UNIVERSITY OF EDUCATION, WINNEBA

ABOVEGROUND BIOMASS, CARBON STORAGE AND FUEL VALUES OF BAMBUSA VULGARIS, OXYNANTERIA ABBYSSINICA AND BAMBUSA VULGARIS VAR.VITATA PLANTATIONS IN THE BOBIRI FOREST RESERVE OF GHANA.

FRANCIS KOBINA-OBO ASSAN

SEPTEMBER, 2018

UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION-KUMASI

ABOVEGROUND BIOMASS, CARBON STORAGE AND FUEL VALUES OF BAMBUSA VULGARIS, OXYNANTERIA ABBYSSINICA AND BAMBUSA VULGARIS VAR.VITATA PLANTATIONS IN THE BOBIRI FOREST RESERVE OF GHANA

FRANCIS KOBINA-OBO ASSAN

BSC. WOOD TECHNOLOGY EDUCATION

8141780003

A Thesis in the Department of WOOD AND CONSTRUCTION TECHNOLOGY, Faculty of TECHNICAL EDUCATION, submitted to the School of Graduate Studies, University of Education, Winneba in partial fulfilment of the requirements for the award of the Master of Philosophy in Wood Science and Technology.

SEPTEMBER, 2018

DECLARATION

STUDENT'S DECLARATION

I Francis Kobina-Obo Assan declare that this Thesis with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or in whole, for another degree elsewhere.

SIGNATURE: …………………………………….

DATE: ……………………………………………

SUPERVISOR'S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of Thesis as laid down by the University of Education, Winneba.

NAME OF SUPERVISOR: PROF. MARTIN AMOAH

SIGNATURE: …………………………………………

DATE: ………………………………………………

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to the almighty God for given me grace to finish this programme. I thank my supervisor Professor Martin Amoah for his support throughout the preparation of this Thesis. I thank Forest Research Institute of Ghana (FORIG) for giving me permission to collect the data from the Bambusetum in the Bobiri Forest. The determination of wet and dry weights of the samples were also done at FORIG wood laboratory. I also express my profound gratitude to Dr. Emmanuel Ebanyenle of Biology and Forest Health Division, Forest Research Institute of Ghana (FORIG), he assisted me with the identification of the bamboo species in the Bambusetum as well as clues to determine their ages using their morphological features. I thank Mr. Boakye and Mr. Boamah of the woodwork machine shop at FORIG, Mr Haruna physics laboratory technician at FORIG. I thank Mr. Michael Kwaku, National Project Coordinator in Ghana for International Network for Bamboo and Rattan (INBAR), for his advice and INBAR articles he gave me, I thank DR. Paul Osei Tutu, West Africa coordinator INBAR, for mailing useful INBAR articles and materials to me. God bless Mr Otobaa an INBAR and BARADEP charcoal trained technician at Daboase W/R, who assisted me in the preparation of the Bamboo Charcoal and guided me with a lot of practical and experiential knowledge on how to make bamboo charcoal and briquettes. I also thank Mr. Marfo a former student of UEW-K, who assisted me with the weighing of the culms, leaves, branches at FORIG. My gratitude again goes to Mr. Emmanuel Awarikabey of Chemical Engineering Laboratory at PMB, KNUST. I also thank laboratory technician student Desmond. I thank all those who contributed immensely to the success of this work. God bless you all. I thank all members of my church for their loyal support.

DEDICATION

I dedicate this work to my son Jeshurun Joojo Assan, my daughters Aviana Delali Assan and Eliana Deladem Assan.

