such as density, moisture content, ash content, volatile matter content, fixed carbon content etc., and though all are inter-related to a certain extent, they are measured and appraised separately. Proximate analysis indicates the percentage of fuel burned in solid and gaseous states and shows the quality of non-combustible ash remaining on the fire-grates or ash pit or entrained with flue gases. From combustion point of view, the volatile matter (VM) content 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/made useful in smoke abatement and air pollution control (Mingle & Boubel, 1968; Lyons *et al.*, 1985).

4.1 Moisture content

Moisture content is an important property for defining the quality of a charcoal. Charcoal fresh from an open kiln contains usually less than one percent of moisture. But on storing, absorption of moisture from the humidity of air is

rapid and there is, with time, a gain of moisture content to about 5-10 %. When the charcoal is not properly burned or where pyroligneous acids and soluble tars have been washed back into the charcoal by rain, its hygroscopicity increases and an equilibrium moisture content of the charcoal can rise to 15 % or even more. The quality specifications for charcoal usually limit the moisture content to around 5 – 15 % of the gross weight of the charcoal. According to Trossero (1991), the charcoal with a higher moisture content tends to shatter and produces fines when heated in a blast furnace, making it undesirable in the production of pig iron.

Lim (1993) and Lim & Vizhi (1993), from their laboratory-scale carbonization experiments of cocoa wood within the temperature range of 400^0 – 650^0 C have showed the moisture content of the charcoal samples within 6 - 9 %. They further observed that with the increase of carbonization temperature, the moisture content of the charcoal increased. Moisture content of charcoal samples produced from the tree species under study, at various terminal temperatures viz. 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C and with the heating rates of 3^0 C/min and 20^0 C/min are given in Table 9 and Table 10 respectively.

From Table 8, it is seen that the moisture content of the charcoal samples produced at 300^0 C terminal temperature with a heating rate of 3^0 C/min varied from 5.90 – 9.33 % whereas, the moisture contents of the charcoal samples produced at 400^0, 500^0, 600^0, 700^0 and 800^0 C with the same heating rate varied from 6.21-9.54 %, 6.75-10.02 %, 7.42-10.35 %, 7.99-11.10 % and 8.07-11.31 % respectively.

Table 8. Physical properties and proximate analysis of oven-dry charcoal produced at various temperatures with a heating rate of 3 °C/min

Species	Charcoal properties	Temperature (°C)					
		300	400	500	600	700	800
A lucida	Moisture (wt %)	8 73 ± 0 08 $_d$	8 92 ± 0 05 $_c$	9 35 ± 0 12 $_c$	9 79 ± 0 12 $_b$	10 15 ± 0 05 $_d$	10 15 ± 0 08 $_d$
	Ash content (wt %)	3 11 ± 0 14 $_{bc}$	3 18 ± 0 15 $_b$	3 19 ± 0 20 $_{bc}$	3 29 ± 0 18 $_b$	3 20 ± 0 21 $_b$	3 30 ± 0 20 $_{bc}$
	Density	0 40 ± 0 04 $_{de}$	0 300 ± 0 04 $_e$	0 278 ± 0 04 $_{fgh}$	0 251 ± 0 01 $_f$	0 23 ± 0 01 $_{fg}$	0 23 ± 0 01 $_f$
	Volatile matter (wt %)	71 26 ± 1 12 $_a$	48 60 ± 1 01 $_{fg}$	31 37 ± 1 02 $_i$	25 21 ± 0 74 $_{fg}$	24 00 ± 0 66 $_d$	22 59 ± 0 60 $_{bc}$
	Fixed carbon (wt %)	25 63 ± 0 86 $_i$	48 22 ± 0 70 $_e$	65 44 ± 0 45 $_{bc}$	71 50± 1 07 $_{bcde}$	72 80 ± 1 23 $_{ef}$	74 11 ± 1 20 $_g$
B assamica	Moisture (wt %)	8 22 ± 0 06 $_g$	8 73 ± 0 08 $_d$	8 92 ± 0 14 $_d$	9 49 ± 0 09 $_c$	10 00 ± 0 12 $_e$	10 00 ± 0 08 $_e$
	Ash content (wt %)	2 48 ± 0 07 $_{de}$	2 59 ± 0 08 $_c$	2 60 ± 0 15 $_d$	2 69 ± 0 16 $_d$	2 70 ± 0 11 $_c$	2 75 ± 0 21 $_d$
	Density	0 485 ± 0 03 $_{bcd}$	0 402 ± 0 02 $_{cd}$	0 341 ± 0 02 $_{cde}$	0 28 ± 0 03 $_{ef}$	0 26 ± 0 04 $_e$	0 26 ± 0 03 $_{de}$
	Volatile matter (wt %)	68 04 ± 0 86 $_{bc}$	51 73 ± 0 66 $_b$	38 42 ± 0 52 $_c$	26 55 ± 0 38 $_d$	22 28 ± 0 30 $_{ef}$	21 27 ± 0 52 $_{de}$
	Fixed carbon (wt %)	29 48 ± 0 42 $_{fg}$	45 68 ± 0 48 $_g$	58 98 ± 0 50 $_{gh}$	70 76 ± 0 78 $_{ef}$	75 02 ± 1 12 $_{cd}$	75 98 ± 1 23 $_{ef}$
C siamea	Moisture (wt %)	8 47 ± 0 04 $_{ef}$	8 69 ± 0 16 $_d$	8 87 ± 0 19 $_d$	9 20 ± 0 14 $_d$	9 35 ± 0 08 $_h$	9 35 ± 0 07 $_h$
	Ash content (wt %)	3 48 ± 0 12 $_a$	3 51 ± 0 14 $_a$	3 50 ± 0 15 $_a$	3 60 ± 0 07 $_a$	3 62 ± 0 12 $_a$	3 75 ± 0 11 $_a$
	Density	0 40 ± 0 01 $_{de}$	0 294 ± 0 01 $_e$	0 251 ± 0 03 $_{gh}$	0 21 ± 0 01 $_g$	0 18 ± 0 02 $_h$	0 17 ± 0 01 $_g$
	Volatile matter (wt %)	71 78 ± 0 84 $_a$	49 68 ± 0 60 $_{cde}$	34 05 ± 0 47 $_g$	23 75 ± 0 57 $_h$	22 17 ± 0 43 $_{ef}$	21 29 ± 0 31 $_{de}$
	Fixed carbon (wt %)	24 74 ± 0 27 $_i$	46 81 ± 0 44 $_f$	62 45 ± 0 59 $_{de}$	72 65± 0 60 $_{bcde}$	74 21 ±1 25 $_{cd}$	74 96 ± 1 05 $_{fg}$
C hystrix	Moisture (wt %)	5 90 ± 0 0018 $_i$	6 21 ± 0 04 $_i$	6 94 ± 0 05 $_h$	7 77 ± 0 08 $_g$	8 50 ± 0 14 $_j$	8 60 ± 0 10 $_j$
	Ash content (wt %)	1 65 ± 0 07 $_j$	1 66 ± 0 08 $_h$	1 81 ± 0 11 $_f$	1 80 ± 0 09 $_g$	1 90 ± 0 08 $_g$	1 95 ± 0 08 $_g$
	Density	0 591 ± 0 02 $_{ab}$	0 521 ± 0 02 $_a$	0 460 ± 0 02 $_a$	0 37 ± 0 05 $_{ab}$	0 30 ± 0 05 $_c$	0 28 ± 0 01 $_{cd}$
	Volatile matter (wt %)	60 49 ± 0 45 $_g$	48 27 ± 0 44 $_g$	35 27 ± 0 35 $_f$	25 14 ± 0 34 $_g$	20 54 ± 0 34 $_h$	17 94 ± 0 26 $_i$
	Fixed carbon (wt %)	37 86 ± 0 37 $_a$	50 07 ± 0 48 $_d$	62 92 ± 0 66 $_d$	73 06 ±0 63 $_a$	77 56 ± 0 65 $_a$	80 11 ± 0 98 $_a$
D peregrina	Moisture (wt %)	7 75 ± 0 14 $_h$	8 07 ± 0 11 $_e$	8 42 ± 0 07 $_e$	8 75 ± 0 11 $_e$	9 09 ± 0 11 $_i$	9 09 ± 0 09 $_i$
	Ash content (wt %)	2 29 ± 0 08 $_{ef}$	2 33 ± 0 16 $_{cde}$	2 35 ± 0 20 $_e$	2 34 ± 0 10 $_e$	2 35 ± 0 17 $_d$	2 45 ± 0 15 $_e$
	Density	0 50 ± 0 02 $_{abcd}$	0 433 ±0 03 $_{bcd}$	0 387 ± 0 04 $_{bc}$	0 36 ± 0 02 $_{ab}$	0 33 ± 0 03 $_{ab}$	0 32 ± 0 03 $_b$
	Volatile matter (wt %)	70 75 ± 0 60 $_a$	49 19 ± 0 42 $_{ef}$	37 94 ± 0 40 $_c$	29 92 ± 0 38 $_{ab}$	24 97 ± 0 34 $_b$	23 16 ± 0 47 $_b$
	Fixed carbon (wt %)	26 26 ± 0 28 $_{hi}$	48 56 ± 0 30 $_e$	59 71 ± 0 42 $_g$	67 74 ± 0 66 $_g$	72 68 ± 1 06 $_f$	74 39 ± 1 04 $_g$
D procerum	Moisture (wt %)	8 57 ± 0 04 $_e$	8 69 ± 0 06 $_d$	9 23 ± 0 11 $_c$	9 71 ± 0 07 $_b$	9 85 ± 0 14 $_f$	9 87 ± 0 07 $_f$
	Ash content (wt %)	2 57 ± 0 10 $_d$	2 50 ± 0 13 $_{cd}$	2 65 ± 0 08 $_d$	2 66 ± 0 12 $_d$	2 71 ± 0 08 $_c$	2 74 ± 0 09 $_d$
	Density	0 50 ± 0 04 $_{abcd}$	0 400 ± 0 03 $_{cd}$	0 321 ± 0 04 $_{def}$	0 28 ± 0 02 $_{ef}$	0 25 ± 0 05 $_{ef}$	0 25 ± 0 04 $_e$
	Volatile matter (wt %)	65 57 ± 0 66 $_e$	59 25 ± 0 80 $_a$	40 91 ± 0 66 $_b$	30 15 ± 0 50 $_a$	25 58 ± 0 66 $_a$	23 13 ± 0 42 $_b$
	Fixed carbon (wt %)	31 86 ± 0 40 $_d$	38 25 ± 0 30 $_h$	56 44 ± 0 60 $_i$	67 19 ± 0 67 $_g$	71 71 ± 0 80 $_f$	74 13 ± 0 81 $_g$
E varuna	Moisture (wt %)	6 47 ± 0 05 $_j$	7 21 ± 0 04 $_g$	8 53 ± 0 13 $_e$	8 91 ± 0 07 $_e$	9 31 ± 0 04 $_h$	9 39 ± 0 07 $_h$
	Ash content (wt %)	1 97 ± 0 20 $_{ghi}$	2 09 ± 0 18 $_{efg}$	2 15 ± 0 17 $_e$	2 15 ± 0 12 $_{ef}$	2 10 ± 0 10 $_{efg}$	2 22 ± 0 06 $_{ef}$
	Density	0 56 ± 0 12 $_{ab}$	0 482 ±0 02 $_{abc}$	0 411 ± 0 01 $_{ab}$	0 38 ± 0 02 $_a$	0 35 ± 0 03 $_a$	0 34 ± 0 01 $_{cd}$
	Volatile matter (wt %)	66 25 ± 0 87 $_{de}$	46 38 ± 0 83 $_i$	35 21 ± 0 42 $_f$	26 68 ± 0 56 $_d$	22 60 ± 0 40 $_e$	20 83 ± 0 48 $_e$
	Fixed carbon (wt %)	31 78 ± 0 38 $_d$	51 53 ± 0 42 $_c$	62 64 ± 0 44 $_{de}$	71 17± 0 56 $_{cdef}$	75 30 ± 0 62 $_{bc}$	76 95 ± 1 22 $_{de}$
E acuminata	Moisture (wt %)	8 35 ± 0 08 $_f$	8 89 ± 0 07 $_c$	9 73 ± 0 18 $_b$	10 17 ± 0 06 $_a$	11 10 ± 0 12 $_a$	11 31 ± 0 10 $_a$
	Ash content (wt %)	1 73± 0 09 $_{ij}$	1 87 ± 0 15 $_{gh}$	1 80 ± 0 09 $_f$	1 85 ± 0 15 $_g$	1 99 ± 0 12 $_{fg}$	2 03 ± 0 10 $_{fg}$
	Density	0 60 ± 0 03 $_a$	0 512 ± 0 02 $_{ab}$	0 406 ± 0 04 $_{bcd}$	0 321 ± 0 02 $_{cd}$	0 30 ± 0 04 $_c$	0 30 ± 0 03 $_{bc}$
	Volatile matter (wt %)	62 66 ± 0 51 $_f$	48 51 ± 0 63 $_{fg}$	36 06 ± 0 60 $_e$	26 58 ± 0 42 $_d$	20 52 ± 0 43 $_h$	19 28 ± 0 57 $_{gh}$
	Fixed carbon (wt %)	35 61 ± 0 29 $_b$	49 62 ± 0 40 $_d$	62 14 ± 0 45 $_{de}$	71 57± 0 62 $_{bcde}$	77 49 ± 0 70 $_a$	78 69± 1 05 $_{bc}$

