CHARACTERIZATION OF PROPERTIES AND ESTIMATION OF POWER GENERATION POTENTIALS OF RESIDUES OF SOME WOODY BIOMASS SPECIES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

Master of Technology(Research)

in

Mechanical Engineering

by

ALI PADARBINDA SAMAL
Roll No: 612ME305

Dept. of Mechanical Engineering

National Institute of Technology, Rourkela

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Prof. S.K. Patel and Prof. M. Kumar

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Dedicated

To

My Parents

Declaration

I hereby declare that the work which is being presented in this thesis entitled "**Characterization of Properties and Estimation of Power Generation Potentials of Residues of Some Woody Biomass Species"** in partial fulfilment of the requirements for the award of M.Tech. (Research) degree, submitted to the Department of Mechanical Engineering, National Institute of Technology, Rourkela, is an authentic record of my own work under the supervision of Prof. S.K. Patel and Prof. M. Kumar. I have not submitted the matter embodied in this thesis for the award of any other degree to any other university or Institute.

Date: 28-06-2015 **ALI PADARBINDA SAMAL**

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**CHARACTERIZATION OF PROPERTIES AND ESTIMATION OF POWER GENERATION POTENTIALS OF RESIDUES OF SOME WOODY BIOMASS SPECIES**" submitted by Mr. **ALI PADARBINDA SAMAL,** Roll no. 612ME305 in partial fulfilment of the requirements for the award of Master of Technology (Research) Degree in Mechanical Engineering with specialization in Thermal Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree.

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Date: 28.06.15 **Ali Padarbinda Samal**

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ABSTRACT

In view of continuous increase in energy demand, and the environmental and economic concerns associated with the use of conventional fuels have made scientists and technocrats to look for alternative renewable energy sources for power production. The inherent advantages of carbon neutrality, lower ash content, lower SO_x and NO_x emissions, and wide availability have made biomass as a prime source of power generation. In this article, three different components taken from residues of five different woody plant species have been considered which have no commercial use. These plant species are *Ficus benghalensis* (local name- Banyan), *Azadirachta indica* (local name- Neem), *Ficus religiosa* (local name- Pippal), *Madhuca longifolia* (local name- Mahua) and *Eucalyptus globulus* (local name- Eucalyptus). Proximate analyses and gross calorific values (GCV) of all the biomass species including a coal sample have been determined. Among all the five biomass species studied, the fixed carbon content (FC) in Neem bark was observed to be the highest while its leaf has the lowest value, the volatile matter content (VM) in both Mahua branch and Eucalyptus leaf is the highest while Pippal bark has the lowest and the ash content (A) in bark of Mahua is the highest while the leaf of Eucalyptus biomass species has the lowest ash content. Similarly, the leaf of Eucalyptus is the most suitable one with the highest calorific value followed by leaves of Pippal and Mahua. Next in the order, the barks of Banyan and Neem, and the branches of Pippal, Mahua and Eucalyptus were also found to have considerably high amount of energy contents suitable for power generation. In addition, bulk densities of all the biomass species including the coal sample have been determined. Leaves of all the biomass species have been found to have lower bulk densities as compared to their barks and branches. It is worthy to note that among all the studied biomass species, branch of Eucalyptus has the highest bulk density while leaf of Neem has the lowest. Further, the ash fusion temperatures of some selected components of Banyan, Neem, Pippal and Mahua biomass have been measured as these temperatures are the influential factors for the determination of bed agglomeration and other boiler fouling related problems. The results showed comparatively higher values of softening temperature ST (1077-1329 ^{0}C) and hemispherical temperature HT (1193-1450 ^{0}C) indicating safe boiler operation. Leaf and branch of Pippal and leaf and bark of Mahua were separately mixed with coal sample in different ratios, and their various percentage compositions related to proximate analyses and energy values were determined to explore the best coal-biomass mixture for power generation. It is evident from the results that the ash content decreased and volatile matter increased when the biomass percentage increased in the coal-biomass blend. The ultimate analysis has also been carried out on selected biomass species of Banyan, Mahua and Pippal. Carbon and Hydrogen contents of both Pippal and Mahua leaf were found to be higher and their corresponding calorific values were also high. The variation in energy values of plant components is undoubtedly related to the combined effects of their C and H contents. As the calorific value is the most salient property of any fuel, including biomass fuel, an attempt has been made to derive numerous regression equations using proximate and ultimate analysis data for prediction of gross calorific values of studied biomass species. The equations have been obtained statistically using regression analysis. The two linear regression equations with the best results obtained on the basis of proximate and ultimate analyses are $GCV = -49.02 + 0.968\times FC + 0.719\times VM + 0.459\times A$ and $GCV = 9.8 + 0.0613\times O - 1.44\times N - 0.829\times C + 8.18\times H$ respectively. The two nonlinear regression equations with best results obtained are $GCV = 237.85 - 8.278\times M - 5.723\times VM - 3.098\times FC - 0.055\times M^2 + 0.129M\times VM + 0.089\times M\times FC + 0.0319\times VM^2 + 0.061\times VM\times FC - 0.021\times FC^2$ and $GCV = 70.408 + 0.153\times O - 3.115\times C + 1.035\times H - 0.041\times O^2 + 0.101\times O\times C - 0.069\times O\times H - 0.0317\times C^2 + 1.217\times H^2$ respectively. The results regarding computation of land requirement show that around 84, 618, 254, 148 and 289 hectares of land area are needed for energy plantation considering

Banyan, Neem, Pippal, Mahua and Eucalyptus biomass species respectively. The above calculation serves the purpose of electricity generation of 7300 MWh per year for a cluster of 10-15 villages on decentralized power generation mode. Further, the requirements of blends of coal-Pippal branch and coal-Mahua bark to generate 7300 MWh/year of electricity was calculated and it was observed that the requirement of coal decreases with increase in the percentage of biomass in these blends. In case of coal-Pippal branch blend, the requirement of coal decreased from 5798 t/year to 5038 t/year and in coal-Mahua bark blend, coal requirement reduced from 5798 t/year to 5076 t/year as both biomass contents increased from 0 to 15%.

Key words: ash fusion temperature, bulk density, calorific value, decentralized power generation, proximate analysis, regression analysis, ultimate analysis, woody biomass.

NOMENCLATURE

A - Ash content

AAE - Average absolute error

ABE - Average bias error

AFT - Ash fusion temperature

C - Carbon content

FC - Fixed carbon content

FT - Fluid temperature

GCV - Gross calorific value

H - Hydrogen content

HHV - Higher heating value

HT - Hemispherical temperature

IDT - Initial deformation temperature

LHV - Lower heating value

M - Moisture content

N - Nitrogen content

NCV - Net calorific value

O - Oxygen content

R - Coefficient of correlation or R-value

R^2 - Coefficient of determination or R-squared value

S - Standard error of estimate

ST - Softening temperature

ΔT – Maximum rise in temperature in ^0C

VM - Volatile matter content

w - Initial weight of the sample in g

W.E. - Water equivalent

wt.% - Weight percentage

μ - Mean value

σ - Standard deviation

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 Overview

The steady rise in energy demand with increasing economic and environmental concerns regarding emissions from conventional power plants have made renewable energy as the most attractive option for power generation. The depleting trend of fossil fuel has compelled the scientists to diversify the fuel mix and find a promising energy source that can substitute the conventional fuel. Unstable situation of traditional fossil fuel, climbing costs of gas and oil, and probable deficiencies in future may tend to apprehension regarding the security of energy supply required for sustainable economic development. Conventional fuels are limited and are non-renewable. Due to these reasons, it is now imminent to explore non-traditional source of energy which must be environment friendly and renewable. Biomass, with its advantages of carbon neutrality, low greenhouse gas (GHG) emission and wide availability has effectively made it to the most sustainable energy source on earth.

Sustainable development is paramount in a developing nation like India. Energy requirement in economic development is inevitable with the Indian economy relying solely on agriculture and industry which greatly rely upon energy. India is the ninth largest economy on the planet, whose gross domestic product (GDP) rise has been 8.7% and 7.5% in the last 5 years and 10 years respectively. In 2010 alone, the true GDP development of India was the fifth largest on the planet. This high level of economic development is setting immense demand on India’s energy availabilities. During 2011-12, India emerged as the fourth largest user of natural gas and crude oil in the world, after the United States of America, China, and Russia. India’s energy requirement has expanded tremendously albeit declining global economy. In India, more than 65% of the electricity is produced from coal fired power plants [**1**]**.** With the limited availability of coal and other conventional fuels and possible deficiency in future has raised questions regarding the security of energy supply required for sustainable development in India.

With the advantages of wide availability of bio-energy, readily available human resources, lower investment, energy development by planting rapidly-growing biomass species has become an essential and attractive way of power generation in India. Sustainable production and application of biomass in generating energy can unravel basic problems associated with climatic contamination, energy emergency, power transmission losses and waste land development. The total area covered by forest in India is about 697,898 km^2 which comprises 21.23% of the geographical area of the country. Around 3 crore hectares of waste land is available for forestation in India which is quite substantial **[2].** Thus, biomass seems, by all accounts, to be a standout amongst the most promising source of renewable energy in India.

Although biomass projects have been demonstrated to be a success, yet its research prospective are still in its nascent stage. Properties of biomass fuels vary from species to species and largely influence the design and efficiency of power plants. In order to have a full realization of the benefits of biomass energy prospective in energy production, it is crucial to have a principal understanding of its different properties like chemical compositions (including both proximate and ultimate analysis), energy values, bulk densities, ash fusion temperatures, combustion reactivity, etc. The present thesis outlines the findings of studies on proximate analysis, ultimate analysis, calorific values, bulk densities, ash fusion temperatures, and also the regression analyses regarding calculation of heating values from proximate and ultimate analyses data of different residual components of ***Ficus benghalensis*** (local name- Banyan), ***Azadirachta indica*** (local name- Neem), ***Ficus religiosa*** (local name- Pippal), ***Madhuca longifolia*** (local name- Mahua) and ***Eucalyptus globulus*** **(**local name-

Eucalyptus) biomass species (all woody) and their impact on power generation has been discussed.

1.2 Different Sources of Renewable Energy

The ever increasing energy demand with consequential increase in consumption of fossil fuels has led the scientists to explore other suitable substitute for power generation. Renewable energy sources with the advantage of being continuously replenished by natural processes have given the scientists some ray of hope. The various alternative energy sources are given below:

i. Solar energy
ii. Wind energy
iii. Ocean energy
iv. Geothermal energy
v. Nuclear energy
vi. Biomass energy

1.2.1 Solar Energy

Harnessing the heat and light of radiant energy produced by the sun using a variety of sophisticated technologies just as solar photovoltaic, solar heating and solar thermal electricity generator is called as solar energy. Solar energy provides a climate-friendly, clean, exceptionally abundant power supply to humankind, reasonably well-spread over the globe. Solar energy availability is more in the countries nearer to the equator, those countries with most of the world’s population and will encounter massive economic growth over the next few years. They will probably hold about 7 billion populations by 2050 against 2 billion in cold and temperate countries (including most of Europe, Russia, the United States of America and parts of China). The expenses of solar energy have been falling quickly and are more competitive now. Solar photovoltaic (PV) electricity and solar thermal electricity are more competitive against conventional power production in developing countries, typically to satisfy demand peaks. Roof-top PV in developing sunny countries can compete with high retail power costs **[3].**

While the capability of creating powers from sunlight is enormous, there are noteworthy difficulties which need to be overcome in making a move from current research facility models to possible business frameworks.

1.2.2 Wind Energy

Wind energy is the transformation of wind force into a helpful manifestation of energy, by the use of turbines to produce electrical power, wind pumps for pumping of water and windmills for harnessing mechanical power. Wind energy is a free and abundantly available renewable asset. In addition, it is a great source of non-polluting and clean source of energy. Wind plants don’t emit any form of air pollutant or greenhouse gases like conventional power plants. India is among the top five producers of wind energy in the world. Around 68% of the aggregate renewable energy created in India is from wind energy. Regardless of the fact that the cost associated with wind power has diminished drastically in the last 10 years, the initial technology for installment needs a larger initial investment as compared to traditional power plants. Approximately 80% of the expense is associated with the mechanical parts including the installation and site selection **[3].** With its limited year round availability and a good site for installation are some drawbacks.

1.2.3 Ocean Energy

Energy produced from the ocean is divided into two types such as, mechanical energy derived from the waves and tides, and thermal energy derived from the heat of the sun. More than 70% of the earth's surface is covered by seas and oceans, which in turn is the largest solar collector. The heat from the sun warms the surface water of ocean a lot more as compared to the deep ocean water, and this difference in temperature generates thermal energy. Ocean mechanical energy is unique in relation to ocean thermal energy. Despite the fact that the sun influences all ocean activity, tides are driven fundamentally by the gravitational force of the moon, and waves are driven basically by the winds. Thus, waves and tides are discontinuous sources of energy; on the other hand ocean thermal energy is reasonably steady. Likewise, dissimilar to thermal energy, the production of electricity from both tidal and wave energy normally includes mechanical equipments. Ocean thermal energy is used for many applications, including generation of electricity. There are three types of electricity conversion systems: open-cycle, closed-cycle, and hybrid. Closed-cycle systems use the ocean's warm surface water to vaporize a working fluid, which has a low-boiling point, such as ammonia. The vapor expands and rotates a turbine which in turn generates electricity. Open-cycle systems heat the ocean water by working at low pressures. This produces steam that passes through a turbine/generator to produce electricity. Hybrid systems consolidate both closed-cycle and open-cycle systems.

In western coast of India, the Gulf of Cambay and the Gulf of Kutch are the two most attractive locations where the greatest tidal heights are 10-12 m and 7-9 m with regular tidal ranges of 6.5 m and 5.3 m respectively. Additionally, the Ganges Delta in the east coast of India is an important place for small scale tidal power development. The greatest tidal range in Sunderbans is around 4-6 m with an average tidal range of 2.87 m. The potential of tidal power in India stands in the range between 8000-9000 MW with Gulf of Cambay providing 7000 MW, Gulf of Kutch about 1200 MW and Sundarbans less than 100 MW [**4**].

1.2.4 Geothermal Energy

Geothermal energy is the internal heat or thermal energy generated in the earth crust. This internal energy warms the ground water between 2500 meters down and this hot water, otherwise called as "geothermal deposits" are used to produce electricity. This energy originates from radioactive decay which accounts 80% and from the formation of planet whose share is 20% **[5].** Geothermal gradient is the difference between the temperature of the planet core and its surface. It is cost effective, reliable and sustainable but remains limited to the tectonic plate region. Theoretically, the availability of geothermal energy can adequately fulfil energy needs but the exploration being expensive; it is still in its beginning stage. With the availability of cheap coal in India for power production, the geothermal energy is not exploited at all.

1.2.5 Nuclear Energy

The energy produced by the exothermic nuclear process is called as nuclear energy. The energy may be released through nuclear fusion, fission or by radioactivity. The process consists of conversion of a small amount of mass to energy as per the relation of $E=mc^2$, where E is the energy, m is the mass, and c is the velocity of light. Nuclear power plants actively provide 13% of the world's electricity and 5.7% of the energy as of 2012. In India, it has supplied around 4% of the total electricity. This energy is procured only by the nuclear fission reaction and the commercial power production from nuclear fusion is not yet employed. Nuclear energy is a sustainable source of energy which can significantly reduce carbon emission though, the *Chernobyl disaster (1986), Fukushima Daiichi disasters (2011)* were major setbacks. Also, the cost of design and maintenance of nuclear power plants are quite high. India is aiming to produce 25% of electricity from indigenous nuclear power plants. Due to lack of indigenous uranium reserve, India is exploiting its thorium for power generation **[6].**

1.2.6 Biomass Energy

Biomass is defined as a non-fossilized, biodegradable organic material originating from plants, microorganisms and animals. Biomass also includes products, by-products, residues and wastes from woody, agricultural industries including the biodegradable organic waste from industrial and municipal operation. It also comprises liquids and gases collected from decomposition of non-fossilized and biodegradable organic material **[7].**

Biomass may be defined as the biological matter derived from living matters for the derivation of energy. It is the most ancient form of energy source known to mankind which is abundant and renewable. Biomass mainly consists of matter such as residue parts of plant, namely, leaves, barks, branches, trunks, etc. This may also include the commercial wastes from wood and furniture factories such as saw dust, chipped wood, etc.

Biomass has been maintaining its stance as the most promising renewable energy source in the world. Its diverse quality of being used in any state of matter as liquid, solid or gaseous has made it as the second largest renewable energy source on earth. Presently, the aggregate use of bio-energy is around 12 % of the world's total energy consumption and it tends to increase substantially in the coming years. It is used traditionally for cooking purposes in developing states in India **[8]**.