TABLE OF CONTENTS

Contents **Page**

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

GLOSSARY/ABBREVIATIONS

MC	Moisture Content
EHV	Effective Heating Value
BVY	Bambusa vulgaris young culm
BVM	Bambusa vulgaris Matured culm
BVD	Bambusa vulgaris Dead culm
OXY	*Oxynateria abbyssinica* Young culm
OXM	*Oxynanteria abbyssinica* Matured culm
OXD	*Oxynanteria abbyssinica* Dead culm
BVTY	Bambusa vulgaris var. vitata Young culm
BVTM	Bambusa vulgaris var. vitata Matured culm
BVTD	Bambusa vulgaris var. vitata Dead culm
DBH	Diameter at Breast Height
AGB	Aboveground Biomass
MAE	Mean Absolute Error
RMSE	Root Mean Square Error

ABSTRACT

The purpose of this study was to investigate the recommended species of bamboo culms to be harvested for the production of charcoal. The objectives of the study were; first, to compare the stand distribution of *Bambusa vulgaris, Oxynanteria abbyssinica and Bambusa vulgaris var. vitata*; second, to estimate the aboveground biomass and carbon storage in different components of the bamboo species; third, to develop allometric models that can be used to estimate the aboveground biomass of the bamboo species and fourth, to compare the fuel values of carbonized bamboo species grown in the Bobiri Forest Reserve. Culms were classified and counted according to their ages in five 0.01ha (10m×10m) sub-plots. Weights of components of all 45 samples were taken. The total biomass and carbon storage were determined. The stand density for *B. vulgaris, B. vulgaris var. vitata and Oxynanteria abbyssinica* was 7071, 6267 and 3325 culmsha^{-1}, respectively. The aboveground biomass stored in *B. vulgaris* (115t ha^{-1}) was 61% higher than in *B. vulgaris var. vitata* (71t ha^{-1}) and was 27-fold that of *Oxynanteria abbyssinica.* The carbon storage in *B. vulgaris* standing in aboveground biomass was 50.76ha^{-1} which is 15%, 24%, 44%, 71% and 2.5% more than that of logged forest, unlogged forest intact swamp forest, degraded forest and deforested areas, respectively, in Ghana. The diameter at breast height of the bamboo culm predicted the aboveground biomass well with the R^2 values in the range 0.596 – 0.998. The gross calorific values of the raw culms were in the range of 16.22MJkg^{-1} to 17.23MJkg^{-1} and were comparable to the heating values of most grasses and straws, tropical and sub-tropical tree species. Carbonized bamboo was 27%-557% higher in energy intensity than the raw bamboo. Intensification of bamboo plantation and utilization in Ghana therefore could potentially contribute substantially to carbon mitigation and sustainable energy production.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Bamboo is a perennial evergreen plant with characteristics which are suitable to supplement the conventional timber. The long term effect of effective utilization of bamboo can minimize the depletion of the forest. According to Smajgl *et al.* (2009) the depletion of the forest has resulted in serious environmental problems throughout the world. Ghana is estimated to be at the thirteenth (13^{th}) position in comparison with countries with worse forest depletion (Kajir 2006). The devastating depletion of the forest is estimated to be about 3 per cent per annum (Appiah 2007). Household uses of wood for firewood from the forest account to about 5% of forest depletion in vast majority of the source of energy (INBAR 2010).

Kemausour *et al.,* (2011) opine that Ghana's energy needs is heavily dependent on wood fuel basically of firewood and charcoal products. Ghana is among the top ten countries in the world with the highest consumption of charcoal (FAOSTAT, 2010) and the long term effects on the rain forest is very devastating. One of the efficient ways to check the rate of forest depletion is to utilize bamboo to supplement the conventional wood. Recognizing the potential of bamboo as an important biomass resource, Ghana has in recent years, made some efforts to establish bamboo plantations across the country. Currently, there are approximately 300,000 hectares of bamboo resources occupying 5% of the country's total forest area. *Oxynanteria abbyssinica* and *Bambusa vulgaris* are the two major bamboo species occurring in the natural stands of the country while thirteen exotic bamboo species are found in the botanical gardens and experimental orchards (Obiri and Oteng-Amoako, 2007).