Species	Charcoal properties	Temperature (° C)					
		300	400	500	600	700	800
M bombycina	Moisture (wt %)	6 03 ± 0 12 k	6 53 ± 0 08 h	7 21 ± 0 15 g	7 67 ± 0 04 g	8 31 ± 0 17 k	8 42 ± 0 14 k
	Ash content (wt %)	1 80 ± 0 07ij	1 82 ± 08gh	1 87 ± 0 15f	1 85 ± 0 17g	2 00 ± 0 10fg	2 01 ± 0 14fg
	Density	0 604 ± 0 06 a	0 517 ±0 01a	0 422 ± 0 06ab	0 365±0 01ab	0 32 ± 0 02bc	0 30 ± 0 04bc
	Volatile matter (wt %)	60 58 ± 0 59g	42 38 ±0 44k	30 67 ± 0 54j	26 50± 0 31d	21 59± 0 20g	19 52 ± 0 48g
	Fixed carbon (wt %)	37 62 ± 0 34a	55 80 ±0 30a	67 46 ± 0 46a	71 65±0 73bc	76 41±0 98a	78 47± 1 04bc
M azedarach	Moisture (wt %)	9 08 ± 0 11 b	9 54 ± 0 09 a	10 03 ± 0 09 a	10 25 ± 0 08	10 41 ± 0 10	10 45 ± 0 08 c
	Ash content (wt %)	3 19 ± 0 17b	3 20 ± 0 12b	3 35 ± 0 14ab	3 30 ± 0 17b	3 25 ± 0 13b	3 37 ± 0 12b
	Density	0 382 ± 0 02 e	0 307 ±0 02e	0 242 ± 0 01h	0 21 ± 0 04g	0 18 ± 0 02h	0 17 ± 0 01g
	Volatile matter (wt %)	71 22 ± 1 06a	49 54±0 86d	38 49 ± 0 70c	25 75±0 63ef	21 90±0 44fg	21 44 ± 0 30d
	Fixed carbon (wt %)	25 59 ± 0 30i	47 26± 0 45f	58 16 ± 0 68h	70 95±1 06d	74 85±1 18cd	75 19 ± 1 06fg
M champaca	Moisture (wt %)	8 95 ± 0 13 c	9 21 ± 0 08 b	9 75 ± 0 09 b	10 20 ± 0 08	10 41 ± 0 08	10 44 ± 0 12 c
	Ash content (wt %)	2 10 ± 0 08fgh	2 11± 0 03efg	2 20 ± 0 14e	2 17 ± 0 17ef	2 20± 0 09def	2 42 ± 0 09e
	Density	0 50± 0 08abcd	0 445± 01abc	0 387 ± 0 02bc	0 341±0 04bc	O 31± 0 02bc	0 30 ± 0 01bc
	Volatile matter (wt %)	68 80 ± 0 75b	49 23±0 69ef	37 05 ± 0 40d	30 32± 0 42a	25 82± 0 44a	24 68 ± 0 26a
	Fixed carbon (wt %)	29 10 ± 0 34g	48 66± 0 45e	60 75 ± 0 40f	67 51± 0 44g	71 98± 0 84f	72 90 ± 1 06h
Q dealbata	Moisture (wt %)	6 01 ± 0 08kl	6 39 ± 0 09 h	6 75 ± 0 13i	7 42 ± 0 05h	7 99 ± 0 09i	8 07 ± 0 09i
	Ash content (wt %)	1 87 ± 0 09ghij	1 95± 0 12fgh	1 90 ± 0 07i	2 0 ± 0 12fg	2 10± 0 14efg	2 25 ± 0 08ef
	Density	0 55 ± 0 08abc	0 462±0 03a	0 40 ± 0 03ab	0 313±0 01d	0 28 ± 0 01d	0 28 ± 0 02cd
	Volatile matter (wt %)	63 82 ± 0 61f	44 46 ± 0 49j	31 95 ± 0 40i	25 75±0 24ef	20 58± 0 16h	18 77 ± 0 18h
	Fixed carbon (wt %)	34 31 ± 0 27c	53 59± 0 36b	66 15 ± 0 44b	72 25±0 62a	77 32± 1 07a	78 98 ± 0 88b
Q griffithii	Moisture (wt %)	7 23 ± 0 09i	7 88 ± 0 08 f	8 23 ± 0 12f	8 49 ± 0 08f	9 54 ± 0 06 g	9 61 ± 0 08 g
	Ash content (wt %)	1 85 ± 0 16hij	1 80± 0 18gh	1 90 ± 0 07i	1 92 ± 0 14g	2 05 ± 0 20fg	2 08 ± 0 14fg
	Density	0 575 ± 0 07ab	0 469±0 02ab	0 371± 0 02bcd	0 321±0 01cd	0 30 ± 0 04c	0 28 ± 0 03cd
	Volatile matter (wt %)	68 00 ± 0 68bc	50 10±0 56cd	36 25 ± 0 44e	25 90± 0 36e	22 62± 0 52e	20 14 ± 0 51f
	Fixed carbon (wt %)	30 15 ± 0 34ef	48 10± 0 42e	61 85 ± 0 56e	72 18±0 65a	75 33±1 08bc	77 78± 1 20cd
S wallichii	Moisture (wt %)	9 33 ± 0 08 a	9 47 ± 0 10 a	10 02 ± 0 14 a	10 30 ± 0 06	10 35 ± 0 07	10 39 ± 0 12 c
	Ash content (wt %)	2 89 ± 0 16c	2 97 ± 0 15b	3 01 ± 0 18c	3 02 ± 0 15c	3 11 ± 0 21b	3 11 ± 0 14c
	Density	0 45 ± 0 03 cde	0 369±0 04de	0 301± 0 03efg	0 250 ± 0 02i	0 23 ± 0 04g	0 22 ± 0 02i
	Volatile matter (wt %)	70 70 ± 1 04a	50 41± 0 87c	42 06 ± 0 94a	29 50± 0 84b	24 46± 0 66c	24 21 ± 0 71a
	Fixed carbon (wt %)	26 41 ± 0 80h	46 62± 0 76i	54 93 ± 0 88j	67 48± 1 06g	72 43± 0 11i	72 68 ± 1 25h
T catappa	Moisture (wt %)	8 96 ± 0 08 bc	9 27 ± 0 12 b	9 87 ± 0 11ab	10 33 ± 0 10	10 85 ± 0 09	10 91 ± 0 11 b
	Ash content (wt %)	2 14 ± 0 14fg	2 25± 0 09def	2 20 ± 0 11e	2 30 ± 0 14e	2 30± 0 10de	2 35 ± 0 11e
	Density	0 544 ±	0 457±0 04ab	0 375± 0 03bcd	0 35± 0 06abc	0 33 ± 0 01ab	0 32 ± 0 02b
	Volatile matter (wt %)	67 25 ± 0 66cd	47 44± 0 60h	33 10 ± 0 50h	27 63± 0 38c	23 82± 0 24d	22 14 ± 0 24c
	Fixed carbon (wt %)	30 61 ± 0 25e	50 31± 0 43d	64 70 ± 0 65c	70 07± 1 06i	73 88±0 94d	75 51 ± 1 28i
LSD0.05	Moisture (wt %)	0 11	0 15	0 17	0 17	0 11	0 09
	Ash content (wt %)	0 25	0 29	0 22	0 21	0 22	0 22
	Density	0 09	0 07	0 05	0 03	0 02	0 02
	Volatile matter (wt %)	1 27	0 70	0 69	0 56	0 45	0 56
	Fixed carbon (wt %)	0 72	0 73	0 84	1 11	1 10	1 03