1.3 Power Generation Potential of Different Renewable Energy Sources in the World

Worldwide demand for renewable energy is increasing substantially in recent years, providing approximately 19% of global energy in the year 2012. 4.1% of the estimated energy came from modern renewable energy sources, 3.7% was provided by hydropower, and 1.9% was contributed by solar, geothermal, wind and biomass. As in Table 1.1 shown, total renewable energy capacity surpassed 1,470 GW in 2012, which is 8.5% more than in the year of 2011. Energy produced from hydro electricity climbed 3% to an anticipated 990 GW, whereas different renewable sources developed 21.5% to surpass 480 GW. Comprehensively, wind force represented around 39% of renewable power limit in 2012, emulated by hydropower and solar photo voltaic, both representing more or less 26% share. Renewable sources made up around half of total share of electric production compared to all sources in 2012. By year's end, they embodied more than 26% of global generating limit and supplied an estimated 21.7% of worldwide power, with 16.5% of power provided by hydropower **[9]**.

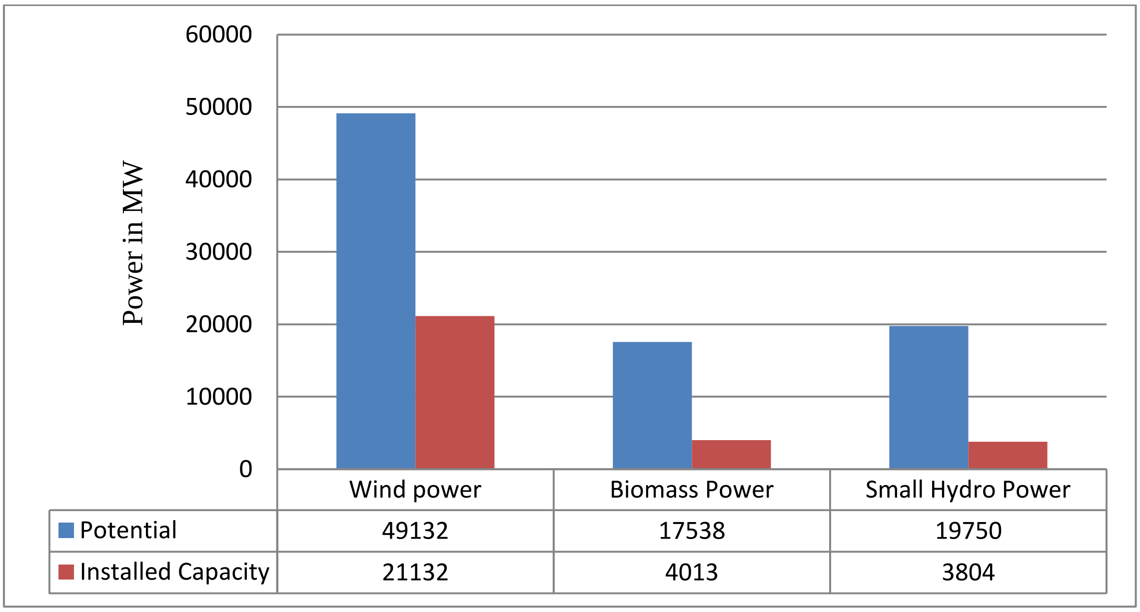
Energy Information Administration **[10]** anticipates that biomass will produce 15.3 billion kWh of electric power or 0.3% of the anticipated 5,476 billion kWh of total generation by 2020. In situations that reflect the effect of a 20% renewable portfolio standard (RPS) and in situations that expect reduction in carbon dioxide emission based on the Kyoto Protocol, power generation from biomass is forecasted to expand significantly.

Table 1.1: Global Electricity Capacity from Renewable Energy in the year 2013 **[9]**

Technology	**Electricity capacity in GW**								
	WORLD	**EU-28**	**BRICS**	**USA**	**China**	**Germany**	**Spain**	**Italy**	**India**
Bio-Energy	88	35	24	15.8	6.2	8.1	1	4	4.4
Hydropower	1000	124	437	78	260	5.6	17.1	18.3	44
Solar PV	139	80	21	12.1	19.9	36	5.6	17.6	2.2
Geothermal power	12	1	0.1	3.4	0	0	0	0.9	0
Ocean power	0.5	0.2	0	0	0	0	0	0	0
Wind power	318	117	115	61	91	34	23	8.6	20

1.4 Power Generation Potential of Different Renewable Energy Sources in India

There is high potential for generations of renewable energy from various sources namely wind, biomass, solar and small hydro. The aggregate potential for renewable energy in India is estimated at 94126 MW as on 31st March, 2014. It comprises biomass power potential of 17538 MW, wind power potential of 49132 MW and small-hydro power potential of 19750 MW **[11].** However, the installed capacities are much less as compared to the potential available. Wind energy is dominating the renewable energy sector accounting of 21132 MW, followed by biomass power projects aggregating 4013 MW capacities, 3804 MW of small hydro power projects and 2647 MW of solar power projects have been installed in the country which are very less as compared to the available potential as shown in Fig. 1.1 **[12].**



	Wind power	Biomass Power	Small Hydro Power
🟦 Potential	49132	17538	19750
🟥 Installed Capacity	21132	4013	3804

Fig. 1.1: Source-wise Estimated Potential and Installed Renewable Power in India as on 31.03.2014 **[11, 12]**

As per the geographic distribution of the evaluated capability of renewable energy as on 31st March, 2014, the report tells that Karnataka state has the highest share of renewable capacity about 14,464 MW which is about 15.37% of the total share in India, followed by

Gujarat with 12,494 MW comprising 13.27% share and Maharashtra with 10.26% share (9,657 MW), predominantly by virtue of wind power potential **[11]**.

Among all the renewable energy sources, biomass with its ease of use in power plants has become the most valuable renewable energy source in 21st century. Efficient thermo-chemical and biochemical conversion techniques including its entire usage in direct combustion process or partial mixing with coal in co-firing process have increased its opportunity by many folds. Vast and year-round availability, recycling potential, absence of pollutants like sulphur, lower ash content have made biomass as the perfect replacement for traditional and limited coal fuel in power generation.

1.5 Classification of Biomass

Biomass is a highly diversified fuel and its various types used for energy production are listed below.

1.5.1 Woody biomass

Forestry byproducts including leaves, barks, branches and other woody parts, and wood industry residues like sawdust, briquettes from sawdust etc. come under this category. These are typified by lower ash and moisture contents, lower void space, higher bulk density and calorific value. These multitudes of advantages make this category as the most preferred bio-fuel to be used for energy production. Parts of dead and dying trees, non-merchantable wood including barks and branches, undersized and defective wood in sawmills, fast growing trees like Eucalyptus are some of the major woody biomasses **[13]**.

1.5.2 Non-woody biomass

Residues from agricultural, dedicated energy crops, municipal and biodegradable wastes come under this category. These biomasses are characterized by high moisture content, greater ash content, high void space and, lower bulk density and energy value. Dry cellulosic agricultural residues like straw of maize, rice, cereals, and energy crops like bagasse are the examples of non-woody biomass.

The average majority of biomass energy is produced from wood and its wastes which comprises 64% of total biomass energy, followed by municipal waste which contributes 24%. Agricultural waste is only 5% of the total biomass energy. Therefore, there is a great potential of energy production from woody biomass **[13].**

1.6 Methods of Electricity Generation from Biomass

Over the last few decades, the advances and availabilities of bio-energy conversion technologies have warranted a remarkable growth in the usage of biomass for electricity production. Essential mechanisms available for nurturing electricity generation from biomass are as follows. It is broadly classified in to two categories namely, thermo-chemical process and combustion process.

1.6.1 Thermo-chemical Process

1.6.1.1 Torrefaction

Nature has made a substantial variety of biomass with fluctuating details. Keeping in mind the end goal to make profoundly effective biomass-to-energy chains, torrefaction in addition with densification, is a promising step to overcome logistic commercial concerns in vast scale environmental friendly power generation solutions. Amid torrefaction, the properties of biomass are changed to acquire a greatly improved fuel quality for ignition and gasification purposes. Torrefaction is a thermo-chemical treatment of biomass at 200–320 ^{0}C and is carried out in the absence of oxygen under atmospheric conditions. During the process, biopolymers like cellulose, lignin and hemicellulose partially decompose giving off different types of volatiles. The final product remained is ‘‘torrefied biomass’’ or ‘‘bio-coal’’ **[14].**

1.6.1.2 Pyrolysis

Pyrolysis is defined as the thermal decomposition of organic materials in the absence of oxygen. It is the basic thermo-chemical process for conversion of biomass into a more functional fuel. The temperature window for pyrolysis process is 300-600 ^{0}C **[15]**. In general, gas and liquid products are produced by pyrolysis and solid residue with rich carbon content is left. Extreme pyrolysis largely produces carbon as the residue, which is called carbonization. Pyrolysis varies from other high-temperature combustion methods as there is no use of oxygen, water or any other agents **[14].**

1.6.1.3 Gasification

Biomass gasification is the thermo-chemical transformation of biomass in an oxygen deficient environment leading to conversion of all the raw materials into gas. Biomass gasifiers are devices that thermo-chemically convert biomass into high energy combustible gas to be used in gas turbine. A temperature of about 600-800 ^{0}C is required for gasification process. Biomass, particularly woody biomass, can be transformed to highly flammable gas to be utilized in internal combustion engines for mechanical or electrical applications. This happens in two stages. In the first stage, partial combustion of biomass forms producer gas and charcoal. In the following stage, the CO_2 and H_2O produced in the former phase are chemically lowered by the charcoal, forming CO and H_2. The composition of the gas is 18-20% CO, an equal portion of H_2, 2-3% CH_4, 8-10% CO_2 and the rest nitrogen **[16].**

A number of gasifiers have been developed over the time. These incorporate the smaller scale fixed bed updraft, downdraft and cross flow gasifiers. For small scale applications, downdraft gasifiers are prominent as the tar production is comparatively low. Low melting point fuels are not suitable to be used for this process. Between various biomass power alternatives, small-scale gasifiers with power production potential of 20–500 kW have the prospective to meet all the rural electricity requirements and leave the excess to feed into the national grid **[17].**

1.6.2 Combustion Processes

Combustion category comprises specifically of two technologies namely, direct firing and co-firing.

1.6.2.1 Direct Firing

The most well-known use of solid fuel biomass is direct combustion which produces the hot flue gases creating steam in the boiler. This technique is not very efficient as direct combustion generates a high amount of moisture which is not desirable. This high moisture behaves as a heat sink during the heating operation which leads to decrease in flame temperature, taking away the thermal energy from production of steam, and eventually causing combustion troublesome. In addition to the moisture, the presence of cellulose reduces the theoretical air requirements for combustion as it contains fuel-bound oxygen **[18].**

1.6.2.2 Co-firing

More than 50% power is generated by coal-fired power plants in India which is the largest emitter of carbon dioxide and other green house gases. In addition to the pollution caused by coal fired plants, the capital investment is huge with only 20 to 50 years of lifespan. It is not feasible to completely retire these conventional plants but can effectively be used by substituting some portion of coal with greener technology like biomass. This effective replacement of conventional fuel with biomass for power generation is known as co-firing.

Co-firing is a fuel diversification strategy defined as the concurrent ignition of two dissimilar fuels in a boiler. It involves replacing a fraction of the conventional fuel with biomass to be used in a boiler **[19]**.

Biomass co-firing is mainly a modified application of existing facilities. This is presently one of the basic ways of exploiting biomass to substitute non-renewable fuels, needing no new investment or expert technology which can be enacted immediately in nearly all coal-fired power plants without much modification of the plant in a short period of time. It has been experimentally proven that between 5-15% of biomass can be used for power production by co-firing without affecting the efficiency of power plant. It is commonly acknowledged that conventional power plants are generally highly polluting in terms of emissions of sulphur, CO_2 and other green house gases (GHG) while it has been well proven that co-firing decreases emissions of CO_2, SOx and to some extent NOx as well **[20].**

It has accordingly developed to be a near-term option for emission reduction and effective power production. Various types of co-firing are explained in the following sub-sections.

1.6.2.2.1 Direct Co-firing

Direct co-firing is defined as the ignition of two heterogeneous fuels in a boiler. It is the simplest and cheapest option available. Normally, biomass is milled and added directly with the pulverized coal for a better combustion. Use of up to 15% of biomass fuel is proved to be effective in this process. But, due to variation in energy values and ash contents, some ash related problems along with corrosion could take place **[21]**.

1.6.2.2.2 Indirect Co-firing

It is a less generalized process which is intricate and extreme. In this process, a gasifier is employed to convert the solid bio-fuel to flue gas. It is an efficient process as there is reduction in corrosion and fouling of boilers. Also, a large portion of coal can be replaced with the generated flue gas. In addition to above, fuels containing heavy metals can be used in this process **[21]**.

1.6.2.2.3 Parallel Co-firing

In parallel co-firing, separate combustion processes are incorporated for both biomass and coal. The steam generated during biomass burning is fed directly to the coal-fired plant which increases the boiler pressure and temperature. This technique is regularly used in paper industries to better use the by-products from paper production**.**

The efficiency of a biomass co-firing facility usually depends upon the size of the facility, types of biomass used, etc. Among all the process discussed above, efficiency of direct co-firing is higher as compared to the rest two methods **[21].**

1.7 Biomass Co-firing: Environmental, Climatic and Financial Benefits

Biomass co-firing offers a relatively low-cost approach to decrease GHG emissions. As the presence of sulphur, nitrogen and other heavy metals like mercury, lead, etc are negligible in biomass; co-firing constructively decreases sulphur dioxide, nitrogen oxide emission which is the main cause of acid rain and other harmful emissions. Biomass combustion is considered to be carbon neutral, because whatever CO_2 is released during combustion is withdrawn from the environment by photosynthesis during the plant's growth. Thus, the co-fired power plants emit less net GHG than coal-fired power plants. The cost to cut emissions is relatively low in co-fired plants because the investment costs for building new co-fired power plants is moderate as compared to other options. Assuming an average level for CO_2 emissions from conventional combustion of 90 kg/GJ, it is assessed that the CO_2 emissions in 2035 could be decreased by 50-450 million tonnes per year if 1-10% of the coal fuel input were replaced by biomass **[22].**

The benefits that can be expected from co-firing include the following **[23]**:

i. The sustainably grown biomass is considered as the GHG neutral fuel. Through co-firing, if we replace 10% of coal, we will reduce GHG emission by 10%. Also it minimizes the net SOx, NOx and many heavy metal emissions, because most biomass contains nearly zero percent sulphur. Therefore, co-firing with biomass may correspond to a practical, cost-effective means for meeting stricter emissions targets.

ii. In co-firing technology, a fraction of high cost fossil fuel is replaced with lower cost biomass fuel. If the co-firing facility is located close to an agricultural or a forestry product processing plant, immense amount of low-cost biomass residues can be accessible which in turn will decrease the overall cost.

iii. Co-firing offers a fast track, low-cost opportunity to include renewable energy capacity economically as it can be added to any coal fired plant immediately, with less modification and minimum investment.

1.8 Benefits and Limitations of Biomass Use in Power Production

1.8.1 Benefits

Apart from the benefits from co-firing as earlier discussed, the generalized advantages of use of biomass in power production are as follows. Effectively managed biomass can offer a wide variety of social and environmental benefits as mentioned below **[22]**:

i. Utilizing biomass in power plants produces clean energy. Fossil fuel burning results in conversion of sequestered stable carbon into carbon dioxide and other pollutants. But, use of biomass is carbon neutral as it refers to achieving zero carbon emission by balancing the carbon released with planting trees. Plants absorb CO_2 through photosynthesis. Therefore, the carbon in wood has always been in a cycle. When the trees are replanted, carbon sequestration begins again. Accordingly, the feasible generation and utilization of biomass in power plants will certainly help in lowering the concentration of carbon dioxide in the environment and consequently the greenhouse effect.

ii. In correlation to coal, the ash content in biomass is very low, which is about 2 to 15% as against 30 to 50% in coal. In this manner, the use of biomass in power production will guide to considerable decline in the quantity of suspended particulate matters in the atmosphere.

iii. Calorific value of biomass is more when compared to those of E and F grade coals mostly used in Indian power plants.

iv. Reactivity of biomass towards oxygen and carbon dioxide is much higher than that of coal. This allows the boiler to operate at lower temperatures resulting in appreciable energy saving.

v. Biomass can be used continuously throughout the year, as opposed to solar and wind which are intermittent. It is more uniformly distributed over the earth's surface than conventional fossil fuel energy sources, and may be harnessed using more cost effective technologies. With the growing concerns regarding political turmoil in Middle East which is the largest producer of oil, use of biomass provides security against price rise and supply shortages.

vi. It is feasible to install biomass gasifiers in any locality, particularly near villages, which reduces transmission losses by generating power in decentralized basis. In addition, the supply of biomass fuels from nearby sources, transportation cost along with the emission from vehicle exhausts can be eliminated.

vii. It offers us the prospect to be more self-sufficient in energy use and facilitates to decrease climate change.

viii. Biomass-based energy has several distinct advantages such as wide availability and uniform distribution that puts it ahead among the renewable energy options for India. Especially, in the remote areas and hilly terrains of India, decentralized power generation using biomass gasification offers a highly viable solution for meeting energy demands of small villages as power, which would not only make them autonomous and self sufficient but will also decrease burden on electricity boards. Decentralized power generation may be defined as the power generation at or near the point of use. In addition, it helps local farmers a better way to administer waste material, cater rural job opportunities and activate new economic possibilities in countries like India and China.

ix. Biomass can prevent soil erosion and will lead to better usage of infertile lands.