Bamboo is known to provide several environmental services, including environmental amelioration, biodiversity preservation, soil conservation and water purification (Kelecha 1980; Ayre-Smith 1963). More recently, the excitement about the cultivation of bamboo has been motivated by its energy value. Bamboo is the fastest growing plant in the world (Wood Book Inc. 2001). This quick growing characteristics of bamboo makes it suitable to supplement timber as well as minimizing the depletion of the forest. Bamboo has a huge bio-energy resource potential due to its fast growth (Liu et al., 2016; Liu et al., 2014; Liu et al., 2013; Peng et al., 2012).

Burkhill (1994) observed that bamboo is used for construction, plywood, particle board, papers and furniture. Other uses are: paper making, ecological purpose such as soil stabilization and erosion prevention on hill slopes and verges (Ammon and Baiadi, 2016). Bamboo has many applications in the rural industries (handicrafts, furniture, utensils and houses). Utilization of bamboo as a raw material for pellet and charcoal production has been a subject of investigation in recent times (Liu et al., 2016; Xiong et al, 2014; Liu et al., 2013). Currently 80 per cent of the rural population in sub-Saharan Africa depend on wood for their fuel needs creating environmental and health hazards. (Ammon and Baiadi, 2016).

In Ghana people in the rural communities use bamboo as fuel wood. The use of bamboo culm for firewood and burning wood for fuel can release toxic smoke which can cause diseases such as asthma, bronchitis, pneumonia and bronchiolitis' (Ammon and Baiadi, 2016). According to Fayehun (2010) toxic smoke is part of the causes of child mortality in some part of Africa. One of the ways to reduce such dangers is to convert bamboo culms to charcoal. Burning of charcoal for fuel does not emit harmful gases like burning the culm for firewood (Fayehun 2010). It is against this background that the characteristics of the *Bambusa vulgaris* (green culm), *Bambusa vulgaris var. vitata* (yellow culm) and *Oxynanteria abbyssinica* culms were investigated scientifically before and after carbonization (charcoal production) so that bamboo charcoal producers will be better informed to select right culms for their charcoal production. So far no studies have been conducted in this manner and there are no published literatures to that effect.

1.2 Statement of the Problem

While Bamboo utilization for craft, construction, environmental protection, food etc. has received publicity, the relationship between the characteristics of raw bamboo culm and their respective charcoal products in their age classes has not received much attention in the published literature. Few studies have attempted to compare bamboo charcoal with wet bamboo culms in their respective age classes (Yen et al., 2010, Nath et al., 2009).

Moreover, previous studies tended to focus on the use of only the matured bamboo for the production of charcoal (Balduino et al. 2016), even though there are juvenile, matured and dead culms which may produce charcoal with different potential values. Also most of these studies were conducted outside Africa and Sub-Sahara Africa with different species as a result the impacts of the characteristics of the *Bambusa vulgaris*, *Bambusa vulgaris var. vitata*, and *Oxytenanthera abyssinica* culms on their respective charcoal products have not received much attention in the published literature thus making it an area worthy of research.

1.3 Purpose of the Study

The purpose of this study was to investigate the recommended species of bamboo culms to be harvested for the production of charcoal.

1.4 Objectives of the Study

In order to gather data (fact) for the study the following objectives were stated as a guide for the study. The study was to:

1. Compare and evaluate the stand distribution of *Bambusa vulgaris, Oxynanteria abbyssinica and Bambusa vulgaris var. vitata.*
2. Estimate the above ground biomass (AGB) and carbon storage in different components of the bamboo species.
3. Develop allometric models that can be used to estimate the above ground biomass of the bamboo species.
4. Compare the fuel values of carbonized bamboo species grown in the Bobiri Forest Reserve of Ghana.