Mean value followed by the same letter shown in subscript are not significantly different

Table 9: Physical properties and proximate analysis of oven-dry charcoal produced at various temperatures with heating rate of 20 °C/min

Species	Charcoal properties	Temperature (° C)					
		300	400	500	600	700	800
A lucida	Moisture (wt %)	10 41 ± 0 12 d	10 72 ± 0 05	11 42 ± 0 15 ef	12 63 ± 0 12	13 07 ± 0 14	13 33 ± 0 07 h
	Ash content (wt %)	3 20 ± 0 12bc	3 24 ± 0 14b	3 23 ± 0 09b	3 25 ± 0 09b	3 13 ± 0 14b	3 18 ± 0 18b
	Density	0 343 ± 0 02ab	0 319±0 03de	0 277 ± 0 05bc	0 24 ± 0 02de	0 22 ± 0 04de	0 200 ± 0 02e
	Volatile matter (wt %)	74 15 ± 1 15ab	50 98± 1 12g	31 90 ± 0 65f	25 98 ±0 54f	24 08±0 23fg	22 42 ± 0 22ef
	Fixed carbon (wt %)	22 65 ± 0 27g	45 78±0 25bc	64 87 ± 0 33a	70 77 ±0 44b	72 79±0 63a	74 40±0 04abc
B assamica	Moisture (wt %)	12 30 ± 0 07 a	12 75 ± 0 18	14 93 ± 0 14 a	15 08 ± 0 08	15 73 ± 0 08	15 96 ± 0 24 b
	Ash content (wt %)	2 40 ± 0 17de	2 43 ± 0 19cd	2 50 ± 0 11c	2 60 ± 0 13c	2 55 ± 0 12c	2 60 ± 0 14c
	Density	0 421 ± 0 02ab	0 365±0 02bc	0 321±0 07abc	0 301±0 06bc	0 275 ±0 04c	0 270 ± 0 01bc
	Volatile matter (wt %)	71 68 ± 1 04cd	56 84± 0 80b	41 53 ± 0 42b	32 20±0 30a	24 95±0 36ef	23 90 ± 0 36cd
	Fixed carbon (wt %)	25 92 ± 0 43e	40 73± 0 44f	55 97 ± 0 40hi	65 20± 0 34h	72 50±0 51bc	73 50±0 55bcd
C siamea	Moisture (wt %)	9 66 ± 0 14 g	10 18 ± 0 06	11 23 ± 0 20 g	11 74 ± 0 14	12 39 ± 0 09	13 01 ± 0 14 ij
	Ash content (wt %)	3 50 ± 0 07a	3 63 ± 0 17a	3 59 ± 0 17a	3 69 ± 0 14a	3 70 ± 0 14a	3 72 ± 0 16a
	Density	0 307 ± 0 03b	0 264± 0 04e	0 247 ± 0 02ab	0 23 ± 0 04ef	0 200 ±0 03e	0 200 ± 0 01e
	Volatile matter (wt %)	74 68 ± 1 10a	49 87± 0 70h	33 43 ± 0 42f	24 53 ±0 35g	21 37 ±0 30i	20 78 ± 0 24h
	Fixed carbon (wt %)	21 82 ± 0 31g	46 50±0 45bc	62 98 ± 0 50b	71 78 ±0 55a	74 93 ±1 07a	75 50 ± 0 92ab
C hystrix	Moisture (wt %)	7 15 ± 0 08j	8 36 ± 0 08 k	11 25 ± 0 21	11 89 ± 0 10	13 01 ± 0 25	14 35 ± 0 19 i
	Ash content (wt %)	1 71 ± 0 03i	1 70 ± 0 04g	1 73 ± 0 10g	1 80 ± 0 07g	1 85 ± 0 12h	1 91 ± 0 07g
	Density	0 567 ± 0 02a	0 507± 0 02a	0 440 ± 0 02a	0 349± 03abc	0 29 ± 0 03bc	0 280 ± 0 01b
	Volatile matter (wt %)	64 47 ± 0 48h	51 20±0 61fg	37 93 ± 0 23d	29 98 ±0 19c	25 79±0 24d	23 86 ± 0 27cd
	Fixed carbon (wt %)	33 82 ± 0 15ab	47 10± 0 20b	60 34 ± 0 45i	68 32±0 50ef	72 36±0 48cd	74 23±0 60abc
D peregrina	Moisture (wt %)	11 67 ± 0 08 b	12 34 ± 0 12	13 39 ± 0 12 b	14 32 ± 0 08	15 03 ± 0 14	16 22 ± 0 24 a
	Ash content (wt %),	2 30 ± 0 01def	2 35 ± 0 07cd	2 50 ± 0 11c	2 40 ± 0 08cd	2 45 ± 0 13cd	2 50 ± 0 10cd
	Density	0 472 ± 0 04ab	0 413±0 03bc	0 387 ± 0 06ab	0 370± 0 08a	0 340 ±0 02a	0 330 ± 0 01a
	Volatile matter (wt %)	73 51 ± 0 55ab	52 39±0 64d	41 96 ± 0 43ab	31 92±0 30a	27 65 ±0 26b	26 95 ± 0 28a
	Fixed carbon (wt %)	24 19 ± 0 25f	45 26±0 31bc	55 54 ± 0 44i	65 68±0 58g	69 90±0 66g	70 55 ± 0 70fg
D procerum	Moisture (wt %)	10 32 ± 0 11 d	10 36 ± 0 12	11 56 ± 0 14 e	12 43 ± 0 16	14 03 ± 0 07	14 69 ± 0 18 e
	Ash content (wt %)	2 50 ± 0 12d	2 60 ± 0 23c	2 57 ± 0 15c	2 60 ± 0 20c	2 59 ± 0 12c	2 63 ± 0 11c
	Density	0 400 ± 0 01ab	0 350±0 03cd	0 300 ± 0 03bc	0 270±0 08d	0 250±0 06cd	0 250 ± 0 01cd
	Volatile matter (wt %)	71 63 ± 1 12cd	62 20± 0 86a	43 52 ± 0 61a	31 10± 0 62b	25 82±0 50d	24 88 ± 0 40bc
	Fixed carbon (wt %)	25 87 ± 0 33e	35 20± 0 30g	53 91 ± 0 63j	66 30± 0 70g	71 59±0 90d	72 49± 0 80def
E varuna	Moisture (wt %)	8 01 ± 0 09i	8 65 ± 0 10j	9 98 ± 0 24j	10 84 ± 0 08	11 58 ± 0 18	13 05 ± 0 15i
	Ash content (wt %)	2 04 ± 0 09fgh	2 03 ± 0 12ef	2 04 ± 0 14def	2 15 ± 0 09ef	2 12 ±0 15efg	2 12 ± 0 17efg
	Density	0 500 ± 0 02ab	0 437±0 03a	0 407 ± 0 04ab	0 380± 0 08a	0 360 ±0 04a	0 350 ± 0 02a
	Volatile matter (wt %)	69 62 ± 0 65e	50 95 ±0 47g	37 86 ± 0 37d	29 89± 0 32c	27 33 ±0 25b	26 15 ± 0 28a
	Fixed carbon (wt %)	28 34 ± 0 22d	47 02±0 24bc	60 10 ± 0 29i	67 96± 0 40f	70 50±0 67fg	71 73± 0 66efg
E acuminata	Moisture (wt %)	9 80 ± 0 10f	10 54 ± 0 11	12 56 ± 0 08 c	13 39 ± 0 20	14 93 ± 0 21	15 70 ± 0 14 c
	Ash content (wt %)	1 75 ± 0 03i	1 79 ± 0 04fg	1 98 ± 0 05ef	2 04 ± 0 11ef	2 08±0 07efg	2 20 ± 0 09efg
	Density	0 551 ± 0 03ab	0 450±0 03a	0 352±0 04abc	0 300±0 04bc	0 29 ± 0 03bc	0 290 ± 0 02b
	Volatile matter (wt %)	65 78 ± 0 57g	51 30±0 54fg	36 38 ± 0 41de	27 32 ±0 52e	23 25 ±0 30h	21 96 ± 0 20i
	Fixed carbon (wt %)	32 47 ± 0 14b	46 91±0 15bc	61 21 ± 0 41de	70 64 ±0 45b	74 67 ±0 57a	75 84 ± 0 60a

Continued........