1.8.2 Limitations

Besides some important benefits of biomass combustion, it has also some limitations as listed below **[22].**

i. A particular fuel is always assigned to a certain combustion unit. Generally, the conventional boilers are designed for a range of volatile mass and ash content. When biomass is co-fired, it is imperative to change some features of the existing boiler.
ii. Biomass is relatively less efficient as compared to coal. When co-firing is employed, calorific value of the mixed fuel is low as compared to the conventional coal fuel.
iii. Milling and pelletization of biomass is mandatory before it can be mixed with pulverized coal to be used in boiler. Also, the moisture content should be maintained as per the boiler specification.
iv. Presence of large amounts of alkalis in biomass, mainly potassium and also the presence of chlorine may increase the fouling problems.
v. It is very demanding to obtain large feedstock in large processing plants throughout the year. Considerable forest area is required near the power plant to facilitate the combustion effectively.
vi. As evident, the bulk density of biomass is very low as compared to coal. This makes the biomass to occupy large space in a boiler making the combustion process less efficient.

Lack of encouragement from government, insufficiency in training and work experience and other misconceptions have hampered the development of biomass as one of the most significant renewable energy source in India.

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Energy Challenges and Renewable Energy Scenario in India

According to the report by *Ministry of Statistics and Programme Implementation* **[1]** the total domestic energy production will touch 669.6 million tons of oil equivalents (MTOE) by 2016-2017 and 844 MTOE by 2021-2022. This will satisfy around 71% and 69% of believed energy consumption in those years respectively. The balance to be met from imports is projected to be about 267.82 MTOE and 375.68 MTOE by 2016-2017 and 2021-22 correspondingly. The Indian economy has encountered remarkable economic development in the most recent decade. India to sustain its high rate of GDP growth, it is essential to be self sufficient by sustainable development. This high magnitude of sustained economic growth is putting tremendous demand on its energy resources which can only be fulfilled practically by the use of renewable energy sources.

The high economic growth in developing countries like India has negative outcomes like higher energy requirement and higher carbon dioxide (CO_2) emissions. The requirement for energy has to be minimized by utilizing energy efficiently and better usage of renewable energy. *Parikh and Parikh* **[24]** studied energy needs in India and options regarding low carbon and found that reduction in CO_2 emissions by 30% is possible by 2030 with some additional costs by implementing diverse options like nuclear, biomass, solar and wind energy as alternative energy sources for energy production.

Release of CO_2 gas into the atmosphere is typically by burning fossil fuels. Electricity is the highest consumer of energy and has registered a stable growth rate as compared to other forms of energy. *Dunn and Flavin* **[25]** observed that carbon dioxide is the most vital greenhouse gas that causes the "anthropogenic climate change". India being a developing country with more than 1.2 billion populations with a huge territorial area of 2,973,189 square kilometres and vast natural resources, the increase in electricity consumption is nearly connected with both economic development and increased pollutant emissions. Formation of new commercial enterprises, plants, business hubs and development of consumer goods industries to bolster its ever expanding populace has prompted a substantial rise in electricity consumption in India and subsequently, the CO_2 emission levels. The only way to minimize the anthropogenic climate change is by implementing various renewable energy programs especially biomass energy.

Including the above causes, the constant regional and political problems in the Middle East have made India to look for other alternatives for its energy security in future. *Rastogi* **[26]** analyzed India's energy consumption pattern, consumption of oil and oil products where she calculated the risk factor in India as it imports around 71% of its oil requirement, up to 66% of which comes from the Middle East. Hence, there is a critical obligation to follow a comprehensive energy security model to protect India's energy future.

As per the report by *AP Energy publication* **[27]**, India is committed to increase its renewable energy share which can immensely contribute towards electricity production. It has been forecasted that it will supply around 15% of the total electricity need by 2020. Energy sector in India is thriving to be at par with global energy standards with sustainable energy production by decreasing carbon emission substantially by frequent use of renewable energy. The government is also launching new energy initiatives to curb climatic issues. Ministry of New and Renewable Energy and Ministry of Power jointly initiated Jawaharlal Nehru National Solar Mission, which is one of the most noteworthy environment friendly energy solution initiatives existing in India. Also, the National Solar Mission concentrating on 20 GW grid solar powers, 2 GW of off-grid capacity including 20 million square meters solar thermal collector area and 20 million solar lighting systems by 2022 is under consideration. The last three years witnessed a remarkable progress in renewable energy sector with the launch of a number of new initiatives. Biomass energy and wind power have become the fastest developing renewable energy sectors in the country. Cumulative deployments of 2079 MW wind power and 411 MW of biomass power only in the year 2013 showed the increasing trend in use of renewable energy. Modern biomass demand has increased many folds which has turned out to be the driving force for international trade. Bio-fuels and wood pellets have become particularly the entity of bio-fuel trade. Worldwide production and transport of wood pellets surpassed 22 million tons excluding 8.2 million tons of pellets traded globally. Liquid bio-fuels like ethanol and biodiesel has increased and stood at 83.1 billion liters and 22.5 billion liters respectively**.**

As per *British Petroleum* **[28],** renewable energy consumption in the year 2013 stood at 11.7 MTOE in India. It rose to 4.2 % of total energy consumption as compared to only 1.65% in 2010. There is a change of 8.3% of consumption of renewable energy in 2013 over 2012 which shows a positive sign towards mitigating CO_2 and other harmful emissions.

Perceiving the potential of renewable energy, India has been enacting one of the largest renewable energy programmes on the planet. Among the renewable energy options, bio-energy has a massive portfolio consisting of efficient biomass stoves, biogas, biomass combustion, co-firing and gasification. *Ravindranath and Balachandra* **[29]** analyzed the technical and economical sustainability of bio-energy in India where energy system dominated by fossil fuel is confronting a serious resource crisis. They discovered the requirement for making access to quality energy for the large section of deprived populace, and the requirement for feasible economic development by planning and executing various innovative policies and projects to encourage bio-energy technologies. Yet, as per some preliminary studies, the success rate is marginal in contrast to the potential available. This constrained achievement is an acceptable marker of the requirement for a genuine reassessment of the bio-energy program. Further, an acknowledgment of the requirement for receiving a sustainable energy path to address the above obstacles will be the guiding force in this reassessment.

Municipal and industrial residues for example, waste water, municipal solid wastes (MSW) and crop residues such as rice husk and bagasse are being utilized for power generation. *Ravindranath et al.* **[30]** studied the rural biomass availability and found that fuel wood, animal manure and crop residues are the predominant biomass fuels but are used inefficiently. They elaborated the capability of energy from crop residues, animal compost, MSW and urban waste that might be preserved for different applications.

Cooking in rural India is generally done using inefficient conventional wood stoves without any suitable chimney or ventilation. This results in serious pollution problems inside the house affecting health of inhabitants. As per the report published by *Ministry of New and Renewable Energy* **[12]**, with new innovation creating ample opportunities to substitute traditional stove by improved and efficient stove which subsequently safeguard excess use of wood fuel, reducing GHG emissions and domestic pollution. The renovated stoves use wood fuel efficiently, thus by reducing the pollution and increasing efficiency. The efficiency of these renovated cook stoves are found to be around 30-35% which is well above the efficiency level of old stoves. Therefore, modern efficient biomass cook stoves have the potential to conserve conventional fuels.

2.2 Biomass as a Renewable Energy Source and its Potential

Thermal power plants use coal for combustion which emits mainly carbon dioxide (CO_2), oxides of nitrogen (NOx), oxides of sulphur (SOx), CFCs, and other trace gases. CO_2 created in combustion is of incredible concern in perspective of its effect on global warming. *Raghuvanshi et al.* **[31]** studied the CO_2 emissions from coal based power generation in India and suggested use of renewable energy to curb emissions. They found that combustion of coal resulting carbon dioxide is presently contributing over 60% to the greenhouse effect. When 1 tonne of fossil fuel is burnt, 750 kg of CO_2 is released to the atmosphere. On the other hand, use of biomass as a fuel in power plants will decrease the emission of particulate matters as it contains the least percentage of sulphur and other emission related particles.

The effects of utilization of biomass in fractional substitution of fossil fuels has an extra significance in regards to global warming since biomass combustion can possibly be CO_2 neutral. The above is especially the situation with respect to woody and agricultural plants, which are intermittently sowed and collected. By photosynthesis, these plants remove CO_2 from the atmosphere. *Werther et al.* **[32]** analyzed that biomass residues with high energy potential include forest-related residues which accounts for nearly 65% of the biomass potential such as wood chips, bark, leaf and sawdust. Also the agricultural residues make up the rest which are straw, paddy husks, bagasse, etc. A number of developed countries like USA (5%), Finland (19%), Sweden (17%) and Austria (14%) obtain a major amount of their principal energy from biomass. Presently out of 54 EJ of primary energy, biomass energy provides 2 EJ per year in Western Europe. Energy demands, incentives for use of bio-energy, continuous research and ecological needs are the factors that will affect the future of biomass.

Case studies by *Chauhan* **[33, 34]** on biomass potential in states of Punjab and Haryana shows that around 40.142 MT/year and 24.697 MT/year of the overall crop residue is produced from a variety of crops, of which just about 71% is utilized, resulting in the availability of 29% as a net surplus in both the states. It has been approximated that roughly 1.5101 GW and 1.4641 GW of power in the state of Punjab can be produced through basic surplus and net surplus biomass respectively. For state of Haryana where basic surplus is calculated as 45.51%, productive surplus as 37.48% and 34.10% as net surplus of total biomass available.

As of 2011, about 400 million people didn’t have access to electricity in India. It was also found that, about 836 million people (i.e., around 72% of population) relied on traditional biomass for cooking. So, a huge proportion of the country’s inhabitants still need access to cleaner and contemporary forms of energy **[35].** Therefore an efficient and productive exploitation of biomass as a power producing source in India is still in its nascent stage and it needs to be exploited.

2.3 Biomass Conversion Processes

There are various types of biomass conversion processes. *Kucuk and Demirbas* **[36]** studied three such processes namely, chemical, thermo-chemical, and biochemical processes. The study suggested important parameters for chemical method such as pre-hydrolysis, concentration of acid, temperature, time of reaction and moisture content of exploited material. For thermo-chemical processes, the parameters are pressure, temperature, reaction time and added catalysts or reactants. For biochemical processes, the factors are reaction temperature, moisture, pH and reaction time.

Among all the biomass conversion process including the above three, co-firing is the most efficient**.** It is a well-demonstrated innovation. It recommends a close term answer for lessening CO_2 emission from generally used fossil fuel power plants. Practical choices for long term CO_2 reduction technology, for example, oxy-firing, CO_2 sequestration and carbon loop combustion are continuously being talked about. An incremental addition in CO_2 decrease could be attained by quick usage of biomass co-firing in about all fossil fuelled power plants with least alterations and reasonable financing. If a majority of conventional power plant functioning across the globe accept co-firing method, the aggregate fall in CO_2 emissions would be significant. Co-firing is found to be the most proficient method for electricity production from biomass, and subsequently recommends CO_2 avoidance cost less than that for CO_2 sequestration from present power plants. The present examination by *Basu et al.* **[37]** is on a few co-firing choices together with a novel choice of external firing or indirect firing utilizing combustion or gasification in the existing power plant. They analyzed two of the indirect or external firing options alongside compared the merits and cost advantages of direct firing of biomass in pulverizing mills with gasification. It was found that efficiency of direct co-firing is higher as compared to indirect co-firing.

The design of devices used in such biomass conversion processes plays an important role. *Mukunda et al.* **[38]** made a study about such devices and thoroughly emphasized the requirement for the renewable energy especially the use of biomass in developing countries. They classified the biomass in terms of woody and pulverized, and also compared its energetic with fossil fuels. Gasifier-combustor, combinations of gasifier, engine, and alternator for production of heat and electricity are some of the technologies involved and are used for both woody and pulverized biomass. Emphasis is given to the use of pulverized biomass in cyclone combustors to obtain high-grade heat. The techno-economic aspects are conversed to show the feasibility of these mechanisms in the existing global scenario. It is deduced that the vital constraint for the exploitation of bio-energy technologies comes from the absence of recognition of their actual potential.

2.4 Chemical Properties and Ash Fusion Temperature Test of Biomass

The study of chemical properties such as proximate analysis, ultimate analysis, calorific value, ash fusion temperature, etc are important in selection of a fuel to be used in power plant. *Kumar et al.* **[39]** studied the characteristics of four herbaceous non-woody plants species namely, *Eupatorium, Anisomales, Sida,* and *Xanphium* and calculated the power generation potential. They compared the calorific values of biomass species with locally available coal and found the superior energy value of biomass compared to coal.

Similar studies were carried out by *Kumar and Patel* **[40]** on two non-woody biomass species namely, *Ocimum canum* and *Tridax procumbens*. Later, in a similar way *Kumar et al.* **[41]** explored power generation potentials of three forestry non-woody biomass species namely, *Sida Rhombifolia, Vinca Rosea,* and *Cyperus.* In addition, they studied bed agglomeration problems associated with boilers, and found the biomass considered for the study showed higher fusion temperatures and are safe to be used.

In addition, blends of coal and biomass plays a vital role in mitigating emissions. *Demirbas* **[42]** studied the blending characteristics of biomass with coal in coal-fired boiler. He compared the co-firing technology with other conversion processes and found that co-firing is more efficient and advantageous**.** Later, *Demirbas* **[43]** suggested the significant variation of fuel properties with respect to coal. He found that the ash content varies between 1-16% while nitrogen percentage varies between 0.2-1%. Similarly, carbon percentage varies between 35-43%. Variation of sulphur in biomass is very less and lies below 0.1%. Other important variations as compared to coal are high moisture content, high chlorine content, low bulk density and low heating value. Biomass has less carbon content as compared to coal. But, the oxygen content is higher in case of biomass. Irrespective of these variations, he suggested that biomass still stands as the most eligible renewable fuel to replace fossil fuels.

The studies of ashes of biomass are important when bed agglomeration of boiler is taken into consideration. *Hiltunen et al.* **[44]** studied the different types of ashes of biomass fuels. They divided the biomass ashes into 3 groups in accordance to their ash composition such as i) Ca, K rich and Si lean biomass ash, ii) Si rich and K, Ca lean biomass ash, and iii) K, Ca and P rich biomass ash. The first group belongs to woody biomass while the rest belong to agricultural biomass. They also studied the effect of combustion of these fuels and their effect on the circulating fluidized bed boilers which are very popular for biomass combustion.

Important ash related problems associated with boiler are slagging and fouling. Slagging is defined as the deposition of ash on furnace surfaces which is directly exposed to flame radiation. On the other hand, fouling is the deposition in convective section of the boiler. Slagging and fouling can cause excessive deposition of ash on the heat transfer surfaces of boilers. This decreases the effectiveness of boiler functioning and in extreme condition, it can shut down the power unit. Ash fusion temperatures play vital role in determining these above problems. The ash composition and characterization of the softening temperature can be related to the formation of slagging and fouling in boilers **[45].**

2.5 Derivation of Regression Equations from Proximate and Ultimate Analyses

Calorific value of a biomass fuel is one of the most important properties for the design of a bio-energy system. The experimental methods to evaluate the calorific value are time consuming as well as expensive and have higher possibilities of experimental errors. Therefore, a number of equations have been derived to predict calorific values from proximate and ultimate analyses data. *Erol et al.* **[46]** derived 13 new formulae for approximating the calorific value of biomass from its proximate analysis data. They analyzed 20 different biomass samples for deriving the equations. Least square regression analysis was used for developing the equations with the R-squared values ranging from 0.829 to 0.898. Standard deviations are between 0.4419 and 0.5280 for the thirteen different equations. The equation of net heating value i.e., $\mathrm{NHV} = -166 - 1.33(\mathrm{Ash}) - 0.005(\mathrm{VM}) + 1.92(\mathrm{VM} + \mathrm{Ash}) - 0.0227(\mathrm{VM} \times \mathrm{Ash}) - 0.0122(\mathrm{VM})^2 + 0.0299(\mathrm{Ash})^2 + 6133(\mathrm{OM})^{-1} - 0.82(\mathrm{Ash})^{-1}$ has been found to have high accuracy among all the formulae where VM are OM contents of volatile matter and moisture respectively.

Similarly, *Parikha et al.* **[47]** derived an equation for finding HHV (higher heating value) from proximate analysis data using 450 data points and validated with another 100 data points. The equation is found to be HHV = 0.3536(FC) + 0.1559(VM) – 0.0078(Ash) where FC is fixed carbon content. The average absolute error (AAE) is found to be 3.74% while the average bias error (ABE) is found to be 0.12%. This study provides a useful fact regarding modeling of pyrolysis and combustion process.