1.5 The Significance of the Study

The Food and Agriculture Organization of the United Nations estimates that 2.4 billion People still rely on wood and charcoal for their daily fuel. The world market for charcoal is estimated at $6.8 billion dollars in 2010. Its value could have reached more than $15 billion according to estimates if informal sales were to be included (FAO, 2012). Africa cuts an estimated 4 million hectares of forest to produce charcoal each year, double the average of any other region, including Brazil. A city like Abidjan, the Capital of Ivory Coast consumes 300,000 tons of charcoal per year, while Kenyan employment experts advance that charcoal production accounts for

200,000 jobs nationwide (FAO, 2014). According to Pauli, (2010) only 4 percent of world's electricity is produced in Africa, and only 8 percent of communities in rural sub-Sahara have access to electricity, over 70 percent of the population's income is spent on fuel. Ghana's energy mix is largely dominated by wood fuel and it is estimated that out of 10.7 million tonnes of wood fuel consumed in the country in 1985, 8.6 million tonnes (80%) was used from firewood and charcoal production (Kemausour et al., 2011). A more recent data on Ghana's energy profile indicate that the quantity of firewood and charcoal consumed in the country in 2010 was more than 35 million m^3 and 2.5 million tonnes, respectively, and thus Ghana is among the top ten countries in the world with the highest consumption of charcoal (FAOSTAT, 2010).

Obviously, the desire for Ghana to look for alternative biomass materials which are more sustainable and environmentally friendly has occupied its attention. It has been reported that the country has the potential to produce 0.9 million tonnes of bamboo charcoal which could replace 64% of the country's wood consumption for charcoal production (Liese and Kohl, 2014). Bamboo can be seen growing in natural forests, homesteads and plantations. In most parts of the world, the largest stock of bamboo still grows in natural forests, the primary habitat of bamboo. Bamboo is a renewable organic resource for sustainable development. Bamboo charcoal and Bamboo briquette charcoal are also a way of utilizing bamboo efficiently and widening the field bamboo use (Zhang 2014). Bamboo can be harvested for charcoal every year when we plant bamboo forest and even in the wild.

This study was determined to establish the suitable age or period that when bamboo culm is harvested it can produce charcoal with high quality characteristics. When the characteristics of different ages of bamboo culms are compared before and after carbonization, the result achieved will help bamboo charcoal producers to identify the suitable age of bamboo culm to be harvested for the production of quality bamboo charcoal. Secondly the study will help bamboo charcoal producers to identify the minimum age and the maximum age to harvest bamboo culms for the production of quality bamboo charcoal.

Moreover, result of this study will aid bamboo charcoal producers to plan their rotation age (age of harvesting bamboo culms). It is obvious that quality and efficient bamboo charcoal which produce from culms of suitable ages will minimize forest depletion as users of wood charcoal will turn to use bamboo charcoal. The overall benefits of the study will augment the global effort to minimize the depletion of the forest and to reduce the devastating effect of global warming.

1.6 Limitations and Delimitations of the Study.

Some challenges were encountered during the study. These challenges came as a result of factors which were beyond control. First, the research was to be conducted on bamboo of accurate and precise age but it was obvious that the personnel who manage the Bambusetum in the Bobiri Forest had not recorded such data. The ages of the bamboo culms were therefore selected based on the colour of the outline, status of the culm sheath, the outward appearance of culms, and the development of branches and leaves.

Secondly, more helping hands were needed to collect the data for the above ground biomass determination from Bobiri forest but for financial constraints only two persons were employed to assist thus measurement of the DBH and determining the weight of the culms (top, middle and bottom), branches and leaves were only completed after three days. This may affect the result of the study. Finally the cost of laboratory analysis for culms (top, middle, and bottom), branches, leaves, with the respective charcoal and briquettes of all the three species under study was too high as a result a lot of detail tests such as energy yield and heating values of briquettes were avoided. The study could have been more comprehensive if those omitted tests were to be added.

1.7 General Layout of the Report

The research report is presented in six chapters. Chapter one is the introductory section of the research report and it is principally devoted to give an overview and the justification of the study. It comprises of the background of the study, statement of the problem, Purpose of the study, objectives of the study, significance of the study, limitations of the study and general layout of the report.