Species	Charcoal properties	Temperature (° C)					
		300	400	500	600	700	800
M bombycina	Moisture (wt %)	6 74 ± 0 08$_k$	8 86 ± 0 12$_i$	10 47 ± 0 06$_i$	10 69 ± 0 14	12 41 ± 0 20	12 5 ± 0 12$_k$
	Ash content (wt %)	1 83 ± 0 08$_{hi}$	1 94 ±0 03$_{efg}$	1 85 ± 0 06$_{fg}$	1 94 ± 0 03$_{fg}$	2 00 ±0 06$_{gh}$	2 05 ± 0 08$_{fg}$
	Density	0 545 ± 0 04$_{ab}$	0 447±0 03$_a$	0 361±0 05$_{abc}$	0 300±0 05$_{bc}$	0 290±0 02$_{bc}$	0 290 ± 0 03$_b$
	Volatile matter (wt %)	63 37 ± 0 49$_h$	44 80 ± 0 55$_j$	33 33 ± 0 49$_i$	27 87 ±0 32$_e$	24 29±0 25$_{fg}$	22 97 ± 0 20$_h$
	Fixed carbon (wt %)	34 80 ± 0 27$_a$	53 26± 0 24$_a$	64 82 ± 0 37$_a$	70 19±0 40$_{bc}$	73 71±0 55$_a$	74 98±0 68$_{abc}$
M azedarach	Moisture (wt %)	10 07 ± 0 06$_e$	10 30±0 14$_{fg}$	10 39 ± 0 21$_i$	11 08 ± 0 18	12 70 ± 0 11	13 65 ± 0 10$_g$
	Ash content (wt %)	3 25 ± 0 12$_{ab}$	3 19 ± 0 09$_b$	3 20 ± 0 15$_b$	3 21 ± 0 08$_b$	3 20 ± 0 18$_b$	3 30 ± 0 20$_b$
	Density	0 301 ± 0 02$_b$	0 281±0 01$_d$	0 239 ± 0 05$_c$	0 220 ± 01$_f$	0 180± 0 02$_e$	0 180 ± 0 01$_i$
	Volatile matter (wt %)	74 50 ± 1 08$_a$	53 91 ±0 87$_c$	40 37 ± 0 66$_{bc}$	27 50 ±0 51$_e$	22 21 ± 0 35$_i$	21 22 ± 0 36$_i$
	Fixed carbon (wt %)	22 25 ± 0 39$_g$	42 90 ±0 50$_e$	56 43 ± 0 66$_h$	69 29±0 85$_{cd}$	74 59±0 88$_a$	75 48 ± 1 15$_{ab}$
M champaca	Moisture (wt %)	11 19 ± 0 14$_c$	12 10 ± 0 09	12 20 ± 0 14$_d$	12 46 ± 0 17	14 63 ± 0 16	15 16 ± 0 12$_d$
	Ash content (wt %)	2 17 ± 0 05$_{efg}$	2 15 ±0 12$_{de}$	2 24 ± 0 17$_d$	2 25 ±0 19$_{de}$	2 27 ±0 15$_{def}$	2 29 ± 0 14$_{def}$
	Density	0 481 ± 0 03$_{ab}$	0 446±0 04$_a$	0 407 ± 0 04$_{ab}$	0 365 ±0 04$_a$	0 340 ±0 03$_a$	0 330 ± 0 04$_a$
	Volatile matter (wt %)	71 05 ± 0 54$_d$	52 71 ±0 60$_d$	39 83 ± 0 40$_c$	33 04 ±0 43$_a$	28 78 ±0 30$_a$	26 75 ± 0 31$_{bc}$
	Fixed carbon (wt %)	26 78 ± 0 20$_e$	45 14±0 31$_{cd}$	57 83 ± 0 37$_g$	64 71 ±0 34$_h$	68 95±0 37$_{hi}$	70 96 ± 0 36$_{fg}$
Q dealbata	Moisture (wt %)	6 53 ± 0 08$_i$	8 20 ± 0 14$_i$	8 87 ± 0 12$_k$	9 61 ± 0 12$_i$	12 50±0 14$_{fg}$	12 92 ± 0 08$_{ij}$
	Ash content (wt %)	0 525 ± 0 02$_{ab}$	0 441±0 01$_a$	0 355±0 06$_{abc}$	0 291±0 07$_{cd}$	0 270± 0 01$_c$	0 270 ± 0 02$_{bc}$
	Density	1 85 ± 0 09$_{hi}$	1 90 ±0 12$_{efg}$	1 91 ± 0 14$_{fg}$	2 00 ± 0 08$_{fg}$	2 05± 0 07$_{igh}$	2 03 ± 0 06$_g$
	Volatile matter (wt %)	67 35 ± 0 61$_i$	45 92 ±0 50$_i$	35 54 ± 0 42$_e$	28 47±0 17$_d$	23 65±0 22$_g$	21 79 ± 0 25$_i$
	Fixed carbon (wt %)	30 80 ± 0 22$_c$	52 15 ±0 35$_a$	61 63 ± 0 47$_{cd}$	69 53±0 65$_{cd}$	74 30±0 42$_a$	76 18 ± 0 59$_a$
Q grffithii	Moisture (wt %)	8 39 ± 0 12$_h$	10 15 ± 0 17	12 48 ± 0 18$_c$	13 57 ± 0 14	14 05 ± 0 12	14 29 ± 0 07$_f$
	Ash content (wt %)	1 90 ± 0 09$_{ghi}$	2 02 ±0 07$_{efg}$	1 95 ± 0 12$_{fg}$	2 09 ± 0 14$_{ef}$	2 10 ±0 14$_{efg}$	2 15 ± 0 15$_{efg}$
	Density	0 520 ± 0 01$_{ab}$	0 431±0 01$_a$	0 363±0 06$_{abc}$	0 301±0 06$_{bc}$	0 280 ±0 01$_c$	0 270 ± 0 01$_{bc}$
	Volatile matter (wt %)	69 70 ± 0 52$_e$	51 33±0 46$_{fg}$	37 44 ± 0 33$_d$	29 30±0 19$_{cd}$	25 49±0 14$_d$	24 80 ± 0 15$_{ef}$
	Fixed carbon (wt %)	28 40 ± 0 34$_d$	46 65±0 27$_{bc}$	60 61 ± 0 30$_{ef}$	68 61±0 47$_d$	72 41±0 57$_{cd}$	73 05±0 54$_{cde}$
S wallichii	Moisture (wt %)	10 41 ± 0 08$_d$	10 55 ± 0 08	10 98 ± 0 18$_h$	11 95 ± 0 14	12 66 ± 0 09	12 77 ± 0 09$_j$
	Ash content (wt %)	2 95 ± 0 07$_c$	3 00 ± 0 08$_b$	3 20 ± 0 09$_b$	3 25 ± 0 19$_b$	3 20 ± 0 10$_b$	3 19 ± 0 08$_b$
	Density	0 370 ± 0 03$_{ab}$	0 317±0 02$_d$	0 301 ± 0 01$_{bc}$	0 270±0 04$_d$	0 250±0 05$_{cd}$	0 240 ± 0 02$_d$
	Volatile matter (wt %)	72 90 ± 1 19$_{bc}$	52 66 ±1 15$_d$	40 83 ± 0 60$_{bc}$	31 98±0 47$_a$	28 85± 0 20$_a$	26 83 ± 0 31$_{bc}$
	Fixed carbon (wt %)	24 15 ± 0 54$_f$	44 34±0 63$_d$	55 96 ± 0 69$_{hi}$	64 77 ±0 68$_h$	67 95 ±0 78$_i$	69 98 ± 0 88$_g$
T catappa	Moisture (wt %)	10 33 ± 0 12$_d$	10 76 ± 0 07	11 32 ± 0 16$_{fg}$	12 94 ± 0 16	14 19 ± 0 14	14 85 ± 0 20$_e$
	Ash content (wt %)	2 20 ± 0 13$_{ef}$	2 13 ±0 12$_{de}$	2 21 ± 0 08$_{de}$	2 25 ±0 14$_{de}$	2 30 ± 0 17$_{de}$	2 35 ± 0 11$_{de}$
	Density	0 495 ± 0 04$_{ab}$	0 440±0 04$_a$	0 383 ± 0 08$_{ab}$	0 360±0 09$_a$	0 330±0 02$_a$	0 330 ± 0 02$_a$
	Volatile matter (wt %)	71 97 ± 0 65$_{cd}$	51 91±0 42$_{ef}$	35 36 ± 0 39$_e$	29 26±0 30$_{cd}$	26 96±0 24$_{bc}$	25 69 ± 0 21$_{de}$
	Fixed carbon (wt %)	25 83 ± 0 42$_e$	45 96±0 32$_{bc}$	62 43 ± 0 37$_{bc}$	68 49± 0 39	70 74±0 53$_{ef}$	71 96± 0 56$_{efg}$
LSD$_{0.05}$	Moisture (wt %)	0 11	0 14	0 18	0 22	0 23	0 25
	Ash content (wt %)	0 26	0 29	0 22	0 22	0 22	0 22
	Density	0 21	0 08	0 11	0 06	0 04	0 02
	Volatile matter (wt %)	1 22	0 70	1 57	0 85	0 90	1 08
	Fixed carbon (wt %)	1 42	1 68	0 80	1 13	1 88	1 72

Mean value followed by the same letter shown in subscript are not significantly different

Similarly, from Table 9, it is seen that the moisture content of the charcoal samples produced at 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C and with the heating rates of 20^0 C/min varied from 6.53 – 12.30 %, 8.20 – 12.75 %, 8.87 – 14.93 %, 9.61 – 15.08 %, 11.58 – 15.73 % and 12.50 – 16.22 % respectively.