García et al. **[48]** obtained equations for the calculation of higher heating values from their ultimate analyses data. They considered 100 different biomass samples which include commercial fuels, forest and woody residues, herbaceous and agricultural residues, cereals, etc. The results suggest that the HHV depends mainly on oxygen and carbon content of fuel. The equation yields only 6% of error. The equation based on C, H, N, O and S shows a greater error as compared to the equation with the composition of C and O.

In similar way, *García et al.* **[49]** obtained equations for the calculation of higher heating values from their proximate analyses data. They suggested that the non-homogeneity and variation in properties of biomass fuel is largely based on geographical region. They predicted the equations considering the characteristics of biomass in a specific region. They found that the fixed carbon and the ash content of a biomass greatly affect the energy value. They obtained the equations considering 100 biomass data. The equations derived were within 5% error range.

2.6 Decentralized Power Generation Structure in Rural Areas

Decentralised energy, as the name suggests, is produced close to where it will be used, rather than at a large plant elsewhere and sent through the national grid. This local generation reduces transmission losses and lowers carbon emissions. Therefore, decentralized electricity generation potential in rural areas needs to be assessed. *Kumar and Gupta* **[50]** generalized the land and biomass calculation for decentralized power generation in rural areas by considering a cluster of 15-20 villages comprising of nearly 3000 families and one power plant can be planned accordingly which can provide 20000 kWh of electricity per day i.e., 7300 MWh per year. *Kumar et al.* **[39]** considered *Eupatorium. Anisomales, Sida*, and *Xanphium* biomass species, and calculated that around 118, 66, 90 and 114 hectares lands would be required for the continuous generation of said electricity from these three biomass species respectively. Further, in a similar way *Kumar and Patel* **[40]** studied on 18-months old (approx.) *Ocimum canum* and *Tridax procumbens* plant species, and calculated their land requirements to be 650 and 1274 hectares respectively to produce the same amount of electricity. Similarly, *Kumar et al.* **[41]** considered *Sida Rhombifolia, Vinca Rosea*, and *Cyperus* non-woody plants and estimated that around 44, 52 and 82 hectares of land area would be needed to produce the said amount of electricity.

In the similar way, *Kumar and Patel* **[51]** studied the power generation energetic of blends of coal, cattle dung and rice husk considering decentralized power generation process. They found that with the increase in percentage of cattle dung and rice husk, there is a decrease in requirement of coal for power generation. Therefore, total energy contents, land area including the requirements of coal-biomass blends should be calculated pertaining to power generation by decentralized process.

2.7 Summary

It is understood from the literature review that there is a lack of research in context to the study of power generation potential of biomass species which constitute a significant portion of renewable energy source. In addition, there is a significant research gap in studies of chemical properties of biomass fuels which include the analyses of ash fusion temperature, proximate and ultimate parameters. Also, literature pertaining to studies on co-firing aspect of biomass species with locally available coal is limited. It is also observed that, there is a need in studies of decentralized power generation aspects of biomass species. Also the development of regression equations to predict the energy values from their proximate and ultimate analyses data is still in its nascent stage and it needs further analysis.

2.8 Aims and Objectives

The aims and objectives of the present project work are as follows:

i. Selection and collection of woody biomass species from local area.

ii. Experimental investigation of proximate analysis of different components of residues of a few selected woody biomass species.

iii. Characterization of these biomass components for their energy values.

iv. Determination of bulk densities of the selected biomass species.

v. Determination of ash fusion temperatures of ashes obtained from selected plant species.

vi. Characterization of coal mixed biomass components for their energy values and comparative study of coal and biomass mixed samples in different ratios.

vii. Determination of ultimate analysis of some selected biomass species.

viii. Establishment of regression equations for calculation of calorific values from proximate and ultimate analyses data of the biomass samples.

ix. Estimation of power generation potentials, requirements of land area and coal-biomass blends for decentralized power generation.

CHAPTER 3

EXPERIMENTAL WORK

3. EXPERIMENTAL WORK

3.1 Materials Selection

Five different types of woody biomass species such as *Ficus benghalensis* (local name- Banyan), *Azadirachta indica* (local name- Neem), *Ficus religiosa* (local name- Pippal), *Madhuca longifolia* (local name- Mahua) and *Eucalyptus globulus* (local name- Eucalyptus) were procured from the local area for the present project work. Three components i.e. leaf, bark and branch each from residues of the above mentioned five woody biomass species constituting fifteen different samples were separately considered for proximate analysis and calorific value determination. The equilibrium in moisture contents of these components were attained by placing these samples in a cross-ventilated room for 20-30 days. The air dried samples were grinded into powder form before carrying out experimental work. For the ultimate analysis, three selected woody biomass species namely as Banyan, Pippal and Mohua were considered taking the same three residual components i.e., leaf, bark and branch from each of them. Thus, a total of nine samples were studied for ultimate analysis.

3.2 Proximate Analysis of Studied Biomass Samples

Proximate analysis of a sample is the quantitative analysis of distribution of constituent products obtained when the sample is heated under designated conditions. As per *ASTM D121* **[52]**, proximate analysis segregates the constituents to four categories: i) moisture, ii) ash, iii) volatile and iv) fixed carbon. Proximate analysis is generally considered for characterizing biomass and coal samples.

3.2.1 Moisture Content Determination

The moisture content of a fuel, here in case of biomass, is defined as the quantity of water present in the sample which is expressed as weight percentage (wt.%) of the sample. The moisture content is expressed as either dry basis or wet basis. In wet basis, the aggregate content of water, ash and ash free matter is considered. But in dry basis, only ash and ash free matter is expressed as weight percentage. As the content of moisture is a determining factor for selection of a biomass fuel, the basis on which moisture is determined must be always mentioned **[53].**

As per *BIS 1350* **[54],** one gram of air dried –72 mesh size of considered biomass materials were taken in borosil glass discs and were heated at a temperature of 100 ^{0}C for one hour in furnace. Required size of –72 mesh size biomass materials were collected using a –72 mesh sieve. A –72 mesh size sieve has 72 holes per square inch and the negative sign indicates passing of particles through the holes. The discs were then taken out of the oven after the designated time and the samples were weighed. The percentage losses in weights were calculated using the expression given below which give the percentage (%) moisture contents in the samples.

$$\%\ Moisture\ content = (Wt.\ of\ residue\ obtained \times 100) / Initial\ wt.\ of\ simple \qquad \textbf{(3.1)}$$

3.2.2 Ash Content Determination

Ash is an inorganic residual matter collected after complete burning of the biomass. The ash content is an indispensable ingredient of the biomass that comprises of a variety of elements whose presence hugely affects the ash fusion characteristics. Ash material usually contains calcium, ferrous carbonate, magnesium and phosphorus with clay, sand, etc. These constituents of ash usually influence the boiler properties significantly under the elevated temperatures of combustion and gasification as it forms clinker which is a form of slag. Slagging, fouling and clogged ash removal problem are some of the severe problems associated with boilers which are due to the higher ash contents of a fuel **[55]**.

Fig. 3.1: Muffle Furnace

The step-by-step procedure followed for ash content determination is given below:

1. One gram each of air dried –72 mesh size biomass samples were taken in a shallow silica disc and kept in a muffle furnace maintained at the temperature of 775- 800 ^{0}C.
2. The photograph of muffle furnace used for this experiment is shown in Fig. 3.1 whose measuring range is 0-1000 ^{0}C. The temperature of this furnace can be measured with a resolution of 1 ^{0}C and accuracy of ±5 ^{0}C.
3. The samples were heated at this temperature till complete burning. Usually, half an hour was required in complete burning of these selected biomass samples.
4. The weights of the residues obtained in each of the cases were taken in an electronic balance. These weight results were expressed in percentage using the equation similar

to that used in determination of moisture content. This represents the ash contents in each sample **[54]**.

3.2.3 Volatile Matter Determination

Volatile matter is defined as the portion of the fuel that will rapidly volatilize when it is burnt at a high temperature under a specific condition. This heating process results in formation of char when the fuel has low volatile matter whereas this produces volatile gases when the fuel has high volatile mass content. Biomass commonly has high content of volatile matter that may go up to 80%, while coal has low content of volatile matter which may be less than 20% or even insignificant in case of anthracite coal **[53].** The constituents of volatile matter are methane, hydrogen, carbon monoxide, ammonia, tar, etc. Residual moisture is not taken into account in volatile matter **[52].**

In a regular procedure, one gram each of –72 mesh size powdered samples were taken in a pre-weighed cylindrical silica crucible covered with the close-fitting silica lid. The crucibles were then kept in a muffle furnace chamber, which was heated at a temperature of 925±10 ^{0}C. They were held at this temperature exactly for seven minutes. The crucibles were taken out from the furnace and cooled in air. The weights of samples in crucibles were measured in an electronics balance as soon as possible. The percentage losses in weight of each of the samples were calculated **[54]**. The percentage volatile matter is determined by the following formula:

Volatile Matter (wt.%, dry basis) = % loss in weight – moisture content (wt.%, dry basis) **(3.2)**

3.2.4 Determination of Fixed Carbon Content

The fixed carbon value is achieved by subtracting the aggregate percentages of moisture, volatile matter and ash from 100. Fixed carbon content is deemed to be the measure of solid carbon residue that remains after the combustion of sample when the volatile matter is removed. The residue is the result of the thermal disintegration of coal or biomass. The fixed carbon value is utilized as a factor for deciding the productivity of coal and biomass. It improves the reactivity of a particular fuel at lower combustion temperature **[54]**.

Fixed Carbon Content (wt.%, dry basis) =100 – {Moisture + Volatile matter + Ash, (wt %, dry basis)} **(3.3)**

3.3 Calorific Value Determination

Calorific value or energy value is one of the most significant properties of any fuel. It is responsible for designing the power plant and controlling plant's parameters. Calorific value of any fuel may be defined as the quantity of heat energy produced by complete combustion of a specified quantity of fuel in presence of oxygen. It is generally evaluated using a calorimeter. In case of biomass, energy value is expressed in kcal/kg or MJ/kg unit.

There are two types of calorific values based on the effect of water vapour on energy value. Those are i) gross calorific value (GCV) or higher heating value (HHV), and ii) net calorific value (NCV) or lower heating value (LHV). *Gross calorific value* or *higher heating value* is defined as the quantity of heat produced by combustion when the water vapour produced during combustion is allowed to return to the liquid state under standard condition of temperature and pressure i.e., GCV considers the latent heat of vaporization of water. *Net calorific value or lower heating value* is defined as the quantity of heat energy produced by combustion when the water produced during combustion remains gaseous and doesn't return to liquid state. Here, the condensation of water is not taken into consideration. It is usually determined using an adiabatic calorimeter **[56].**

In the present project, the higher heating values of these species were calculated using an Oxygen Bomb Calorimeter **[54].** This calorimeter used in the present study was capable of measuring the gross calorific values of all the solid fuels. The resolution of the temperature scale present in the calorimeter is 0.01 ^{0}C and its accuracy is ±0.02 ^{0}C. The measuring range is 0-10 ^{0}C.

Initially, the biomass samples were briquetted using a briquetting device. One gram of briquetted sample was taken in a nichrome crucible. To facilitate ignition, 10-15 cm long cotton thread was positioned over the sample in the crucible. The cotton thread was suspended using a fuse wire which was connected to the two electrodes of the calorimeter as shown in Fig. 3.2. Oxygen gas was filled in to the calorimeter up to a pressure of about 25 to 30 atm. The bucket containing the calorimeter was filled with two liters of water. It was constantly stirred to get uniform temperature. The ignition of sample was started when the current was switched on and the increase in temperature of water was recorded by an inbuilt thermometer. The following empirical formula was used to calculate the gross calorific value in kcal/kg **[57].**

$$\text{Gross calorific value} = \{(W.E. \times \Delta T) / (w) - (\text{heat released by cotton thread} + \text{heat released by fused wire})\} \quad \mathbf{(3.4)}$$

where, W.E. = water equivalent of apparatus in cal/^{0}C

ΔT = maximum rise in temperature in ^{0}C

w = initial weight of the sample in g

The calorific value in kcal/kg as obtained by using Equation 3.4 is then multiplying by a conversion factor of 4.1868×10^{-3} to express it in the corresponding SI unit of MJ/kg.

Fig. 3.2: Oxygen Bomb Calorimeter

3.4 Bulk Density Determination

Bulk density of a carbonaceous material gives an idea about the weight of the material to be accommodated in a given volume of a boiler. It is an important characteristic of a fuel which directly affects the transportation and storage costs. The design and function of storage, transportation and combustion devices directly depend on the bulk density of a fuel. It is defined as the weight per unit volume of a material, expressed in kilograms per cubic meter (kg/m^3).

The bulk densities of the biomass samples were determined according to the ASTM E873-82 standard **[58].** A cubical container with a standard volume of 216 cm^3 was used for determination of bulk density. –72 mesh size powdered biomass was poured into the container until the container was overflowed. After filling the container with the sample, it was tapped on a wooden table for approximately 10 times to allow the material to settle down. The excess material was removed by moving a steel roller across the top. The weight of the material with the container was recorded. The net weight of the sample was obtained by subtracting the weight of the empty container. The bulk density in g/cm^3 of the sample was calculated by the following formula.

$$\textit{Bulk density} = \frac{(Weight\ of\ the\ container\ and\ sample)-(weight\ of\ container)}{Volume\ of\ the\ container} \quad \textbf{(3.5)}$$

The bulk density in g/cm^3 as obtained by using Equation 3.5 is then multiplied by a conversion factor of 1000 to express it in the corresponding kg/m^3.

3.5 Ash Fusion Temperature Determination

Ash fusion temperature is a determining factor for selection of a fuel for combustion in boilers. The behaviour of any fuel's ash is vital when it is exposed to a very high temperature, i.e. boiler temperature. If the fusion temperature for a fuel is lower than boiler operation temperature, there is a chance of boiler slagging and fouling. Conventional fuel like coal and renewable fuel like biomass have ashes that form hard glassy slag better known as clinker that can pose a mechanical problem in combustion process. Therefore, the determination of ash fusion temperature is essential to design furnaces effectively. The following temperatures are recorded during the determination of ash fusion temperatures: (i) *initial deformation temperature (IDT)* i.e., the temperature at which first sign of change in shape occurs; (ii) *softening temperature (ST)* i.e., the temperature at which the sample starts shrinking and the corners of the sample melt, (iii) *hemispherical temperature (HT)* i.e., the temperature at which the cubical sample becomes hemispherical in shape, and (iv) *fluid temperature (FT)* i.e., the temperature at which the sample melts and lays flat as a fused mass **[41].**

The ash fusion temperatures of biomass ashes were calculated using a German standard test method *DIN: 51730* **[59].** Ashes of selected biomass were produced by heating the samples to a maximum 700 ^{0}C. Cubic ash samples of 3 mm size were put inside the Leitz high temperature microscope (make: Leica, Wetzlar, Germany) and heated up to a maximum temperature of 1450 ^{0}C. This microscope can be safely used up to the temperature of 1600^{0}C. It has an accuracy of ±5 ^{0}C and resolution of 1^{0}C. The external shape of the cubes was observed and the temperatures were noted during the deformation, shrinkage, and flow of the ash sample cubes.

Fig. 3.3: Leitz Heating Microscope

3.6 Ultimate Analysis: Determination of Chemical Composition

Ultimate analysis test provides a complete result as compared to the proximate analysis. Biomass contains a number of ash free organic components. The key components are carbon, oxygen, and hydrogen. Apart from these three major components, biomass also contains a small proportion of nitrogen and sulphur. The quantitative determination of carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) in biomass is defined as ultimate analysis. The elemental analysis was done using an elemental analyzer. In general practice, 200 mg of each sample were heated at 900 ^{0}C in presence of oxygen. During the experiment, carbon was transformed into CO_2, hydrogen into H_2O, sulphur into SO_2 and nitrogen into N_2. Carbon, hydrogen and sulphur were quantitatively identified using an *infra red detector,* while N_2 is deduced using a thermal conductivity detector **[56].**

In the present work, the elemental analysis of some selected biomass samples were determined by means of the CHN analyzer at Sophisticated Analytical Instrumentation Facility, Punjab University, Chandigarh, India.

Every measurement taken during an experimental work is associated with some sort of uncertainty that needs to be properly specified. The details of the Uncertainty in measurement are explained in the next section.

3.7 Uncertainty in Measurement

Uncertainty in measurement is the doubt that exists about the result of any measurement. Two numbers are needed to express the uncertainty. One is the width of the margin, or *interval.* The other is a *confidence level,* and states how sure we are that the true value is within that margin.

3.7.1 Standard Deviation

The usual way to quantify the spread of values is standard deviation. The standard deviation of a set of numbers tells us about how different readings typically are from the average of the set. The symbol 'σ' denotes the standard deviation and the complete process of calculating the estimated standard deviation for a series of *n* measurements can be expressed as **[60]**:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \qquad \textbf{(3.6)}$$

where, x_i = result of the *i*th measurement,

$\bar{x}$ = arithmetic mean of the *n* results considered.