Chapter two present an exhaustive review of relevant literature related to the study area. The literature review is geared towards justifying the specific objectives of the study. The chapter three involves the research methodology adopted for the study to apply the research design and the approach employed and their justification. It provides information on the sample size, the appropriate sampling technique and various test which run to analyze the samples. In addition, the chapter describes the data collection, validity and reliability of the instrument used, data collection procedures and data analysis.

Chapter four involves the presentation of the results of the study under suitable theme based on the objectives of the experiment. The findings are presented in the form of tables, figures and graphs. Chapter five present discussions of major findings of the study and the inferences make from some findings with reference to related previous studies. The major findings of the study are discussed under suitable theme developed from the objectives of the experiment.

Finally, chapter six present a summary of the major findings of the study and relevant conclusion drawn from the findings indicating how the study has contributed to knowledge. The necessary recommendations and suggestions for further research based on the findings of the study are also presented in this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter is dedicated to the review of relevant literature regarding the characteristics of culms of three bamboo species (*Bambusa vulgaris, Bambusa var. vittata* and *Oxynanteria abbyssinica*) for the production of charcoal, aboveground biomass of bamboo. Bamboo carbonization theory and bamboo carbonization process will also be reviewed. It also shows how the study builds on and criticize the present knowledge on bamboo charcoal, bamboo age, and bamboo charcoal production.

2.1 General Information on Bamboo

Bamboos are perennial woody plants that belong to the family of poacease (Graminaea) family and (bambusea) sub family. The grass family Poaceae (or Gramineae) can be divided into one small subfamily, Centothecoideae, and five large subfamilies, Arundinoideae, Pooideae, Chloridodeae, Panicoideae, and Bambusoideae. In distinction to its name, bamboos are classified under the subfamily Bambusoideae (Huang, 2014). Wang and Chew et al., (1992) stated that there are about 60 to 70 genera and over 1,200 – 1,500 species of bamboo in the world. About half of these species grow in Asia, most of them within the Indo-Burmese region, which is also considered to be their area of origin. The family Gramineae is one of the biggest among angiosperms with 450 genera and 4,500 species (Rao, Williams 1998). They are sometimes called tree grasses because of their tree morphological (Grosser and Liese, 1971). Some bamboo may stand as much as 120 feet (37 meters) high and have stems of 1 foot (30 centimeters) in diameter. Bamboo culm is a tall straight, hollow stem that has hard thick joint (world book Inc. 2001). Bamboo is an extremely diverse plant, which easily adapts to different climatic and soil conditions. The culm matures in its fourth year; by which time it also reaches its peak strength. After the fifth year it becomes increasingly brittle and weak. Most bamboo culms are green in colour, although others are yellow, black, rust or even purple-black. Some bamboos are striped, in yellow or green.

The main constituents of bamboo culms are cellulose, hemi-cellulose and lignin, which amount to over 90% of the total mass. The minor constituents of bamboo are resins, tannins, waxes and inorganic salts. Compared with wood, however, bamboo has higher alkaline extractives, ash and silica contents (Tomalang *et al.*, 1980; Chen et al., 1985; Scurlock et al, 2000) Bamboo contains other organic composition in addition to cellulose and lignin. It contains about 2-6% starch, 2% deoxidized saccharide, 2-4% fat, and 0.8-6% protein. The carbohydrate content of bamboo plays an important role in its durability and service life. Durability of bamboo against mold, fungal and borers attack is strongly associated with its chemical composition.

The ash content of bamboo is made up of inorganic minerals, primarily silica, calcium, and potassium. Manganese and magnesium are two other common minerals. Silica content is the highest in the epidermis, with very little in the nodes and is absent in the internodes. Higher ash content in some bamboo species can adversely affect the processing machinery. Since the amount of each chemical composition of bamboo varies with age, height, and layer, the chemical compositions of bamboo are correlated with its physical and mechanical properties. Such variation can lead to obvious physical and mechanical properties changes during the growth and maturation of bamboo (Li, 2004). Bamboo is a heterogeneous and anisotropic material. Some studies have argue that the mechanical properties of bamboo are extremely unstable related to the microstructure characteristics, culm height, culm location, density and moisture content (Jiang, 2012; Pannipa, 2013). However Zhou (2011) presented findings to support increasing strength of bamboo culms because on the contrary comprehensive tests rather revealed a further increase of strength properties with age, with radial and tangential bending strength up to 8 years and for tensile strength and compression strength (parallel to the grain) up to 5 years.