From a comparison of the values of moisture content of the charcoal samples produced within 300^0 – 800^0 C with a heating rate of 3^0 C/min with those of charcoal samples produced with a heating rate of 20^0 C/min within the same range of carbonization temperature, it was observed that the charcoal samples produced at a higher heating rate contained more of moisture. It can be concluded that with the increase of heating rate, the moisture content of the charcoal samples increased. The increase of moisture content of charcoal with increase of carbonization temperature may be attributed to the fact that when the temperature is raised, more and more volatiles would evolve through the pores in wood surface and as a result of this there would be large macroporosites, more open pore structure and large macropore surface area (Demirbas, 2001) and hence more moisture would be accommodated. When the heating rate applied was more intense, the degrees of macroporosites and open pore structure were increased and hence accounted for higher moisture content in the charcoal obtained by carbonization with higher heating rate.

4.2   Ash Content

Ash content is another important property used in evaluating charcoal. The ash content of charcoal varies from about 0.5 % to more than 5 % depending

on the species of wood, the amount of bark included in the wood in the kiln and the amount of earth and sand contamination.

The ash content of the charcoal samples produced from the tree species by carbonizing at $300^0 - 800^0$ C with two different heating rates are presented in Tables 8 & 9.

From Table 4, it can be seen that the ash content of the woods of various tree species under the present study ranged from 1.06 % to 2.65 %. However, on carbonization within $300^0 - 800^0$ C, it was observed that the ash content of all the species increased slightly more than that of wood samples. But no distinct trend in change of ash content of charcoal could be established either for increase of carbonization temperature or for heating rate. Our findings are in good agreement with those of Lim & Malar Vizhi (1993), Lim (1993), Lim *et al.* (1994), Lim & Lim (1992) who observed that ash content of charcoal showed no consistent pattern of dependence on either terminal temperature or holding time.

4.3 Density

Density values of the charcoal samples produced from the tree species by carbonizing at 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C terminal temperatures and with heating rates of 3^0 C/min and 20^0 C/min are presented in Tables 8 & 9.

From Tables 8 & 9, it is seen that with the increase of carbonization temperature, the density decreased at both the heating rates. At 300^0 C, with a heating rate of 3^0 C/min, the density values of the charcoal samples of fifteen tree species varied from 0.382 – 0.600. At 400^0 C, with the same heating rate it varied

from 0.294 – 0.521 while at 500^0, 600^0, 700^0 and 800^0 C the density values varied

from 0.242 – 0.460, 0.210 – 0.370, 0.180 – 0.350 and 0.170 – 0.340 respectively.

Similarly, at 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C, with a heating rate

of 20^0 C/min, the density values of the charcoal samples produced from the tree

species varied from 0.301 – 0.567, 0.281 – 0.507, 0.239 – 0.440, 0.220 – 0.380,

0.180 – 0.360 and 0.180 – 0.350 respectively.

From the results shown in Table 4, it is clear that there seems to have

some co-relation between the lignin content of wood with its density. Higher the

lignin content of the wood, higher is its density.

From Tables 8 & 9, it is further observed that species with higher density

values (Table 4) yielded the charcoal samples of higher density. In the present

investigation, it was found that species like *C. hystrix, D. peregrina, E. varuna,*

E. accuminata, M. bombycina, M. champaca, Q. dealbata, Q. griffithii and *T.*

catappa yielded charcoal in both the heating rates with comparatively higher

density values. Increase of heating rate from 3^0 C/min to 20^0 C/min seems to have

no effect on the density of the charcoal samples.

4.4 Volatile matter (VM) content

The volatile matter other than water in charcoal comprises all those liquid

and tarry residues not fully driven off during the process of carbonization. If the

carbonization is prolonged and at a high temperature then the volatile matter

content is low. Normally the volatile matter in charcoal can vary from as high as

40 per cent and down to 5 per cent or less. To determine it, a weighed sample of

dry charcoal is heated at 900° C to a constant weight. The weight loss is the volatile matter and is usually specified free of moisture content.

The volatile matter, ash content and fixed carbon content of charcoal samples produced from fifteen tree species at temperatures ranging from 300^0 to 800^0 C with a heating rate of 3^0 C/min are presented in Table 8 and with a heating rate of 20^0 C/min are presented in Table 9.

From Table 8, it is seen that volatile matter decreased with the increase of carbonization temperature. Differences of volatile matter content in charcoal samples obtained at various terminal temperatures with a heating rate of 3^0 C/min were found to be significant only among some of the species and not all. The volatile matter content of the charcoal samples produced at 300^0 C terminal temperature ranged from 60.49 % to 71.78 % whereas at 400^0 C, it ranged from 42.33% to 59.25 %. Similarly the volatile matter content of the charcoal samples produced at 500^0, 600^0, 700^0 and 800^0 C ranged from 30.67 % to 40.91 %, 23.75 % to 30.32 %, 20.52 % to 25.82 % and 23.13 % to 24.68 % respectively (Table 7). Charcoal samples produced from *M. champaca* (24.68 %), *S. wallichii* (24.21%), *D. peregrina* (23.16 %) and *D. procerum* (23.13 %) at 800^0 C terminal temperature showed the higher volatile matter content.

When the heating rate of carbonization was increased to 20^0 C/min, charcoal samples produced at 300^0 C and 400^0 C, showed higher volatile matter contents as compared to those of the charcoal samples produced at similar terminal temperatures with a heating rate of 3^0 C/min (Tables 8 & 9). At 300^0 C, the volatile matter content ranged from 63.37 % to 74.68 % whereas at 400^0,

500^0, 600^0, 700^0 and 800^0 C, volatile matter content of the charcoal samples ranged from 44.80 % to 62.20 %, 31.90 % to 43.52 %, 27.32 % to 33.04 %, 21.37 % to 27.65 % and 20.78 % to 29.65 % respectively. Volatile matter content of the charcoal samples produced at 800^0 C, was found to be the highest in *D. peregrina* (26.95 %) while the lowest of it was in *C. siamea* (20.78%).

From the results presented in Tables 8 & 9, it is clear that with the increase of carbonization temperature, the volatile matter content of the charcoal samples decreased at both the heating rates. Our findings are in good agreement with those of Fuwape (1993; 1996a, 1996b) who carbonized some agroforestry tree species and some fast growing multipurpose species of Nigeria. Lim *et al.* (1994), Lim (1993), Sensöz & Can (2002) also reported a similar trend of variation of volatile matter content in charcoal samples produced from some other wood and biomass materials.

Further it was observed that when the rate of heating was increased from 3^0 C/min to 20^0 C/min within the carbonization temperature range of 300^0 to 800^0 C, the range of volatile matter content of the charcoal samples also increased.

4.5   Fixed carbon (FC) content

Fixed carbon content is an important parameter of charcoal. It ranges from a low of about 50 % to a high of around 95 %. Fixed carbon content in charcoal is usually estimated as a "difference" that is to say, all other constituents viz. volatile matter and ash content are deducted from 100 as a percentages and the reminder is assumed to be the percentage of "fixed" carbon or 'pure' carbon.

From metallurgical point of view, fixed carbon content of charcoal is a very important parameter, since it is the fixed carbon, which is responsible for reducing the iron oxides of the iron ore to produce iron.

Fixed carbon content of the charcoal samples produced from the tree species at 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C and with a heating rate of 3^0 C/min are presented in Table 8 and those with the heating rate of 20^0 C/min are presented in Table 9.

From Tables 8 & 9, it can be seen that fixed carbon content of the charcoal increased with the increase of carbonization temperature.

At 300^0 C, with a heating rate of 3^0 C/min, the charcoal of *C. hystrix* (37.86 %), *M. bombycina* (37.62 %), *E. acuminata* (35.61 %) and *Q. dealbata* (34.31 %), showed higher fixed carbon contents as compared to the charcoal samples of other tree species under study. Similarly, at 400^0 C, with the same heating rate, the charcoal of *M. bombycina* (55.80 %), *Q. dealbata* (53.59 %), *E. varuna* (51.53 %), *C. hystrix* (50.07 %) and *T. catappa* (50.31 %) showed higher percentage of fixed carbon content. At 500^0 C, charcoals of *M. bombycina* (67.46%), *Q. dealbata* (66.15%), *T. catappa* (64.70 %), *C. hystrix* (62.92 %), *C.siamea* (62.45 %), *E. varuna* (62.64 %) and *E. acuminata* (62.14 %) had higher fixed carbon content.