3.7.2 Propagation of Uncertainty

The propagation of uncertainty is to combine measurements with the assumptions that as measurements are combined, uncertainty increases and hence the uncertainty propagates through the calculations.

When adding two measurements, the uncertainty in the final measurement is the sum of the uncertainties in the original measurements:

$$(\mathrm{A} \pm \delta A) + (B \pm \delta B) = (A + B) \pm (\delta A + \delta B) \tag{3.7}$$

When subtracting two measurements, the uncertainty is again equal to the sum of the uncertainties in the original measurements and is given by:

$$(\mathrm{A} \pm \delta A) - (B \pm \delta B) = (A + B) \pm (\delta A + \delta B) \tag{3.8}$$

When multiplying two measurements, the uncertainty in the final measurement is found by summing the percentage uncertainties of the original measurements and then multiplying that sum by the product of the measured values:

$$(\mathrm{A} \pm \delta A) \times (B \pm \delta B) = (AB)\left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B}\right)\right] \tag{3.9}$$

When dividing two measurements, the uncertainty in the final measurement is found by summing up the percentage uncertainties of the original measurements and then multiplying that sum by the quotient of the measured values and is given as follows **[60]**:

$$\frac{(\mathrm{A} \pm \delta A)}{(B \pm \delta B)} = \left(\frac{A}{B}\right)\left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B}\right)\right] \tag{3.10}$$

CHAPTER 4

REGRESSION ANALYSIS

4. REGRESSION ANALYSIS

Calorific value is one of the most significant aspects of a fuel. In case of biomass combustion, the design aspect of the boiler mainly depends upon the calorific value. It can be determined by two ways i.e., i) experimentally, and ii) analytically. The experimental methods are already discussed in the previous chapter. The chemical composition of biomass is generally calculated by *ultimate analysis* which needs special instruments and extremely trained and skilled personnel. In contrast, *proximate analysis* can be done using simpler equipments and a normally skilled person. The calorific value on the other hand is determined experimentally by a *calorimeter* which needs special skill to operate **[61]**. On the other hand, in analytical method regression equations are established to find the gross calorific value without conducting any fresh experiments. Gross calorific value (GCV) is a function of various variables associated with proximate and ultimate analyses. Based on proximate analysis data, GCV has been expressed as a function of four variables such as contents of ash (A), moisture (M), volatile matter (VM) and fixed carbon (FC) **[49]**. Similarly with the help of ultimate analysis data, regression equations have been developed for GCV in terms of four parameters like carbon content (C), hydrogen content (H), oxygen content (O) and nitrogen content (N) **[48]**. But data should be available from previously conducted experiments to establish these equations. In this project, a statistical technique called *regression analysis* is considered to establish equations using software called *Statistica*. The theoretical background of regression analysis and the procedure followed for developing regression equations are explained in this chapter.

4.1 Data Collection

From our experimental results, fifteen sets of data each related to proximate analysis and calorific value are available as discussed in Chapter 3. Similarly, there are nine sets of ultimate analysis data available for regression analysis. All these data obtained from our experimental work are utilized to establish the regression equations for determination of gross calorific value.

4.2 Regression Analysis

Regression analysis is commonly used for forecasting and prediction purposes. It is a statistical technique for examining relationship among different variables. Generally, it is used to develop a relationship between a dependent variable and one or more independent variables. The values of *independent variable(s)* are usually known and utilizing them the value of the *dependent variable* is predicted **[62].**

Regression analysis can be classified into two broad categories depending on the number of independent variables. They are *simple* and *multiple regression analyses.* The *simple regression analysis* has one independent variable whereas the *multiple regression analysis* has more than one. Besides that on the basis of relationship between dependent and independent variables, regression analysis can be classified into two groups such as, *linear regression analysis* and *nonlinear regression analysis.* The relationship between dependent and independent variables are of two types such as, *direct relationship* and *inverse relationship*. In direct relationship, there is a direct association between independent and dependent variables i.e., with increase in the value of independent variable, the dependent variable also increases. In this case, the slope of the graph is positive. On the other hand in inverse relationship, with increase in the value of independent variable, the dependent variable decreases. This relationship is characterized by a negative slope **[60].**

4.2.1 Linear Regression Analysis

Linear regression analysis is a statistical approximation in which a dependent variable is linearly related to one or more independent variables. When only one independent variable is considered, it is called as *simple linear regression analysis* and the corresponding relationship is as shown in Equation 4.1. Least square method is used to derive the linear equation which can be defined as a technique for fitting a straight line through a set of points in such a way that the sum of the squared vertical distances from all the N number of points to the line is minimized. The least square line approximating the set of points (X_1, Y_1), (X_2, Y_2)… (X_N, Y_N) has the equation as shown below **[63].**

$$Y = a_o + a_1 X \tag{4.1}$$

where, Y = dependent variable,

X = independent variable, and

a_0, a_1 = constant parameters.

The values of a_o and a_1 are obtained using the following two equations

$$a_o = \frac{(\sum Y)\,(\sum X^2) - (\sum X)(\sum XY)}{N \sum X^2 - \sum X^2}$$

$$a_1 = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N \sum X^2 - \sum X^2} \tag{4.2}$$

Now if more than one independent variable is taken into consideration, it is known as *multiple linear regression analysis*. More independent variables are considered to increase the accuracy of the estimate **[60]**. For p number of independent variables X, the dependent variable Y is expressed as

$$Y = a_o + a_1 X_1 + a_2 X_2 + \ldots + a_p X_p \qquad \textbf{(4.3)}$$

where, a_i is a constant parameter.

4.2.2 Nonlinear Regression Analysis

It is a form of regression analysis in which the parameters are modeled as per a function which is a nonlinear combination of dependent and independent variables. When only one independent variable is considered, it is called as *simple nonlinear regression analysis*. When more than one independent variable is taken into consideration, it is known as *multiple nonlinear regression analysis.* There are a number of nonlinear regression functions such as, exponential, hyperbolic, geometric, Gompertz, etc. as shown below **[63]**:

Exponential function: $Y = ab^X$ **(4.5)**

Hyperbolic function: $Y = \frac{1}{a_o + a_1 X}$ **(4.6)**

Geometric function: $Y = aX^b$ **(4.7)**

Gompertz function: $Y = pq^{b^X}$ **(4.8)**

Least square method in nonlinear regression analysis is usually not easy. Therefore, the curve fitting is often done using iterative procedures based on algorithms like Gauss-Newton, steepest descent and Levenberg-Marquardt's method **[64].**

4.3 Standard Error of Estimate

The standard error of estimate (S) in regression analysis is used to measure the reliability of the estimating equation. In linear regression, a line is considered to be a more reliable estimator if the data points are close to the regression line than when the points are farther away from the line. Like standard deviation, the standard error of estimate is a measure of dispersion. The standard deviation measures the dispersion of a set of observations about their mean. But, the standard error of estimate measures the variability, or scatter of the observed values around the regression line in simple regression. In case of multiple regression analysis, it estimates the dispersion around the multiple-regression plane. The standard error of estimate is defined by the following formula **[60]:**

$$S = \sqrt{\frac{\sum(Y - \hat{Y})^2}{N-k-1}} \qquad \textbf{(4.10)}$$

where, Y = sample values of dependent variable,

$\hat{Y}$ = corresponding estimated values from the regression equation,

N = number of data points in the sample, and

k = number of independent variables.

The denominator of this equation indicates that in multiple regression analysis with k independent variables, the standard error has N-k-1 degrees of freedom. When S = 0, the estimating equation is considered as a perfect estimator of the dependent variable Y. In this case, all the data points would lie right on the regression line.

The standard error of estimate can be used like standard deviation. Assuming the observed points are normally distributed around the regression line, one can expect to find

68.28% of the points within ±1S, 95.45% of the points within ±2S, and 99.73% of the points within ±3S **[60]**.

4.4 Correlation Analysis

Correlation analysis is a statistical tool that describes the degree to which one variable is linearly related to another. In regression analysis, it is used to measure how well the regression line explains the variation of the dependent variable. There are two measures for finding out correlation between two variables, viz. *coefficient of determination* and *coefficient of correlation* which are explained below **[60]**.

4.4.1 Coefficient of Determination

In case of simple regression analysis, the coefficient of determination is a measure of degree of linear relationship between two variables X and Y. It is also called as *R-Squared value* and denoted by R^2. It is developed from two types of variations of Y values i.e., around the fitted regression line and around their own mean as shown below.

$$R^2 = 1 - \frac{\sum(Y-\hat{Y})^2}{\sum(Y-\bar{Y})^2} \tag{4.11}$$

where, $\sum(Y-\hat{Y})^2$ = variation of the Y value around the regression line,

$\sum(Y-\bar{Y})^2$ = variation of Y values around their own mean.

When the value of R^2 is 1, every data point lies on the regression line which suggests there is a perfect correlation between X and Y. When the value of R^2 is 0, no data point lies on the regression line which shows there is no correlation between X and Y. R-squared value close to 1 indicates a strong correlation between the variables while R-squared value near 0 means there is a little correlation between the variables **[60].**

Similarly in multiple regression analysis, it is called as *coefficient of multiple determination* and is used to measure the strength of the relationship among more than two variables**.**

4.4.2 Coefficient of Correlation

The coefficient of correlation is the square root of coefficient of determination. It is also called *R value* and denoted by *R*. When the slope of the estimating equation is positive, *R* is the positive square root whereas in case of negative slope, *R* is the negative square root. Thus, in case of simple regression analysis, the sign of *R* indicates the direction of the relationship between two variables. The coefficient of correlation is more difficult to interpret than R^2. This is the reason why R^2 is generally considered for the evaluation of regression equations **[60].**

4.5 Error Evaluation of Regression Equation

Accuracy of the derived regression equations were determined by two statistical parameters, i.e. average bias error (ABE) and average absolute error (AAE), which are defined as:

$$ABE = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{Predicted\ value - Measured\ value}{Measured\ value} \right) \times 100\% \qquad \textbf{(4.7)}$$

$$AAE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{Predicted\ value - Measured\ value}{Measured\ value} \right| \times 100\% \qquad \textbf{(4.8)}$$

where, N = number of data points.

Smaller the AAE, smaller is the error of the derived regression equation. While a positive ABE means the predicted value is higher as compared to the calculated value **[61].**

CHAPTER 5

RESULTS AND DISCUSSION

5. RESULTS AND DISCUSSION

5.1 Proximate Analyses of Studied Biomass Components

Studies of proximate analyses of fuels are important because they give an approximate idea about the energy values and extent of pollutant emissions during combustion. The proximate analyses and gross calorific values of different components of Banyan, Neem, Mahua, Pippal and Eucalyptus biomass species are outlined in Table 5.1. In addition, the proximate analysis and gross calorific value of a non-coking semi bituminous type coal collected from Ananta mines are also shown in Table 5.1.

It is evident from Table 5.1 that the ash contents in both cases of Banyan and Neem biomass species; their leaves have the highest ash contents followed by their branches and barks. In both cases of Pippal and Eucalyptus biomass species, barks of both the species have the highest ash contents followed by their branches and leaves. In Mahua biomass species, the bark contains the highest ash followed by its leaf and branch. The leaf of Eucalyptus has the lowest ash content (i.e., 5 wt.%) while Mahua bark has the highest ash content (i.e., 23 wt.%) among all the 15 studied biomass samples. Moreover ash contents of all the biomass components are found to be much less than that of the coal sample which has ash content of 41 wt.%.

From Table 5.1 it can be noticed that, in Banyan biomass species, the fixed carbon content in the bark is the highest and is followed by its leaf and branch. In case of Neem biomass species, the bark has the highest fixed carbon content followed by its branch and leaf. In Pippal biomass species, the leaf has higher fixed carbon content followed by its bark and branch. Mahua leaf has greater fixed carbon content in contrast to its bark and branch. In Eucalyptus plant species, the fixed carbon content in branch is highest followed by its leaf and bark. Overall, Neem bark contains the highest amount of fixed carbon content (i.e., 25 wt.%) among all the 15 studied samples while its leaf contains the least percentage of fixed carbon content (i.e., 13 wt.%). It can be observed that fixed carbon content of coal is higher as compared to the biomass samples.

Table 5.1: Proximate Analyses and Gross Calorific Values of Different Components of Studied Biomass Species and Coal

Component	**Proximate analysis (wt.%, dry basis)**				**Gross calorific value (dry basis) (MJ/kg)**
	Moisture content	**Ash content**	**Volatile matter**	**Fixed carbon content**	
Banyan					
Leaf	8	17	57	18	15.817
Bark	13	10	56	21	15.893
Branch	12	14	60	14	13.443
Neem					
Leaf	9	20	58	13	14.059
Bark	12	7	56	25	17.856
Branch	11	12	62	15	14.285
Pippal					
Leaf	10	9	59	22	19.711
Bark	11	20	51	18	13.862
Branch	13	11	60	16	15.775
Mahua					
Leaf	9	14	57	20	19.414
Bark	10	23	53	14	14.783
Branch	8	10	68	14	17.295
Eucalyptus					
Leaf	8	5	68	19	22.139
Bark	10	11	63	16	17.505
Branch	8	9	62	21	18.840
Coal					
Ananta	8	41	21	30	17.773

Table 5.1 shows that the moisture content is more or less same among all the 15 studied biomass samples which range between 8 wt.% to 13 wt.%. The bark of Banyan and branch of Pippal has the highest moisture content (i.e., 13 wt.%) while leaves of Banyan and

Eucalyptus, and branches of Mahua and Eucalyptus have the lowest moisture content (i.e., 8 wt.%) among all the 15 studied biomass samples. Moisture content in coal is also the lowest.

Also the volatile matter content, as observed from Table 5.1, shows a very similar distribution in leaves and barks of Neem and Banyan biomass species which range between 56 wt.% to 58 wt.%. But their branches contain higher amount of volatile matter compared to their other components. It can be observed that the branches of all the studied biomass species have the highest volatile contents while their barks have the lowest except Eucalyptus. In Eucalyptus plant species, the leaf has the highest volatile matter content whereas its branch has the lowest. The branch of Mahua and leaf of Eucalyptus plant species have the highest volatile matter content (i.e., 68 wt.%) while bark of Pippal has the lowest volatile matter content (i.e., 51 wt.%) among all the 15 studied biomass species. In case of the coal sample, volatile matter content is very low as compared to the biomass species.

High volatile and fixed carbon contents make ignition easier at low temperatures, inferring high reactivity and enhancing the process of combustion. High ash contents may cause deposit of slag, creating higher thermal resistance to heat transfer and decreasing combustion efficiency. High amount of moisture adds weight to the fuel, so it reduces its effective bulk density while increases transport costs and storing size. High amount of ash and moisture decreases the energy value of a fuel **[49]**.

5.2 Gross Calorific Values of Studied Biomass Components

Power generation potential of any energy sources can be evaluated on the basis of its calorific value. It provides a rough idea about the quality of fuel for power production. This is why calorific value of any fuel source is an important criterion for selection of fuel during electricity generation in power plants.

The leaf of Banyan biomass species is considered for the sample calculation of its gross calorific value. Water equivalent of the Bomb Calorimeter used for the experiment is 1987 cal/^{0}C. The maximum rise in temperature was observed to be 1.29 ^{0}C. The initial weight of the sample was measured as 0.67g. Heat released by cotton thread and fused wire used inside the calorimeter is specified as 48 kcal/kg.

So, gross calorific value of Banyan leaf = $\frac{1987\times1.29}{0.67} - 48$ = 3778 kcal/kg.

Multiplying the above by the conversion factor of 4.1868×10^{-3} to express it in the corresponding SI unit of MJ/kg, we get 15.817 MJ/kg. Similarly, gross calorific values for other biomass species were calculated and are presented in Table 5.1.

Comparison of the calorific values presented in Table 5.1 shows that the leaf and bark components of Banyan biomass species are more or less similar with around 15.8 MJ/kg. Banyan branch has the lowest calorific value in comparison to its other components. In Neem biomass species, the bark has the highest calorific value followed by its branch and leaf. It is interesting to observe that leaves of Pippal, Mahua and Eucalyptus biomass species show higher calorific values compared to their respective branches and barks. It is worthy to note that among all the studied biomass samples, leaf of Eucalyptus shows the highest calorific value (i.e., 22.139 MJ/kg) followed by leaves of Pippal and Mahua. Among all the components, the branch of Banyan has the lowest calorific value i.e., 13.443 MJ/kg. Gross calorific value of the coal sample was found to be 17.773 MJ/kg.