Major morphological characteristic of bamboo is divided into rhizome and the culm system. The culm is the upper ground part of bamboo that contains most of the woody material. It is complemented by branching system, sheath, foliage leaves, flowering, fruits and seedlings. The diameter tapers from the bottom to the top with the reduction in culm wall thickness (Yen, & Lee, (2011). Unlike trees bamboo have no secondary growth. Normally, the culm is straight hollow and cylinder-formed with nodes and internode parts (Panipa 2013). Bamboo can reach it maximum height in 4 to 6 months with a daily increment of 15 to 18cm. It might have 40 to 50 stems in one clump, which adds to the 10 to 20 culms yearly (Latif et al., 1993; Pannipa 2013). In addition bamboo culm take 3 to 6 years to mature, which depend on the species. Therefore, bamboo growth is more rapid than any other plant of this size on the planet (Wang, 1987; Pnnipa, 2013).

2.2 Growth Characteristics of Bamboo Plant

Bamboo is a fast growing species and a high yield renewable resource. Generally, all bamboo mature quickly. The fast growth characteristic of bamboo is an important incentive for its utilization. Unlike trees, bamboos grow to full height and girth in a single growing season. Bamboo, is mainly compost of hemicelluloses, cellulose and lignin that can produce higher value-added products by pyrolysis processes.

Furthermore, it possesses many other advantages such as easy propagation, fast growth and low ash content (Scurlock *et al*., 2000). Zhang *et al*. (2002) observed that the height or growth of bamboo culm is realized by the internodes growth. The cell division varies with the difference internode location. The speed of growth is also different in internodes. After the end of height growth, the height, thickness and volume of bamboo stems do not change. Consequently, the maturity process begins. In this duration, cell wall thickens and specific gravity increases, moisture content decreases and physical and mechanical properties increase (Pannipa 2013). Bamboo stems are generally hard and vigorous, and the plant can survive and recover after sever calamities, catastrophes and damage.

Young bamboo shoot were the first sign of new plant life after the nuclear bombing of Nuroshima and Nagasaki (Lobovikov *et. al* 2009). Their natural habitat is tropical regions and they are not invasive (Lobovikov *et. al*., 2009). Bamboos are also adaptable to various types of habitat. They grow in plains, hilly and high altitude mountainous regions, and in most kinds of soils, except alkaline soils, desert, and marsh (Wang and Shen 1987). Latif et al., (1993) mention that bamboo could grow from sea level to as high as 3000 meter. Bamboo is suitable on well drained sandy to clay loom or from underlying rocks with pH of 5.0 to 6.5. The unique growth habit of bamboos and their fast growth rates provide an excellent opportunity to improve the biomass. This is very important to many of the poorer countries where forest resources are fast depleting and people are faced with many hardships caused by the lack of timber and fuel wood (Anon, 1980). Rhizome is the underground portion of the bamboo plant. It is the plant's structural foundation. There are buds also at the nodes of the rhizome, which develop over the ground into culms. There are two main categories of rhizomes: monopodial and sympodial. Monopodial rhizomes grow horizontally, often at a surprising rate, and thus their nickname of 'runners'. The rhizome buds develop either upward, generating a culm, or horizontally, with a new tract of the rhizomal net. Monopodial bamboos generate an open clump with culms distant from each other and can be invasive. Sympodial rhizomes are short and thick, and the culms above ground are close together in a compact clump, which expands evenly around its circumference. The roots emerge from the rhizome nodes and culm nodes that are below the soil surface. The roots provide anchorage in the soil and make possible the uptake and distribution of water and nutrients to other parts of the plant. Bamboo shoot is an emerging stem or culm. It originates from the buds of the underground rhizome. The rhizome, culm and branches of the bamboo plant are segmented by solid nodes. These are key growth points, from where new vegetative axes develop and grow.