At 600^0 C, the charcoal samples of all the tree species except those of *D. peregrina, D. procerum, M. champaca* and *S. wallichii* showed more than 70 % of fixed carbon contents. At 700^0 C terminal temperature, the charcoal samples of all the species showed more than 70 % of fixed carbon content varying from

71.71 % to 77.56 %. Similarly, at 800^0 C, fixed carbon content ranged from 72.90 % to 80.11 %.

When the rate of carbonization temperature was increased to 20^0 C/min, the fixed carbon contents of the charcoal samples produced at various terminal temperatures were found to be low as compared to the fixed carbon contents of the charcoal samples produced in the corresponding terminal temperatures. With this heating rate, the fixed carbon content of the charcoal samples produced from the tree species at 300^0 C varied from 21.82 % to 34.80 %. Similarly, with the same heating rate, the fixed carbon content of the charcoal samples produced at 400^0, 500^0, 600^0, 700^0 and 800^0 C terminal temperatures ranged from 40.73 % to 53.26 %, 53.91 % to 64.87 %, 64.71 % to 71.78 %, 67.95 % to 74.93 % and 69.98 % to 76.18 % respectively.

The trend of the variations in the value of volatile matter and fixed carbon in the charcoal produced at different terminal temperatures is similar to values reported by Hoffman and Fitz (1968), Brocksiepe (1971), Buekens & Schoeters (1987) and Fuwape (1996a). The higher values of fixed carbon in charcoal with an increase in carbonization temperature may be due to the removal of volatile matter in the woods during the carbonization process, leaving the stable carbon.

The increase of fixed carbon content was rather large as terminal temperature increased from 300^0 to about 500^0 C, but after 500^0 C the increase was gradual and rather insignificant. This behaviour is observed for both the heating rates. Our results are (in) consistent with the results reported by Bhattacharya et al. (1989) for other biomass.

Tressero (1991) reported that in a blast furnace charge at a large charcoal iron works, Minas Gerais in Brazil, a charcoal is considered to be good to excellent if its carbon content ranges from 75 - 80 %, volatile matter content ranges from 20 - 25 %, moisture content of maximum 10 % and ash content ranges from 3 - 4 %.

From the data presented in Table 8, it is seen that at 800^0 C with a heating rate of 3^0 C/min, charcoal samples with more than 75 % of fixed carbon were produced by *B. assamica* (75.98 %), *C. hystrix* (80.11 %), *E. varuna* (76.95 %), *E. acuminata* (78.69 %), *M. bombycina* (78.47 %), *M. azedarach* (75.19 %), *Q. dealbata* (78.47 %), *Q. griffithii* (77.78 %) and *T. catappa* (75.51 %) whereas at this temperature with a heating rate of 20^0 C/min, *C. siamea* (75.50 %), *E. acuminata* (75.84 %) and *M. azedarach* (75.48 %) produced charcoal with more than 75 % of fixed carbon content.

Similarly, at 700^0 C with a heating rate of 3^0 C/min, charcoal samples with more than 75 % of fixed carbon content were produced by *B. assamica* (75.02 %), *C. hystrix* (77.56 %), *E. varuna* (75.30 %), *E. acuminata* (77.49 %), *M. bombycina* (76.41 %), *Q. dealbata* (77.32 %) and *Q. griffithii* (75.33 %), whereas at this terminal temperature and with a heating rate of 20^0 C/min, no species has produced charcoal with more than 75 % of fixed carbon content. Hence, a slow heating rate may be more suitable to produce charcoal with higher percentages of fixed carbon content. From the view point of fixed carbon content and volatile matter content, a maximum terminal temperature of 700^0 C is just sufficient to achieve charcoal with desired quality, when the heating rate of about 3^0 C/min is employed. The other charcoal samples with less than 75 % of fixed carbon contents may be used for domestic purposes.

Part 4

Again an excellent chapter
The results and the discussion
are certainly convincing and
also in agreement with reported
literature.

Part 5

A comparison of the yields and properties of charcoal samples produced in earth mound kiln with those of charcoal samples produced in Laboratory-scale reactor

When wood is carbonized in traditional earth mound kiln, part of the wood charged is burnt in order to release the necessary energy for drying and carbonizing the wood mass and thereby the yield of charcoal is always lower than that in a modern carbonization plant. In spite of the lower yield of charcoal in the traditional earth mound kiln, even today, this method is commonly used by charcoal producers in developing countries. Earlier workers (Lusadisu, 1989; Schenkel, 1991; Ramilson, 1990; Eimer & Ndamana, 1987; Briane and Haberman, 1984; Quivy, 1992; Hibajene, 1994 and Okello et al., 2001) have reported the yield and fixed carbon content of charcoal produced in traditional earth mound kiln in some charcoal producing countries (Table 10).

Table 10: Comparison of yield and fixed carbon content of charcoal samples produced in traditional earth mound kilns in different countries

Country	Types of kiln	Mass yield (wt %)	Fixed carbon (wt %)	Reference
Zaire	Traditional earth mound kiln	30.3 – 34.3	-	Lusadisu, 1989
	-do-	21.2 – 29.8	-	-do-
	-do-	21.1 – 25.6	70.9 – 85.1	Schenkel, 1991
Burundi	-do-	12	-	Ramilson, 1990
	-do-	15.6 – 18.0	-	Eimer & Ndamana, 1987
France	-do-	30.6 – 32.4	72.6 – 78.2	Briane & Haberman, 1984
Cuba	-do-	22.5 – 28.8	82.1 – 89.1	Quivy, 1992
Zambia	-do-	21.5 – 27.0	65.2 – 71.6	Hibajene, 1994
Kenya	-do-	10.2 – 18.2	-	Okello et al. (2001)
N.E. India	-do-	21.5 – 23.9	62.1 – 65.3	Present study

As a mat/er of interest, we collected the charcoal samples produced in field conditions by different charcoal producers in Mairang and Umsning Blocks of the State of Meghalaya by using traditional earth mound kiln and their yield, density, moisture content, ash content, volatile matter content and fixed carbon content were determined and presented them site wise in Table 11.

From the results shown in Table 11, it is seen that yield of charcoal varied from 21.54 – 23.86 %, density varied from 0.447 – 0.506, moisture content varied from 8.81 – 9.42 %, ash content varied from 6.44 – 7.21%, volatile matter content varied from 27.98 – 31.35 % and fixed carbon content varied from 63.15 – 65.29 %. The higher values of ash content may be due to the contamination of the charcoal with earth and sand particles, which may come from the earth layers used for shielding the wood mass against air. From the value of density, fixed carbon content and volatile matter content of the charcoal samples, it can be concluded that the carbonization temperature in the earth mound kiln may be maximum of 600^0 C only.

With a view to compare the yield and properties of the charcoal samples produced in earth mound kiln with those produced in the laboratory-scale reactor, we conducted field level carbonization experiments with two species included among the fifteen tree species selected for the detailed study. Out of these two species *C. hystrix* was found to be of superior quality and *S. wallichii* was found to be of inferior quality as determined from the laboratory-scale carbonization experiments.

Table 11: Yield and properties of charcoal produced in earth mound kilns in field condition in the state of Meghalaya

Location	Yield (wt %)	Moisture content (wt %)	Density (g/cc)	Fixed carbon (wt %)	Ash content (wt %)	Volatile matter (wt %)
Mairang	23.86	9.03	0.473	63.81	6.12	30.07
Mairang	23.84	8.94	0.486	65.29	5.79	28.92
Mairang	23.39	9.21	0.479	65.02	7.00	27.98
Mairang	22.55	9.17	0.493	64.58	6.54	28.88
Mairang	22.10	9.00	0.506	64.31	6.86	28.83
Umsning	21.69	8.81	0.500	64.79	6.44	28.77
Umsning	22.88	9.42	0.517	63.15	6.97	29.88
Umsning	23.15	9.30	0.488	62.19	6.46	31.35
Umsning	21.54	9.36	0.447	62.08	7.08	30.84
Umsning	21.66	9.11	0.475	63.54	7.21	29.25
Average	22.67	9.14	0.486	63.88	6.65	29.48

The carbonization was carried out in the earth mound kiln of common size. The size of the kiln was of 3 meter in length, 1 meter in breath and 2 meter in height. The earth layer applied to shield the wood mass against air was of approximately 8 – 12 cm thick. Air-dried wood of each of the species were used separately for carbonization. The total time required for carbonization of a batch of wood mass of each of the species ranged from 10 – 12 days. Time to time, the temperature inside the kiln was measured with the help of a thermocouple and it was found that the inside temperature ranged from 400^0 to about 600^0 C.

Since, the maximum temperature inside the earth mound kiln was found to be about 600^0 C, we thought it to be logical to compare the yield and properties of the charcoal samples produced in the field level carbonization experiments with those of the charcoal samples produced in the laboratory-scale reactor at the terminal temperature of $400^0 – 600^0$ C.