Uncertainties in measurements of proximate analyses and gross calorific values have been calculated and presented in Table 5.2. Every experiment is repeated thrice. The ash content of Banyan leaf is taken for the sample calculation of uncertainty in measurement. The three experimental values of ash contents of Banyan leaf in wt.% are 17, 18 and 16. For this set of values, the mean (µ) and standard deviation (σ) are calculated as

$$\mu = \frac{17+18+16}{3} = 17$$

$$\sigma = \sqrt{\frac{(17-17)^2+(17-18)^2+(17-16)^2}{3-1}} = 1$$

Now considering 95% confidence level, the uncertainty in measurement of ash content in Banyan leaf = 17 ± 2× 1 = 17 ± 2 wt.%.

Unlike above, the calculation of uncertainty in measurement of gross calorific value is different as it involves readings of more than one variable i.e. maximum rise in temperature inside Bomb Calorimeter (say, A) and weight of sample (say, B). Taking Banyan leaf for sample calculation, its three weights were 0.67 g, 0.68 g and 0.68 g and the corresponding maximum rise in temperatures were observed to be 1.29 ^{0}C, 1.28 ^{0}C and 1.34 ^{0}C. For these two sets of readings, the mean (µ) and standard deviation (σ) are calculated as

$$\mu_B = \frac{0.67+0.68+0.68}{3} = 0.6767 \text{ g}$$

$$\sigma_B = \sqrt{\frac{(0.6767\ -0.67)^2+(0.6767\ -0.68)^2+(0.6767\ -0.68)^2}{3-1}} = 0.00577 \text{ g}$$

$$\mu_A = \frac{1.29+1.28+1.34}{3} = 1.303\ ^0\text{C}$$

$$\sigma_A = \sqrt{\frac{(1.303\ -1.29)^2+(1.303\ -1.28)^2+(1.303\ -1.34)^2}{3-1}} = 0.03215\ ^0\text{C}$$

Here, at 95% confidence level: $A \pm \delta A = \mu_A \pm 2 \times \sigma_A = 1.303 \pm 2{\times}0.032 = 1.303 \pm 0.064\ ^0\text{C}$ and $B \pm \delta B = \mu_B \pm 2 \times \boldsymbol{\sigma_B} = 0.6767 \pm 2{\times}0.0058 = 0.6767 \pm 0.0116$ g. Since, W.E. and heat released by cotton thread and fused wire are constant terms, uncertainty in measurement of GCV using Equations 3.4 and 3.10

$$= \text{W.E.} \times \left(\frac{(\mathrm{A} \pm \delta A)}{(B \pm \delta B)}\right) - \text{(heat released by cotton thread + heat released by fused wire)}$$

$$= 1987 \times \left(\frac{A}{B}\right)\left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B}\right)\right] - (48)$$

$$= 1987 \times \left(\frac{1.303}{0.6767}\right)\left[1 \pm \left(\frac{0.064}{1.303} + \frac{0.0116}{0.6767}\right)\right] - 48$$

$$= 3777.97 \pm 205 \text{ kcal/kg}$$

Converting it into SI units, the uncertainty in measurement of GCV of Banyan leaf was found to be 15.817±0.860 MJ/kg. Similarly, uncertainty in measurement was calculated for all other samples and is shown in Table 5.2.

Table 5.2: Uncertainty in Measurements of Proximate Analyses and Gross Calorific Values of Different Components of Studied Biomass Species and Coal

Component	**Proximate analysis (wt.%, dry basis)**				**Gross calorific value (dry basis) (MJ/kg)**
	Moisture content	**Ash content**	**Volatile matter**	**Fixed carbon content**	
Banyan					
Leaf	8±2	17±2	57±0	18±4	15.817±0.860
Bark	13±2	10±2	56±2	21±2	15.893±0.238
Branch	12±0	14±4	60±4	14±0	13.443±0.033
Neem					
Leaf	9±0	20±2	58±2	13±2	14.059±0.187
Bark	12±2	7±2	56±2	25±2	17.856±0.286
Branch	11±0	12±2	62±2	15±0	14.285±0.144
Pippal					
Leaf	10±2	9±0	59±4	22±2	19.711±0.824
Bark	11±2	20±5	51±4	18±4	13.862±1.977
Branch	13±2	11±2	60±3	16±2	15.775±0.479
Mahua					
Leaf	9±2	14±2	57±4	20±2	19.414±0.486
Bark	10±2	23±3	53±5	14±4	14.783±0.406
Branch	8±2	10±2	68±2	14±4	17.295±0.572
Eucalyptus					
Leaf	8±0	5±0	68±3	19±0	22.139±1.004
Bark	10±2	11±2	63±2	16±4	17.505±2.043
Branch	8±0	9±2	62±2	21±2	18.840±0.963
Coal					
Ananta	8±2	41±2	21±0	30±2	17.773±0.228

5.3 Determination of Bulk Densities

Bulk densities of different components of all the studied biomass species and the coal sample were determined and are listed in Table 5.3. As per this table, leaves of all the biomass species have lower bulk densities as compared to their barks and branches. In case of Banyan, Pippal and Mahua biomass species, the barks have the highest bulk densities followed by their branches and leaves. In Neem and Eucalyptus biomass species, both the branches have the highest bulk densities followed by their barks and leaves. It is worthy to note that among all the studied biomass species, branch of Eucalyptus has the highest bulk density (i.e., 366 kg/m^3) while leaf of Neem has the lowest (i.e., 213 kg/m^3). In case of the coal sample, the bulk density is very high as compared to all the biomass species (i.e., 690 kg/m^3).

The bulk densities of agricultural biomass species lie in a range of 40-200 kg/m^3 **[65]**. When bulk densities of the presently studied woody biomass species are compared with the agricultural biomass species, it can be observed that all the studied woody biomass species have higher bulk densities. However, the bulk densities of the presently studied biomass species have lower values as compared to the studied coal sample. For this reason, biomass has to be ground and compacted into dense and durable pellets or briquettes in order to facilitate handling, storage and transportation.

Uncertainty in measurements of bulk densities of different biomass species have been calculated and shown in Table 5.3. The sample calculation of its uncertainty is same as that already shown for ash content of Banyan leaf in Section 5.2.

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Table 5.3: Bulk Densities and Uncertainty in Measurements of Bulk Densities of Different Components of Biomass and Coal

Components	**Bulk Density (kg/m^3)**	**Uncertainty in Measurement of Bulk Density (kg/ m^3)**
Banyan		
Leaf	245	245±10
Bark	282	282±7
Branch	279	279±6
Neem		
Leaf	213	213±6
Bark	273	273±0
Branch	292	292±5
Pippal		
Leaf	227	227±10
Bark	347	347±5
Branch	306	306±0
Mahua		
Leaf	296	296±5
Bark	333	333±10
Branch	319	319±5
Eucalyptus		
Leaf	310	310±0
Bark	343	343±5
Branch	366	366±5
Coal		
Ananta	690	690±10

5.4 Ash Fusion Temperature Determinations of Selected Biomass Components

Ash fusion temperatures (AFTs) of six selected biomass samples comprising of two samples from each of the three components (i.e., leaf, bark and branch) were measured. The components with higher ash content were selected for AFT measurement i.e., leaves of Banyan and Neem, barks of Pippal and Mahua, and branches of Banyan and Pippal. The results of ash fusion temperatures of the studied biomass species have been listed in Table 5.4.

Table 5.4: Ash Fusion Temperatures of Different Biomass Samples

Biomass ash samples	**Ash fusion temperatures, ^{0}C**			
	IDT	**ST**	**HT**	**FT**
Banyan leaf	1165	1190	1230	1253
Neem leaf	1203	1231	1245	1254
Pippal bark	1157	1188	1221	1308
Mahua bark	1218	1248	1260	1272
Banyan branch	995	1077	1193	1282
Pippal branch	1016	1329	>1450	>1450

IDT: Initial deformation temperature; ST: Softening temperature; HT: Hemispherical temperature; FT: Flow temperature.

As a representative sample, the photograph of ash sample of Pippal bark just before the start of the experiment for measurement of ash fusion temperatures is shown in Fig. 5.1.

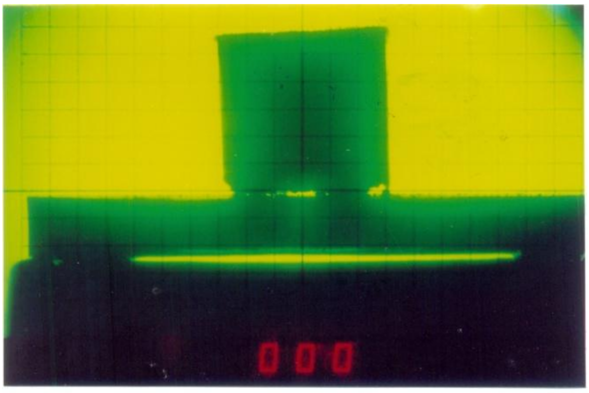
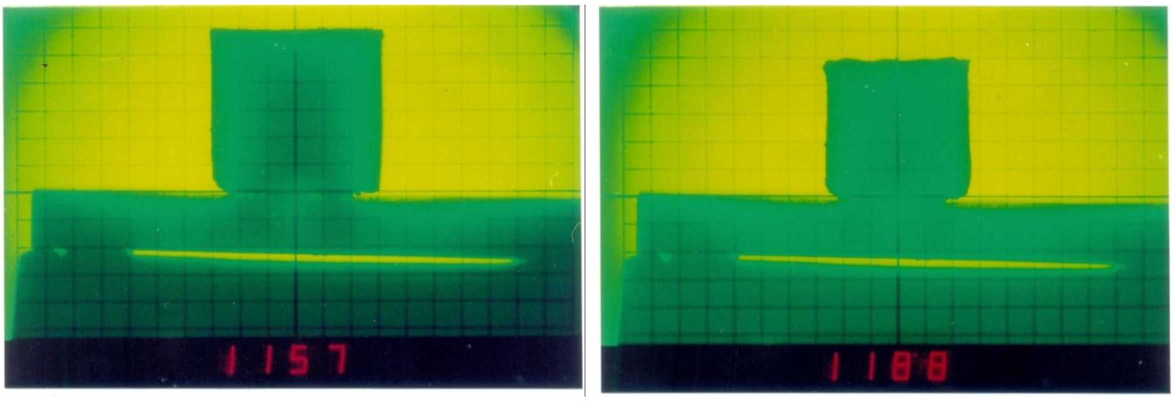
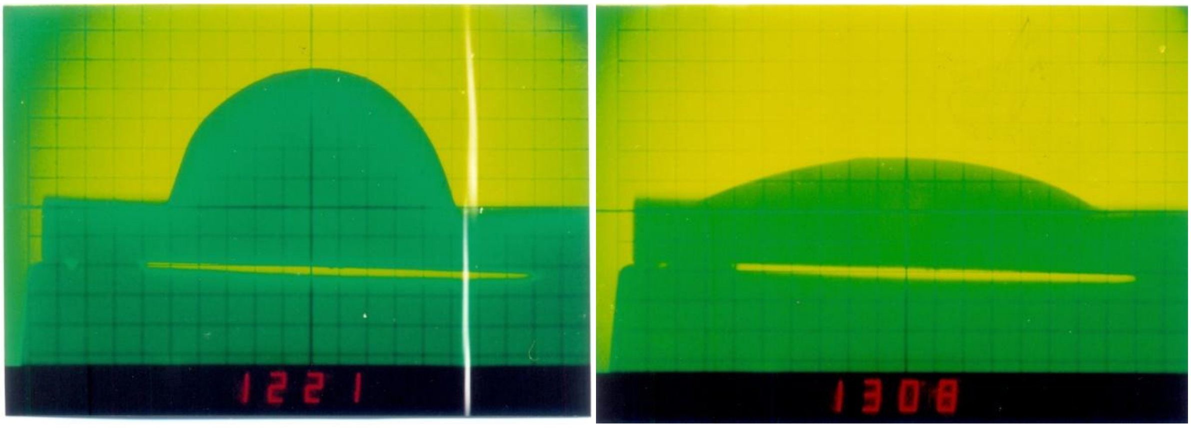


Fig. 5.1: Ash of Pippal Bark before Experiment

Subsequently, four more figures of this sample taken at four different stages during the experiment are shown in Fig. 5.2.



(a) Initial Deformation Temperature (b) Softening Temperature



(c) Hemispherical Temperature (d) Fluid Temperature

Fig. 5.2: Ash Fusion Temperatures of Pippal Bark

The temperature at which shrinkage in the cubic ash sample occurs is noted down and it is called initial deformation temperature (IDT), as shown in Fig. 5.2(a). Fig. 5.2(b) shows rounding of the corners of the cubic ash sample and this is represented as softening temperature (ST). In Fig. 5.2(c), the hemispherical shape of the cubic ash sample obtained during the process of heating has been presented. This is the hemispherical temperature (HT) of the ash sample. In Fig. 5.2(d), the melted ash sample has completely spread over the surface and the concerned temperature is noted down. This is the fluid temperature (FT) of the ash sample.

The results show that the value of IDT is in the range of 995-1218 ^{0}C. Similarly, the value of ST ranges from 1077 to 1329 ^{0}C. The values of HT and FT for Pippal branch are above 1450 ^{0}C whereas that of the rest of the components lie in the ranges 1193-1260 ^{0}C and 1253-1308 ^{0}C respectively. Due to limitation of the instrument, measurement above 1450 ^{0}C could not be done. Therefore, those two reading are recorded as >1450 ^{0}C in Table 5.3. In order to ensure no formation of agglomerated mass inside the combustors, the IDT of ash should be at least 150 ^{0}C more than the operation temperature of the boiler. The results suggest that IDTs of all the studied biomass samples are well above the biomass based boiler operating temperature which is around 800-900 ^{0}C **[44]**. This confirms that the use of none of the studied biomass samples would be problematic during combustion in boilers. Further, since 1450 is well above 900, it is felt not necessary to measure exact values of HT and FT of Pippal branch. Different colors shown in Fig. 5.2 have no significance so far as values are concerned. In this equipment, the sample is always shown in green with a yellow background to facilitate the observation of any shape change in the sample.

Ash fusion temperature is broadly utilized as a measure of ash fusibility and its agglomeration attributes. The designers and operators can have prior knowledge about the probable clinker formation during combustion of solid fuels in the boilers. Bed agglomeration during combustion of biomass/coal in a boiler disturbs the combustion process and the boiler has to face an unscheduled shutdown. During boiler operation, the ash having low AFT fuses partially and adheres to the char surface reducing its combustibility forming agglomerated mass with the interruption in air supply, and finally stops combustion operation. In order to ensure no formation of agglomerated mass inside the combustors, the IDT of ash should be at least 150 ^{0}C more than the operation temperature of the boiler **[44]**.

5.5 Chemical Characteristics of Blends of Coal and Biomass

The results presented in Tables 5.5 and 5.6 are related with co-firing technology. In the present project work, the studies on coal-biomass mixed briquette such as coal-Pippal branch and coal-Mahua bark were considered because they have been found to have higher ash fusion temperatures. As it is clear from Tables 5.5 and 5.6, the ash contents in the coal-biomass mixed briquettes decreased while their volatile matter contents increased with an increase in biomass content in the briquette. This is undoubtedly due to lower ash content and higher volatile matter content in the biomass sample. It is also evident from these two tables that the fixed carbon contents in the coal-biomass mixed briquette increased with increase in biomass content in the briquette. This is because of much lower ash content in the biomass samples.

Tables 5.5 and 5.6 also clearly indicate that the addition of biomass in the coal in the studied range (0-15%) has a very negligible effect on the energy value of the coal. This is because of no appreciable change in the total carbon and hydrogen contents of the samples. The elements carbon and hydrogen mainly contribute to the energy value of the carbonaceous material.

Similarly considering two more blends of coal and biomass such as coal-Mahua leaf and coal-Pippal leaf for analyses of proximate and calorific value. It is well observed from Tables 5.7 and 5.8 that, with increase in biomass content in the blends, there is a decrease in ash content, while there is an increase in the volatile and fixed carbon content. The study clearly indicates that the addition of biomass with coal has a very insignificant effect on the energy value.

It is always beneficial to use a fuel which has low ash content for smooth boiler operation. It is observed that when biomass is mixed with coal, the ash content decreases substantially. Therefore, the use of biomass with coal in co-firing process would be very much helpful in mitigation of emission and bed agglomeration problems. It is evident that the requirement of coal decreases with increase in the percentage of biomass in the blends which is a positive step towards minimizing the use of conventional fossil fuels like coal since biomass is abundantly available.

Table 5.5: Proximate Analysis and Gross Calorific Values of Coal-Biomass (Pippal Branch) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8	41	21	30	17.773
90 : 10	5	29	32	34	17.517
85 : 15	7	27	31	35	17.388

Table 5.6: Proximate Analysis and Gross Calorific Values of Coal-Biomass (Mahua Bark) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8	41	21	30	17.773
90 : 10	6	30	30	34	17.412
85 : 15	7	28	30	35	17.257

Table 5.7: Proximate Analysis and Calorific Values of Coal-Biomass (Pippal Leaf) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8	41	21	30	17.773
90 : 10	9	30	29	32	17.325
85 : 15	10	28	29	33	17.219

Table 5.8: Proximate Analysis and Calorific Values of Coal-Biomass (Mahua Leaf) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8	41	21	30	17.773
90 : 10	6	30	32	32	17.387
85 : 15	7	28	32	33	17.241

Uncertainty in measurements of the chemical characteristics of studied blends of coal and biomass are calculated and presented in Tables 5.9-5.12. The calculations are same as that described in section 5.2.