The yield and properties of the charcoal samples produced in the traditional earth mound kiln from *C. hystrix* and *S. wallichii* are compared with those of the charcoal samples produced in the laboratory-scale reactor within the temperature range of $400^0 – 600^0$ C and with heating rates of 3^0 C/min and 20^0 C/min. The results are presented in Table 12. From Table 12, it can be seen that the wood of *C. hystrix*, when carbonized in traditional earth mound kiln, the yield of charcoal was 25 % whereas the same wood when carbonized in laboratory-scale reactor with a heating rate of 3^0 C/min, the yields of charcoal obtained at terminal temperatures of 400^0, 500^0 and 600^0 C were 46.5 %, 44 % and 40.3 % respectively.

Similarly, the wood of *S. wallichii* when carbonized in traditional earth mound kiln, the yield of charcoal was 19.8 %, whereas the same wood when carbonized in the laboratory-scale reactor with a heating rate of 3^0 C/min, the yields of charcoal obtained at 400^0, 500^0 and 600^0 C were 27.5 %, 25 % and 23 % respectively.

However, when the heating rate was increased to 20^0 C/min, wood of both the species yielded comparatively lower percentages of charcoal in all the three terminal temperatures:

The moisture content values of the charcoal samples produced from both the species by using earth mound kiln were quite comparable with those of charcoal samples produced in the laboratory-scale reactor at 400^0, 500^0 and 600^0 C and with a heating rate of 3^0 C/min. However, higher moisture content values were obtained when the rate of heating was increased to 20^0 C/min (Table 12).

Density values of charcoal samples produced from the wood of *C. hystrix* were found to be higher than those of charcoal samples produced from the wood of *S. wallichii*. This may be due to the fact that the density of *C. hystrix* (0.870 ± 0.07) was higher than that of *S. wallichii* (0.536 ± 0.05).

The ash content of the charcoal produced from both *C. hystrix* and *S. wallichii* in the traditional earth mound kiln were quite high as compared to those of charcoal produced in the laboratory-scale reactor (Table 12). The higher ash content of the charcoal samples produced in the earth mound kiln may be due to their contamination with earth and sand particles.

The fixed carbon content of the charcoal produced from the wood of *C hystrix* in the earth mound kiln was found to be 67.28 % whereas that of the charcoal samples produced from the same species in the laboratory-scale reactor at 400^0, 500^0 and 600^0 C and with a heating rate of 3^0 C/min were 50.07 %, 62.92 %, and 73.06 % respectively.

Similarly, the fixed carbon content of the charcoal produced from the wood of *S. wallichii* in earth mound kiln was 57.38 % whereas that of the charcoal samples produced from it in the laboratory-scale reactor at 400^0, 500^0 and 600^0 C and with a heating rate of 3^0 C/min were 46.62 %, 54.93 % and 67.48 % respectively.

When the heating rate was increased to 20^0 C/min, the fixed carbon content of the charcoal samples decreased.

Volatile matter content of the charcoal produced from *C. hystrix* in earth mound kiln was 29.62 % whereas those of charcoal samples produced from it in the laboratory-scale reactor at 400^0, 500^0 and 600^0 C with a heating rate of 3^0 C/min were 48.27 %, 35.27 % and 25.14 % respectively. Similarly the volatile matter content of charcoal produced from *S. wallichii* in earth mound was was 30.06 % while those of charcoal samples produced from it in the laboratory-scale reactor at 400^0, 500^0 and 600^0 C and with a heating rate of 3^0 C/min were 50.41%, 42.06 % and 29.50 % respectively.

Table 12: A comparison of yields and properties of charcoal produced from *C. hystrix* and *S. wallichii* in earth mound kilns with those of their charcoal samples produced in the laboratory-scale reactor

Species	Types of experiment	Yield (wt %)	Moisture content (wt %)	Density (g/cc)	Ash content (wt %)	Fixed carbon (wt %)	Volatile matter (wt %)
C. hystrix	Traditional earth mound kiln	25	8.25	0.514	4.66	67.28	28.06
S. wallichii	Traditional earth mound kiln	19.8	9.4	0.310	5.36	57.38	37.26
C. hystrix (400°C, 3°C/min)	Laboratory-scale	46.50	6.21	0.521	1.66	50.07	48.27
C. hystrix (500°C, 3°C/min)	Laboratory-scale	44	6.94	0.460	1.81	62.92	35.27
C. hystrix (600°C, 3°C/min)	Laboratory-scale	40.3	7.77	0.370	1.80	73.06	25.14
S. wallichii (400°C, 3°C/min)	Laboratory-scale	27.5	9.47	0.369	2.97	46.62	50.41
S. wallichii (500°C, 3°C/min)	Laboratory-scale	25	10.02	0.301	3.01	54.93	42.06
S. wallichii (600°C, 3°C/min)	Laboratory-scale	23.2	10.30	0.250	3.02	67.48	29.50
C. hystrix (400°C, 20°C/min)	Laboratory-scale	37.9	8.36	0.507	1.70	47.10	51.20
C. hystrix (500°C, 20°C/min)	Laboratory-scale	34.8	11.25	0.440	1.73	60.34	37.93
C. hystrix (600°C, 20°C/min)	Laboratory-scale	28.4	11.89	0.349	1.80	68.32	29.98
S. wallichii (400°C, 20°C/min)	Laboratory-scale	24.3	10.55	0.317	3.00	44.34	52.66
S. wallichii (500°C, 20°C/min)	Laboratory-scale	23.1	10.98	0.301	3.20	55.96	40.83
S. wallichii (600°C, 20°C/min)	Laboratory-scale	21.5	11.95	0.270	3.25	64.77	31.98

Part 5

Interesting and logic results,
well explained

Chapter V

SUMMARY AND CONCLUSION

Chapter V

Summary and Conclusion

Charcoal is one of the major biofuels of north-east India, particularly of

the state of Meghalaya. In this state charcoal production is mainly concentrated

in Ri-Bhoi and West Khasi Hills districts. Every year, in the entire state more

than one lakh quintals of charcoal are produced by carbonizing wood in

traditional earth-mound kilns. In the traditional earth-mound kiln carbonization

process attention is given only on charcoal yield and there is no provision for

trapping the other valuable by-products like gas, tar and condensed liquid which

are recently drawing attention of researchers as fuel or source of chemical

feedstock (Demirbas, 1998; Yorgun *et al.*, 2001; Gercel, 2002 a,b; Sevgi, 2003).

In the recent years, with the ever-increasing population pressure and

shifting cultivation, the forest areas in Meghalaya have reduced to a great extent.

At present about 44.2 % of the total geographical area of the state is under

wasteland. Moreover, the reduction in forest cover has left the charcoal producers

of the state with little choice about the selection of tree species for charcoal

production. As a result of this charcoal producers use all types of trees whichever available in the nearby forests and this has in turn affected both the quantity and quality of charcoal. In addition to this, economically important tree species are also used for charcoal production. Therefore, extensive farming of selected promising tree species for charcoal production in the wastelands is highly necessary. However, while selecting tree species for farming in wastelands, emphasis should be given on indigenous tree species (Rabindranath *et al.*, 1991).

With a view to select some promising indigenous tree species of north-east India, particularly of the state of Meghalaya and also to ascertain the actual yields of charcoal, gas, tar and condensed liquid produced during the carbonization of some of the tree species selected on the basis of local charcoal producers' preference, the present study was undertaken. The important findings of the study are summarized below:

From a survey made by visiting different charcoal producing localities in the state of Meghalaya, 41 indigenous tree species were identified which are commonly used for charcoal production by the local charcoal producers using earth-mound kiln (Table 2). Based on the preferences given on these trees by the local charcoal producers and also on their availability in the charcoal producing areas 15 tree species (Table 3) were selected for detailed study. The species were: *Albizzia lucida* Benth., *Beilschmiedia assamica* Meisn., *Cassia siamea* Lamk. *Castanopsis hystrix* DC., *Diospyros peregrina* (Gaertn.) Gurke., *Dysoxylum procerum* Hiern., *Elaeocarpus varuna* Ham., *Eurya acuminata* DC., *Machilus bombycina* King., *Melia azedarach* L., *Michelia champaca* L., *Quercus dealbata*

Hook. f. & Th., *Quercus griffithii* Hook. f. & Thomson ex. Miq., *Schima wallichii* Choisy. and *Terminalia catappa* L.

From the determination of various physico-chemical properties, biochemical composition, and elemental analysis of the wood of the selected tree species, following observations were made.

Moisture content in the species was found to vary from 39.73 % ± 0.73 to 59.79 % ± 0.66. Among all the species *M. azedarach, C. siamea* and *A. lucida* were found to have higher percentages of moisture content while, *C. hystrix, Q. griffithii* and *Q. dealbata* were found to have quite lower percentages of it.

Ash content among the species under study varied from 1.06 % ± 0.07 to 2.65 % ± 0.06.

Density of the species varied from the highest of 0.879 ± 0.085 (*E. acuminata*) to the lowest of 0.477 ± 0.09 (*M. azedarach*). The variations in the density of wood of different tree species may be attributed to their anatomical differences.

Among all the tree species, the highest hemicellulose content was found in *B. assamica* (30.82% ± 0.21) and the lowest was found in *C. hystrix* (24.89% ± 0.19). Similarly, the wood of *M. azedarach* contained the highest percentage of cellulose (46.93% ± 0.34) while the wood of *T. catappa* contained the lowest of it (41.67% ± 0.31). The lignin content of wood of the tree species varied from 20.65% ± 0.30 (*M. azedarach*) to 26.45% ± 0.13 (*M. bombycina*).

Highest extractive content was found in *T. catappa* (6.74% ± 0.74) while the lowest was observed in *C. hystrix* (2.67% ± 0.06). The carbon content of

wood of the 15 tree species varied from 42.68 % (*S. wallichii*) to 46.98 % (*M. bombycina*) whereas hydrogen content varied from 4.93 % (*M. azedarach*) to 6.02 % (*D. procerum*). Similarly, oxygen content of the species varied from 45.32 % (*C. hystrix*) to 49.24 % (*M. azedarach*) and nitrogen content ranged from 0.2 % to 0.4 % only.

Calorific values of wood of *M. bombycina* (21.33% ± 0.78), *E. acuminata* (21.07% ± 0.63), *C. hystrix* (20.71% ± 0.84), *Q. griffithii* (20.66% ± 0.54), *Q. dealbata* (20.37% ± 0.48) and *E. varuna* (20.11% ± 0.45) were found to be higher than those of the wood of other species.

FVI values of *C. hystrix* (17), *E. acuminata* (16.54) and *M. bombycina* (16.28) were much higher than those of the other tree species. *M. azedarach* (3.08) showed the lowest FVI.

Mass balance of carbonization decomposition products of the tree species were determined at various terminal temperatures viz. 300^0, 400^0, 500^0, 600^0, 700^0 and 800^0 C with two heating rates. From the results of mass balance of decomposition products, following observations were made.

Gas Production

With the increase of carbonization temperature, the gas yields from all the species were found to increase in both the heating rates. At a heating rate of 3^0 C/min, within 300^0-400^0 C, the gas production from all the species was slow whereas from 400^0-500^0 C, gas yields increased sharply. Again from 500^0-600^0 C, the rate of gas yields decreased slightly. From 600^0-800^0 C, the rate of gas yields decreased significantly.

When the heating rate was increased from 3^0 C/min to 20^0 C/min, the amounts of gas as well as rates of gas production changed markedly.

The increase of gas production with the increase of heating rate was found to be more in the carbonization temperature up to 500^0C as compared to those in the higher temperature range. However, the total amounts of gas produced at 800^0C with two different heating rates were quite comparable. The increase of gas production at higher heating rate may be related to the fact that higher heating rate lead to a fast depolymerization of the solid materials to primary volatiles.

Char Production

The char yields from all the species were found to decrease with the increase of carbonization temperatures at both the heating rates. Within 300^0 – 400^0 C, the char yields decreased sharply and then decreased gradually up to 800^0C terminal temperature.

The heating rate showed marked effect on char yield. Within the carbonization temperature range 300^0-800^0 C, the char yields obtained with a heating rate of 20^0 C/min were found to be lower than those achieved with the heating rate of 3^0 C/min.

At a heating rate of 3^0 C/min, *C. hystrix* yielded the highest percentage of char at all temperatures. Other species producing higher percentages of char at 800^0 C were *M. bombycina, E, acuminata, Q. dealbata, E. varuna* and *Q. griffithii.*

From the results of the biochemical compositions of the woods of all the species and their mass balance experiment results, it was found that species with higher percentages of lignin contents yielded comparatively higher percentages of char.

Tar Production

Tar yields from all the species increased with the increase of carbonization temperature and reached a maximum at about 400^0 C or 500^0 C and then decreased sharply. With a heating rate of 3^0 C/min, almost all the species excect *E. varuna, C. hystrix, Q. griffithii* and *T. catappa* showed their tar production maximum at 400^0 C.

Condensed liquid production

The yields of condensed liquid from all the species increased with the increase of carbonization temperature and after reaching a maximum at about 400^0 C, the yields started decreasing.

It was further observed that the tree species with higher percentages of holocellulose content yielded higher percentages of condensed liquid.

The quality of charcoal

The charcoal samples produced by carbonizing the woods of 15 sleected tree species in the laboratory-scale reactor at various terminal temperatures viz. 300^0 C, 400^0 C, 500^0 C, 600^0 C, 700^0 C and 800^0 C with two heating rates were characterized for their moisture content, density, ash content, volatile matter content and fixed carbon content by the standard methods.

It was observed that with the increase of carbonization temperature, the moisture content of the charcoal increased at both heating rates (3^0 C/min and 20^0 C/min). However, within the same range of carbonization temperature, when the heating rate was increased, the moisture content also increased.

Ash content of the charcoal samples ranged from 1.06% to 2.65%. However, it was observed that the ash content of all the charcoal samples increased slightly. *when* - - -

The density of charcoal decreased with the increase of carbonization temperature at both the heating rates. It was further observed that species with higher density values yielded charcoal samples of higher density. In the present investigation, it was found that species like *C. hystrix, D. peregrina, E. varuna, E. accuminata, M. bombycina, M. champaca, Q. dealbata, Q. griffithii* and *T. catappa* yielded charcoal in both the heating rates with comparatively higher density values. Increase of heating rate from 3^0 C/min to 20^0 C/min seems to have no effect on the density of the charcoal samples.

The volatile matter content of charcoal samples from all the species decreased with the increase of carbonization temperature at both the heating rates. When the heating rate of carbonization was increased to 20^0 C/min, charcoal samples produced at 300^0 C and 400^0 C, showed higher volatile matter contents as compared to those of the charcoal samples produced at similar terminal temperatures with a heating rate of 3^0 C/min. Further it was observed that when the rate of heating was increased from 3^0 C/min to 20^0 C/min within

the carbonization temperature range of 300^0 to 800^0 C, the range of volatile matter content of the charcoal samples also increased.

Fixed carbon content of charcoal samples increased with the increase of carbonization temperature. At 600^0 C, the charcoal samples of all the tree species except those of *D. peregrina, D. procerum, M. champaca* and *S. wallichii* showed more than 70 % of fixed carbon contents. At 700^0 C terminal temperature, the charcoal samples of all the species showed more than 70 % of fixed carbon content varying from 71.71 % to 77.56 %. Similarly, at 800^0 C, fixed carbon content ranged from 72.90 % to 80.11 %.

The increase of fixed carbon content was rather large as terminal temperature increased from 300^0 to about 500^0 C, but after 500^0 C the increase was gradual and rather insignificant. At 800^0 C with a heating rate of 3^0 C/min, charcoal samples with more than 75 % of fixed carbon were produced by *B. assamica* (75.98 %), *C. hystrix* (80.11 %), *E. varuna* (76.95 %), *E. acuminata* (78.69 %), *M. bombycina* (78.47 %), *M. azedarach* (75.19 %), *Q. dealbata* (78.47 %), *Q. griffithii* (77.78 %) and *T. catappa* (75.51 %) whereas at this temperature with a heating rate of 20^0 C/min, *C. siamea* (75.50 %), *E. acuminata* (75.84 %) and *M. azedarach* (75.48 %) produced charcoal with more than 75 % of fixed carbon content.

Similarly, at 700^0 C with a heating rate of 3^0 C/min, charcoal samples with more than 75 % of fixed carbon content were produced by *B. assamica* (75.02 %), *C. hystrix* (77.56 %), *E. varuna* (75.30 %), *E. acuminata* (77.49 %), *M. bombycina* (76.41 %), *Q. dealbata* (77.32 %) and *Q. griffithii* (75.33 %), whereas at this terminal temperature and with a heating rate of 20^0 C/min, no species has produced charcoal

with more than 75 % of fixed carbon content. Hence, a slow heating rate may be more suitable to produce charcoal with higher percentages of fixed carbon content. From the view point of fixed carbon content and volatile matter content, a maximum terminal temperature of 700^0 C is just sufficient to achieve charcoal with desired quality, when the heating rate of about 3^0 C/min is employed. The other charcoal samples with less than 75 % of fixed carbon contents may be used for domestic purposes.

Woods of *C. hystrix* and *S. wallichii* when carbonized in traditional earth mound kiln, the yield of charcoal was 25 % and 19.8 % respectively, whereas the same woods when carbonized in laboratory-scale reactor, the yield were found to be much higher.

Ash contents of the charcoal produced from both *C. hystrix* and *S. wallichii* in the traditional earth mound kiln were quite high as compared to those of charcoal samples produced in the laboratory-scale reactor.

The fixed carbon contents of the charcoal samples produced from *C. hystrix* and *S. wallichii* in the earth mound kilns were found to be 67.28 % and 57.38 % respectively which corresponds to those of charcoal samples produced from these two species in the laboratory-scale reactor within the temperature range of 500^0 to 600^0 C. With the increase of heating rate, the fixed carbon content of the charcoal samples were found to decrease.

From the present study, it can be concluded that among all the 15 traditionally preferred indigenous tree species of north-east India, *C. hystrix, E. varuna, M. bombycina, E. acuminata, Q. dealbata, Q. griffithii* and *B. assamica* are the most promising tree species for charcoal production. Fuel value indexes

of these tree species indicate their suitability as fuelwood. Hence, these trees may be considered for inclusion in large-scale energy plantation or farm forestry plantation in the wastelands of the region. However, before recommending these species for plantation, their growth rate, biomass productivity, nutrient uptake behaviour and optimum period of harvesting should be investigated.

Since, the yield and quality of charcoal produced in the presently used traditional earth mound kiln is poor, a shift from traditional method to modern method of carbonization is needed. Such a modern method will not only produce charcoal with better yield and quality, but will also reduce environmental pollution. Moreover, provisions should be made to trap the by-products of carbonization such as gas, tar and condensed liquid for utilization as fuel or feedstock for chemicals.

Yes, that is certainly the conclusions one can draw from the results of the investigation

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ANNEXURE – I

Location of the study sites (Rounded portions indicate the location of sites)