Table 5.9: Uncertainty in Measurement of Proximate Analysis and Gross Calorific Values of Coal-Biomass (Pippal Branch) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8 ± 2	41 ± 2	21 ± 0	30 ± 2	17.773 ± 0.228
90 : 10	5 ± 0	29 ± 2	32 ± 0	34 ± 2	17.517 ± 0.289
85 : 15	7 ± 2	27 ± 0	31 ± 2	35 ± 0	17.388 ± 0.321

Table 5.10: Uncertainty in Measurement of Proximate Analysis and Gross Calorific Values of Coal-Biomass (Mahua Bark) Mixed Briquette in Different Ratios

Coal : biomass ratio	Proximate analysis, wt % dry basis				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	8 ± 2	41 ± 2	21 ± 0	30 ± 2	17.773 ± 0.228
90 : 10	6 ± 2	30 ± 0	30 ± 0	34 ± 2	17.412 ± 0.347
85 : 15	7 ± 2	28 ± 2	30 ± 0	35 ± 4	17.257 ± 0.361

Table 5.11: Uncertainty in Measurement of Proximate Analysis and Gross Calorific Values of Coal-Biomass (Pippal Leaf) Mixed Briquette in Different Ratios

Coal : biomass ratio	**Proximate analysis, wt % dry basis**				**Gross calorific value (MJ/kg)**
	Moisture	**Ash**	**Volatile matter**	**Fixed carbon**	
100 : 0	8±2	41±0	21±2	30±2	17.773±0.228
90 : 10	9±0	30±2	29±2	32±0	17.325±0.365
85 : 15	10±0	28±0	29±2	33±2	17.219±0.248

Table 5.12: Uncertainty in Measurement of Proximate Analysis and Gross Calorific Values of Coal-Biomass (Mahua Leaf) Mixed Briquette in Different Ratios

Coal : biomass ratio	**Proximate analysis, wt % dry basis**				**Gross calorific value (MJ/kg)**
	Moisture	**Ash**	**Volatile matter**	**Fixed carbon**	
100 : 0	8±2	41±2	21±0	30±2	17.773±0.228
90 : 10	6±0	30±2	32±0	32±2	17.387±0.249
85 : 15	7±2	28±2	32±2	33±4	17.241±0.325

5.6 Ultimate Analyses of Selected Biomass Components

The study of ultimate analyses of different components of biomass species is essential because it gives an idea about the contents of different elements, such as carbon (C), hydrogen (H), nitrogen (N) and oxygen (O). C and H are exothermically oxidized to CO_2 and H_2O, in the expected case of complete combustion so they contribute positively to gross calorific value, while O is reduced and contributes negatively to it. N is almost totally converted to gaseous N_2 and NOx and least affects the gross calorific value **[48]**. Carbon has calorific value of approximately 33.829 MJ/kg while hydrogen has calorific value of around 144.444 MJ/kg and both play a vital role in determining the calorific value of a fuel **[40].**

The results obtained from the ultimate analysis of nine different samples comprising of three components (i.e., leaf, branch and bark) each of three biomass species (i.e., Banyan, Pippal and Mahua) have been shown in Table 5.13. Gross calorific values of all the above nine different biomass samples are also shown in this table to facilitate comparative study.

It is observed from this table that Banyan bark has the highest hydrogen content and also the highest gross calorific value among all its components. The similar type of result is also seen in leaves of other two biomass species i.e., Pippal and Mahua. Thus, the gross calorific value is observed to have direct relationship with hydrogen content. This may be due to the fact that hydrogen has a gross calorific value much higher compared to other elements. The same type of direct relationship is observed between gross calorific value and the carbon content in Mahua. Although in case of Banyan, the leaf has the highest carbon content but the bark has the highest gross calorific value. But the difference between the results of leaf and bark of Banyan are negligible. Also in case of Pippal, branch has high carbon content while leaf has the highest gross calorific value. This may be due to the fact that higher hydrogen content in leaf is the dominant factor. Further, all the three components of Banyan biomass show approximately similar chemical compositions. Thus, it is worthy to note that the higher calorific values of each component of Banyan, Mahua and Pippal, and their corresponding chemical compositions, particularly C and H concentration are also high as compared to other components of respective species. The above variation in calorific values of plant components is undoubtedly related to the combined effects of their C and H contents which play a vital role in selection of a fuel.

Table 5.13: Ultimate Analyses and Corresponding Gross Calorific Values of Biomass Samples

Components	**Ultimate analysis (wt %, dry basis)**				**Gross calorific value (MJ/kg)**
	Oxygen	**Nitrogen**	**Carbon**	**Hydrogen**	
Banyan					
Leaf	45.831	1.193	44.147	5.102	15.817
Bark	42.098	1.718	43.301	5.193	15.893
Branch	44.362	1.221	42.592	4.720	13.443
Pippal					
Leaf	49.877	1.172	38.034	4.942	19.711
Bark	44.214	0.996	37.350	4.049	13.862
Branch	51.192	1.284	42.303	4.829	15.775
Mahua					
Leaf	48.075	0.984	43.696	5.323	19.414
Bark	50.799	1.046	38.855	4.487	14.783
Branch	47.254	1.566	40.496	4.807	17.295

5.7 Regression Analysis

The regression analysis has been done to establish a relationship between gross calorific value and all other variables associated with proximate and ultimate analyses of the studied biomass species. The ranges of data points considered for development of regression equations are as follows. When proximate analysis values were considered, the moisture content value ranges from 8% to 13%, the ash content ranged in between 5% to 23%, volatile matter range was in between 51% to 68% and fixed carbon ranged from 13% to 25% (all values are in wt.% on dry basis). When ultimate analysis values were considered, the carbon content ranged from 37.350% to 44.147%, hydrogen content ranged from 4.049% to 5.323%, oxygen content was from 42.098% to 51.192% and nitrogen content had the range of 0.984% to 1.718% as obtained from ultimate analysis (here also, all values are in wt.% on dry basis). The experimentally determined gross calorific values varied in the range of 13.443 MJ/kg to 22.139 MJ/kg. The details of regression analysis results are discussed in next two sub-sections.

5.7.1 Regression Analysis using Proximate Analyses Data

All the four variables associated with proximate analysis i.e., percentage contents of fixed carbon (FC), volatile matter (VM), ash (A) and moisture (M) have been considered for finding their regression equations with gross calorific value (GCV) using *Statistica* software package. Assuming linear regression, no regression equation could be established by this software when all the above four independent variables was considered together. Since it is reported in literature that volatile matter and fixed carbon contents largely affect the calorific value while moisture and ash contents have insignificant effects, these two variables were dropped in subsequent stages **[49].**

First, the moisture content was dropped and the regression equation involving rest of the three variables was obtained as shown below.

$$GCV = -49.02 + 0.968 \times FC + 0.719 \times VM + 0.459 \times A \tag{5.1}$$

Similarly, the regression equation involving three variables after dropping ash content was obtained as shown below:

$$GCV = -3.08 + 0.509 \times FC + 0.26 \times VM - 0.459 \times M \tag{5.2}$$

Then, both the moisture and ash contents were dropped and the corresponding equation involving fixed carbon and volatile matter was found to be

$$GCV = -11.8 + 0.502 \times FC + 0.331 \times VM \tag{5.3}$$

Two more regression equations were obtained taking only one variable at a time i.e., fixed carbon or volatile matter as given below.

$$GCV = 9.29 + 0.419 \times FC \tag{5.4}$$

$$GCV = 1.19 + 0.262 \times VM \tag{5.5}$$

In Equations 5.1-5.5, GCV is the predicted gross calorific value in MJ/kg, FC is fixed carbon content in wt.%, VM is volatile matter content in wt.%, A is the ash content in wt.% and M is the moisture content in wt.%.

For all the Equations 5.1-5.5 developed using regression analysis, the statistical performance measures such as, R-squared value (R^2), R value (R), standard error of estimate (S), average bias error (ABE) and average absolute error (AAE) were computed and shown in Table 5.14.

Table 5.14: Developed Linear Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Proximate Analysis Data and Their Statistical Performance Measures

Eq. No.	**Developed equation**	**R-squared value (R^2)**	**R value (R)**	**Standard error of estimate (S)**	**Average bias error (ABE) (in %)**	**Average absolute error (AAE) (in %)**
5.1	$GCV = -49.02 + 0.968 \times FC + 0.719 \times VM + 0.459 \times A$	0.811	0.901	1.251	0.190	5.785
5.2	$GCV = -3.08 + 0.509 \times FC + 0.26 \times VM - 0.459 \times M$	0.809	0.899	1.252	0.435	5.851
5.3	$GCV = -11.8 + 0.502 \times FC + 0.331 \times VM$	0.721	0.849	1.448	0.735	6.357
5.4	$GCV = 9.29 + 0.419 \times FC$	0.343	0.586	2.137	-1.352	6.866
5.5	$GCV = 1.19 + 0.262 \times VM$	0.245	0.495	2.291	1.734	10.462

As evident from Table 5.14, Equations 5.1 and 5.2 have high R^2 values i.e., 0.811 and 0.809. The R^2 values of these two equations are close to 1 which suggests that there exists a strong correlation between the dependent variable and independent variables. The S values of these equations are 1.251 and 1.252. The ABE of these equations are well below 1% while the AAE is below 6% which is acceptable **[48]**. Although Equation 5.3 has high R^2 value and lower S and ABE value, its AAE value is above 6% which is unacceptable. On the other hand, Equations 5.4 and 5.5 have low R^2 values of 0.343 and 0.245 respectively which are nearer to 0. This suggests that FC and VM have weak correlation with GCV when they are taken separately. The standard errors of estimate of these two equations are high and their values are above 2. Higher S values suggest a greater deviation of data points from the regression line. Further, ABE and AAE of Equations 5.4 and 5.5 are very high compared to the other three equations. Therefore, with lower R^2 value, higher S value and higher percentage of errors in terms of ABE or AAE, Equations 5.4 and 5.5 cannot be considered for prediction of GCV. While with lower values of ABE and AAE, lower S value and higher R^2 value, Equations 5.1 and 5.2 can be considered for estimation of gross calorific values of biomass samples from their proximate analysis data. Out of all regression equations developed, Equation 5.1 is found to be the best regression equation developed as it has the highest R^2 value of 0.811, lowest ABE value (i.e., 0.190) and lowest AAE value (i.e., 5.785). The R values of all the regression equations are found to be positive which suggests that the slope of regression line is positive for all the cases.

Similarly considering nonlinear regression analyses, following equations have been developed using proximate analyses data.

Table 5.15: Developed Nonlinear Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Proximate Analysis Data and Their Statistical Performance Measures

Eq. No.	**Developed equation**	**R-squared value (R^2)**	**R value (R)**	**Standard error of estimate (S)**	**Average bias error (ABE) (in %)**	**Average absolute error (AAE) (in %)**
5.6	$GCV = -1138.67 + 19.252 \times A + 26.469 \times VM + 25.033 \times FC - 0.055 \times A^2 - 0.239 \times A \times VM - 0.199 \times A \times FC - 0.152 \times VM^2 - 0.267 \times VM \times FC - 0.164 \times FC^2$	0.887	0.941	1.425	12.472	12.5
5.7	$GCV = 95.048 - 2.406 \times VM - 2.568 \times FC + 0.015 \times VM^2 + 0.058 \times VM \times FC - 0.007 \times FC^2$	0.835	0.913	1.285	0.949	4.911
5.8	$GCV = 237.85 - 8.278 \times M - 5.723 \times VM - 3.098 \times FC - 0.055 \times M^2 + 0.129 M \times VM + 0.089 \times M \times FC + 0.0319 \times VM^2 + 0.061 \times VM \times FC - 0.021 \times FC^2$	0.888	0.942	1.425	0.225	3.609
5.9	$GCV = -275.556 - 8.631 \times M + 5.134 \times A + 2.596 \times VM + 0.055 \times M \times A + 0.152 \times M \times VM + 0.164 M \times FC - 0.032 \times A \times VM + 0.021 \times A \times FC + 0.049 \times VM \times FC$	0.887	0.942	1.426	– 1.737	4.252
5.10	$GCV = 25.586 - 0.556 \times VM + 0.007 \times VM^2$	0.250	0.500	2.375	5.689	12.194
5.11	$GCV = -5.838 + 2.12 \times FC - 0.046 \times FC^2$	0.392	0.626	2.139	1.451	8.932

As evident from Table 5.15, Equation 5.8 has the highest R^2 value i.e., 0.888 among all the nonlinear regression equations developed. When S value is compared, Equation 5.7 has the lowest S value i.e., 1.285. ABE of Equation 5.6 is the highest i.e., 12.472% while Equation 5.8 has the lowest ABE i.e., 0.225% among all the nonlinear regression equations. When AAE is compared, Equation 5.8 gives the best result among all the regression equation i.e., 3.609%. When all the nonlinear regression equations were compared, Equation 5.8 was found to be the best regression equation developed as it has the highest R^2 value (0.888), lowest ABE value (i.e., 0.225%) and lowest AAE value (i.e., 3.609%). The R values of all the regression equations are found to be positive which suggests that the slope of regression line is positive for all the cases.

From the above linear and nonlinear regression equations, it can be inferred that gross calorific value doesn't depend up on a single parameter as shown in Equations 5.4, 5.5, 5.10 and 5.11. All or major proximate analysis parameters should be considered for the calculation of gross calorific value which gives a better result as shown in Equations 5.1-5.3 and 5.6-5.9.

5.7.2 Regression Analysis using Ultimate Analyses Data

All the four variables associated with ultimate analysis i.e., percent contents of oxygen (O), nitrogen (N), carbon (C) and hydrogen (H) have been considered for finding their regression equations with gross calorific value (GCV) using *Statistica* software package. At the first stage, GCV is assumed to have linear relationship with all the four variables i.e., O, N, C and H and the corresponding regression equation was found to be

$$GCV = 9.8 + 0.0613 \times O - 1.44 \times N - 0.829 \times C + 8.18 \times H \quad \textbf{(5.12)}$$

As it is reported in literature that the presence of contents of O and N have the least effect on the calorific value of a fuel, these parameters were dropped first one-by-one and then both in the subsequent stages **[48].** After dropping N, Equation 5.13 was developed in terms of rest of the three variables i.e., O, C and H on the basis of linear regression as shown below.

$$GCV = 6.92 + 0.110\times O - 0.805\times C + 7.73\times H \tag{5.13}$$

Similarly, the linear regression equation involving three variables after dropping O was obtained as:

$$GCV = 13.5 - 1.76\times N - 0.873\times C + 8.47\times H \tag{5.14}$$

Then, both O and N were dropped and the corresponding equation involving C and H was found to be

$$GCV = 13.5 - 0.890\times C + 8.15\times H \tag{5.15}$$

Two more regression equations in terms of only one variable at a time i.e., C or H were obtained as given below.

$$GCV = 14.4 + 0.045\times C \tag{5.16}$$

$$GCV = -1.27 + 3.62\times H \tag{5.17}$$

Then, performance measures like R-squared value (R^2), R value (R), standard error of estimate (S), average bias error (ABE) and average absolute error (AAE) were computed and presented in Table 5.16.

Table 5.16: Developed Linear Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Ultimate Analysis Data and Their Statistical Performance Measures

Eq. No.	**Developed equation**	**R-squared value (R^2)**	**R value (R)**	**Standard error of estimate (S)**	**Average bias error (ABE) (in %)**	**Average absolute error (AAE) (in %)**
5.12	$GCV = 9.8 + 0.0613 \times O - 1.44 \times N - 0.829 \times C + 8.18 \times H$	0.888	0.942	1.051	0.198	3.935
5.13	$GCV = 6.92 + 0.110 \times O - 0.805 \times C + 7.73 \times H$	0.869	0.932	1.017	0.411	3.974
5.14	$GCV = 13.5 - 1.76 \times N - 0.873 \times C + 8.47 \times H$	0.882	0.939	0.962	0.328	4.141
5.15	$GCV = 13.5 - 0.890 \times C + 8.15 \times H$	0.848	0.921	0.999	-0.004	4.275
5.16	$GCV = 14.4 + 0.045 \times C$	0.003	0.055	2.368	1.808	10.733
5.17	$GCV = -1.27 + 3.62 \times H$	0.401	0.633	1.835	0.846	8.206

It is observed that Equations 5.12-5.15 have high R^2 values i.e., in the range of 0.848-0.888. As these values are nearer to 1, the correlation between the dependent variable GCV and independent variables i.e., O, N, C and H is strong. The S values of these equations range from 0.962 to 1.051. Further, ABEs and AAEs of these equations are within 2% and 5%

respectively. Thus, both types of error are within acceptable range **[48]**. On the other hand, Equation 5.16 has a very less R^2 value i.e., 0.003 which is close to 0. Also, in Equation 5.17, the R^2 value is less i.e., 0.401. This suggests that GCV has very little correlation with either C or H when they are individually considered. The S values of these two equations are high which indicates the higher deviation of data points from the regression line. Also, the values of AAE in these two equations are almost more than double as compared to other equations. Therefore, these two equations are not suitable for prediction purposes. Instead, with higher R^2, lower S, lower ABE and lower AAE values, Equations 5.12-5.15 can be considered for estimating gross calorific value of biomass species knowing the values their respective ultimate analysis parameters. Out of all regression equations developed, Equation 5.12 is found to be the best regression equation as it has the highest R^2 value of 0.888, the lower ABE value (i.e., 0.198%) and the lowest AAE value (i.e., 3.935%). The R values of all the regression equations were found to be positive which suggest that the slope of regression line is positive for all the cases.

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Similarly considering the nonlinear regression analyses, following equations have been developed using ultimate analyses data.

Table 5.17: Developed Nonlinear Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Ultimate Analysis Data and Their Statistical Performance Measures

Eq. No.	**Developed equation**	**R-squared value (R^2)**	**R value (R)**	**Standard error of estimate (S)**	**Average bias error (ABE) (in %)**	**Average absolute error (AAE) (in %)**
5.18	$GCV = -184.68 + 5.008\times O + 40.251\times N + 12.774\times C - 89.116\times H - 0.0514\times O^2 - 14.629\times N^2 - 0.167\times C^2 + 10.318\times H^2$	0.923	0.961	0.921	3.319	3.319
5.19	$GCV = 70.408 + 0.153\times O - 3.115\times C + 1.035\times H - 0.041\times O^2 + 0.101\times O\times C - 0.069\times O\times H - 0.0317\times C^2 + 1.217\times H^2$	0.915	0.957	1.009	1.295	1.295
5.20	$GCV = -50.271 + 5.780\times C - 22.727\times H - 0.064\times C^2 - 0.299\times C\times H + 4.556\times H^2$	0.873	0.934	1.291	– 1.189	4.025
5.21	$GCV = -191.293 + 6.254\times O + 6.742\times C - 35.281\times H - 0.065\times O^2 - 0.092\times C^2 + 4.562\times H^2$	0.906	0.952	0.677	– 0.231	1.489

It is observed from Table 5.17 that all the nonlinear regression equation developed using ultimate analyses data have higher R^2 values ranging from 0.873 to 0.923 which suggests that there exists a strong correlation between the dependent variable and independent variables. When S value and ABE value are compared, Equation 5.21 has the lowest value of 0.677 and – 0.231% respectively. AAE value of Equation 5.19 is the lowest i.e., 1.295%. Therefore, with a R^2 value of 0.915, S value of 1.009 and, AAE and ABE values respectively as 1.295%, Equation 5.19 is found to be the best nonlinear regression equation developed considering ultimate analyses data.

From above linear and nonlinear equations, it has been proven that gross calorific value depends upon all (i.e., Equation 5.12, 5.18) or some of the influential ultimate analysis parameters (i.e., Equations 5.7-5.9, 5.19-5.21) rather than individual parameters like C and H (i.e., Equations 5.10 and 5.11).

5.8 Decentralized Power Generation Structure in Rural Areas

Decentralized power generation is defined as the production of electric power at or near the point of use. Problems associated with the increase in intermittent supply of electricity, and fluctuation of voltage and frequency causing damage to electrical equipments has made the decentralized power generation process a necessity in rural areas. Advantages related to the decentralized power generation are subsidized tariffs, lower investment, reliable supply of power, lower distribution losses, local employment, etc **[39]**.

5.8.1 Calculation of Land Requirements

Electricity requirements in rural areas can be assessed by considering a cluster of 15-20 villages comprising of nearly 3000 families and one power plant can be planned accordingly. Approximately 2 kWh/day is the per family electricity requirement for domestic purposes. Therefore, 6000 kWh/day is the electricity need of 3000 families considered. Considering the requirements from irrigation and small-scale industries near the group of villages, an additional 14000 kWh/day (approx.) of energy is also taken into account in calculation **[50].** Adding both, a power plant should be considered which can produce around 20000 kWh of electricity per day which is equal to 7300 MWh/year.

The approximate biomass production in tonnes per hectare (i.e., t/ha) of land for various components of all the five studied biomass species i.e., Banyan, Neem, Pippal, Mahua and Eucalyptus were obtained from field studies and shown in Tables 5.18-5.22 respectively. The calorific values of these components on dry basis in MJ/kg as indicated in Table 5.1 are converted to MJ/t and shown in Tables 5.18-5.22. Then, on multiplying their calorific values in MJ/t with corresponding biomass production rate in t/ha gives their energy values in MJ/ha as shown in the same set of tables.

Table 5.18: Total Energy Contents and Power Generation Structure from Fifteen Years Old (approx.) Banyan Biomass Species

Component	**Calorific value (MJ/t, dry basis)**	**Biomass production (t/ha)** *	**Energy value (MJ/ha)**
Leaf	15817	27.232	430728.544
Bark	15893	22.752	361597.536
Branch	13443	32.320	434477.760

*Data collected from field studies (approximate values).

Table 5.19: Total Energy Contents and Power Generation Structure from Ten Years old (approx.) Neem Biomass Species

Component	**Calorific value (MJ/t, dry basis)**	**Biomass production (t/ha)***	**Energy value (MJ/ha)**
Leaf	14059	8.061	113329.599
Bark	17856	1.725	30801.600
Branch	14285	1.575	22498.875

*Data collected from field studies (approximate values).

Table 5.20: Total Energy Contents and Power Generation Structure from Ten Years old (approx.) Pippal Biomass Species

Component	**Calorific value (MJ/t, dry basis)**	**Biomass production (t/ha)***	**Energy value (MJ/ha)**
Leaf	19711	8.480	167149.280
Bark	13862	7.391	102454.042
Branch	15775	8.640	136296.000

*Data collected from field studies (approximate values).

Table 5.21: Total Energy Contents and Power Generation Structure from Ten Years old (approx.) Mahua Biomass Species

Component	**Calorific value (MJ/t, dry basis)**	**Biomass production (t/ha)***	**Energy value (MJ/ha)**
Leaf	19414	14.168	275057.552
Bark	14783	13.376	197737.408
Branch	17295	12.804	221445.180

*Data collected from field studies (approximate values).

Table 5.22: Total Energy Contents and Power Generation Structure from Ten Years old (approx.) Eucalyptus Biomass Species

Component	**Calorific value (MJ/t, dry basis)**	**Biomass production (t/ha)***	**Energy value (MJ/ha)**
Leaf	22139	6.007	132988.97
Bark	17505	7.400	129537.00
Branch	18840	5.001	94218.84

*Data collected from field studies (approximate values).

In practice, the thermal and overall efficiencies of a power plant are normally taken as 30% and 85% respectively **[51].** The calculation for land requirement taking Banyan tree as sample is shown below.

Referring Table 5.18, the total energy production per one hectare of land is obtained by adding the energy values of all the components of Banyan tree as

430728.54 + 361597.536 + 434477.760 = 1226803.840 MJ/ha.

Considering a thermal efficiency of 30%, the above thermal energy will be converted to an energy output of

1226803.840 × 0.30 = 368041.152 MJ/ha.

Then, taking an overall efficiency of 85% the net energy output will be

368041.152 × 0.85 = 312834.982 MJ/ha.

Now, the above energy value in MJ/ha is converted to MWh/ha by multiplying a conversion factor of 0.0002778 as shown below,

312834.982 × 0.0002778 = 86.906 MWh/ha.

One of the major advantages associated with woody biomass is that when it gets fully grown up, it supplies fuel without being replanted year after year. This ensures continuous supply of fuel as input to the power plant.

Therefore, land required to supply electricity from Banyan biomass species for the whole year = $\frac{7300}{86.906}$ = *83.999 ha.≈ 84 ha.*

Following the same procedure as above, the land area requirements for other four biomass species were estimated and are shown in Table 5.23.

Table 5.23: Land Area Requirements for Banyan, Neem, Pippal, Mahua and Eucalyptus Biomass Species for Production of 7300 MWh Electricity per Year

Biomass species	**Land requirement (in hectare)**
Banyan	84
Neem	618
Pippal	254
Mahua	148
Eucalyptus	289

As observed from Table 5.23, among the five woody biomass species studied Banyan needs the lowest and Neem needs the highest land area for a continuous electricity supply of approximately 20000 kWh per day or 7300 MWh per year.

5.8.2 Calculation of Requirements of Coal-Biomass Blends

Decentralized power generation structure for blends of coal and biomass is developed in this section. Blends of coal with Pippal branch and Mahua bark in different ratios as indicated in Tables 5.5 and 5.6 are considered for the calculation. Referring these two tables, the gross energy that can be obtained in MJ/t are calculated and shown in Tables 5.24 and 5.25 for blends of coal with Pippal and Mahua respectively.

Table 5.24: Available Energy from Coal-Pippal Branch Blends

Sl. No.	**Proportion of components, wt.%**		**Energy value (MJ/t)**
	Coal	**Pippal branch**	
1.	100	0	17773
2.	90	10	17517
3.	85	15	17388

Table 5.25: Available Energy from Coal-Mahua Bark Blends

Sl. No.	**Proportion of components, wt.%**		**Energy value (MJ/t)**
	Coal	**Mahua bark**	
1.	100	0	17773
2.	90	10	17412
3.	85	15	17257

In practice, the thermal and overall efficiencies of a thermal power plant are normally taken as 30% and 85% respectively **[51].** The amounts of various fuels required to supply an annual electricity requirement of 7300 MWh are calculated below.

Total energies from 1 ton of coal-Pippal branch blends at 30% efficiency of power plant at various ratios are calculated as

i) 17773 × 0.30 = 5331.9 MJ/t for 100% coal,

ii) 17517 × 0.30 = 5255.1 MJ/t for blend 90% coal and 10% Pippal branch, and

iii) 17388 × 0.30 = 5216.4 MJ/t for blend 85% coal and 15% Pippal branch.

The corresponding total energies to be generated by the thermal power plant with 85% overall efficiency would be

i) 5331.9 × 0.85 = 4532.115 MJ/t = 1.2590 MWh/t for 100% coal,

ii) 5255.1 × 0.85 = 4466.835 MJ/t = 1.2409 MWh/t for blend with 90% coal and 10% Pippal branch, and

iii) 5216.4 × 0.85 = 4433.940 MJ/t = 1.2317 MWh/t for blend with 85% coal and 15% Pippal branch.

Now, the amount of coal-Pippal branch blends required to supply electricity of 7300 MWh/year is calculated below and the results obtained are shown in Table 5.26.

i) Taking only coal, the amount required is $\frac{7300\ \text{MWh/year}}{1.2590\ \text{MWh/t}} = 5798.253 \approx 5798$ t/year.

ii) For blend with 90% coal and 10% Pippal branch, the total amount of blend required is $\frac{7300\ \text{MWh/year}}{1.2409\ \text{MWh/t}} = 5882.827 \approx 5883$ t/year, which consists of 5295 t/year of coal and 588 t/year of Pippal branch.

iii) For blend with 85% coal and 15% Pippal branch, the total amount of blend required is $\frac{7300\ \text{MWh/year}}{1.2317\ \text{MWh/t}} = 5926.767 \approx 5927$ t/year, which consists of 5038 t/year of coal and 889 t/year of Pippal branch.

Table 5.26: Blends of Coal-Pippal Branch Requirement for Electricity Production of 7300 MWh/year

Sl. No.	**Proportion of components, wt.%**		**Fuel required, in t/year**		
	Coal	**Pippal branch**	**Coal**	**Pippal branch**	**Total**
1.	100	0	5798	0	5798
2.	90	10	5295	588	5883
3.	85	15	5038	889	5927

Following the same procedure as above for the coal and Mahua bark blends, the amount of fuels required to produce electricity of 7300 MWh/year is estimated below and shown in Table 5.27.

Table 5.27: Blends of Coal-Mahua Bark Requirement for Electricity Production of 7300 MWh/year

Sl. No.	**Proportion of components, wt.%**		**Fuel required, in t/year**		
	Coal	**Mahua bark**	**Coal**	**Mahua bark**	**Total**
1.	100	0	5798	0	5798
2.	90	10	5326	592	5918
3.	85	15	5076	896	5972

The above calculations show that in case of both the blends of coal-Pippal branch and coal-Mahua bark, an increase in biomass contents from 0 to 15% enhanced the blend requirements from 5798 t/year to 5927 t/year and 5798 t/year to 5972 t/year respectively in order to ensure a perpetual supply of electricity for a group of 10–15 villages. In addition, it is essential to notice that the requirement of coal decreases with increase in the percentage of biomass in these blends. In case of coal-Pippal branch blend, the requirement of coal decreased from 5798 t/year to 5038 t/year and in coal-Mahua bark blend, the requirement of coal reduced from 5798 t/year to 5076 t/year as both biomass contents increased from 0 to 15%. This is a positive step towards minimizing the use of depleting high cost fuels like coal and substituting it with abundantly available low cost biomass.

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6. CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

On the basis of the results obtained from the present project work, the following conclusions may be drawn:

i. Among all the studied biomass species, the ash content in the Mahua bark was found to be the highest (≈23 wt.%) while the Eucalyptus leaf exhibited lowest ash content (≈5 wt.%). Moreover, ash contents of all the studied biomass components, in general, were found to be much less than that of the coal sample.

ii. The branches of all the studied biomass species, in general, were found to have the highest volatile matter contents while their barks were having the lowest. Among all the studied biomass species, both the Mahua branch and Eucalyptus leaf had the highest volatile matter contents (≈68 wt.%) while Pippal bark had the lowest (≈51 wt.%).

iii. The fixed carbon content in Neem bark was found to be the highest (≈25 wt.%) while its leaf had the lowest value (≈13 wt.%).

iv. Among all the biomass components studied, the leaf of Eucalyptus was found to have the highest calorific value i.e., 22.139 MJ/kg while the branch of Banyan had the lowest calorific value i.e., 13.443 MJ/kg. In general, all the studied biomass samples were found to have higher calorific values than those of the Indian coals, indicating their high potentiality for power generation.

v. The ash fusion temperatures (particularly ST) of all the studied biomass species were found to be much higher than the boiler operation temperature (around 800-900 ^{0}C) which indicates safe boiler operation with these biomass species.

vi. In the studied coal-biomass briquettes, the ash contents and energy values decreased, and the volatile matter contents increased with increase in their biomass contents.

Coal-biomass briquettes, made by incorporating lower amount of biomass, appear to be more suitable for power generation.

vii. The best regression equations obtained are: (i) $GCV = 237.85 - 8.278 \times M - 5.723 \times VM - 3.098 \times FC - 0.055 \times M^2 + 0.129 M \times VM + 0.089 \times M \times FC + 0.0319 \times VM^2 + 0.061 \times VM \times FC - 0.021 \times FC^2$ (considering proximate analyses data) and (ii) $GCV = 70.408 + 0.153 \times O - 3.115 \times C + 1.035 \times H - 0.041 \times O^2 + 0.101 \times O \times C - 0.069 \times O \times H - 0.0317 \times C^2 + 1.217 \times H^2$ (considering ultimate analyses data).

viii. Approximately 84, 618, 254, 148 and 289 hectares of land area are required for power generation of about 7300 MWh/year from each of Banyan, Neem, Pippal, Mahua and Eucalyptus biomass species respectively. Therefore, Banyan biomass species appear to be the prime candidate in power generation.

6.2 SCOPE FOR FUTURE WORK

There is a vast scope for exploring different biomass species for electrical power production and it will play a pivotal role in the future energy production. The following points may be recommended for the future direction of research work in this field:

i. Exploitation of abundant biomass resources should be extended to more plant species for power production. Along with plant species, different municipal wastes, sewage wastes, animal wastes may be considered for further studies.

ii. Pilot plant of power generation may be set up on laboratory scale to validate results.

iii. Studies may be carried on improving the efficiencies of existing biomass power plants.

iv. Interdisciplinary research works on production, conversion and utilization of biomass need to be encouraged. Energy cultivation in wasteland and a system for successful collection and transportation of biomass materials to the power plants need to be developed.

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List of Publication

- Samal A. P., Patel S. K. and Kumar M. (2013), Characterization of the Properties of Different Woody Biomass Species & Estimation of their Power Generation Potential, International Journal of Scientific & Engineering Research, 4(12): pp. 49-53.

- Samal A. P., Patel S. K. and Kumar M. Characterization of Properties and Estimation of Power Generation Potentials of Some Woody Biomass Species, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. Taylor & Francis Group, United Kingdom.

International Conferences

- First International Conference on Emerging Trends in Engineering and Technology. 4-5 October, 2013, Munnar.
- International Conference on Emerging Trends in Renewable Energy (ICETRE). 27-28 December 2013, Bhubaneswar.