Intermodal length varies considerably across bamboo species, ranging from 5 to over 60 centimeters. The internodes of the culm bear branch buds, arranged on alternate sides of the culm. Bamboo culm consists of many internodes and nodes. The parts situated between two nodes are internodes, which are not the same in length, with the longest one usually in the middle, and the shortest one situated on culm stripes. Each node is composed of two annulus, the upper part of which is called culm annulus, while the lower part has the name of sheath annulus (Fu *et al*., 2007).

Culms are also covered by sheaths at the initial stages of growth, which fall off as the plant matures. A typical bamboo culm has a hollow cylinder that tapers and narrows towards the top. The branches of the bamboo plant bear leaves, which are important for photosynthesis.

Flowers: bamboo flowers are varied in colour, size and other characteristics. Flowering takes place with the growth of clusters of specialized leaves, with the specific aim of participating in reproduction. Flowering occurs infrequently and at long intervals. Flowering cycles may vary from one year to over a hundred years. They are of two types: Gregarious: all the culms in a bamboo clump flower together over a period of time, and then die. Sporadic: some culms in a bamboo clump flower, and die thereafter. Sporadic flowering can occur either across a large population of clumps or in a small population. Some bamboos are known to flower sporadically every year (INBAR, 2010).

In Ghana *Bambusa vulgaris* is the most common bamboo species which constitute 95% of the total bamboo resources in Ghana and found mostly in the forest zone. The species was introduced about 70 years ago and has become naturalized and considered as native. They are green in colour, grow in dense clumps and can reach 15-20 m in height. The culms can increase to a diameter of 4-10 cm with a wall thickness of 7-15 mm (Rao *et al.*, 1998). They have woody culms and produce new culms on yearly basis (Anon, 2010). The only native bamboo species in Ghana, to be found mostly in the savannah, is the *Oxynanteria abbyssinica* (INBAR, 2010). *Bambusa vulgaris var vitata* is an attractive yellow culms striped green, widely planted as an ornamental. They grow in clumps and tolerate low light conditions. They can grow to a height of about 15- 20 m, with a culm diameter of about 8 cm. The yellow colour starts to fade when harvested. They thrive on infertile soils and close to water bodies as well. Flowering is extremely rare (Anon, 2010).

2.3 Physical Characteristics of the Bamboo Culm

Physical characteristic of bamboo comprises of age, height, size-diameter, growth rate etc. Unlike wood, bamboo only needs between 3-4 years to mature before they can be harvested and utilized. Age is an important factor for the development of strength properties (Zhang, .2011). It is a general assumption that bamboos mature until about three years and have then reached their maximum strength. Investigations with *Dendrocalamus strictus* have shown that in the green condition older bamboo culms have higher strength properties than younger ones (the moisture content of the latter is much higher) in the dry condition, however, higher values were obtained at the age of one and two years than from older culms (Fu-Chu, 2009).

Suitable age for harvesting bamboo culms remains a subject of debate in the published literature and researchers of bamboo plants. Haygreen and Bowyer (2014) recommended that the suitable age to harvest bamboo to be between 4-6 years old, while Yen (2011) observe bamboo of 2-4 years to be matured for harvesting. Shenxue (2004) also stated that bamboo matures and it is suitable for harvesting from 4-8 years old. The determination of bamboo age is based on the color of the outline, status of the culm sheath, the outward appearance of culms, and the development of branches and leaves. (Shenxue, 2004)

A brief summary of age determination is as follows: 1-year-old bamboo has sheaths that still remain in the culms and the culm surface is covered with a clear white powder, 2-year-old bamboos possess culm sheaths that are beginning to rot, white powder on the surface of the culm disappears gradually, and the culm turns light green. In 3-year- old bamboo, the sheath has begun to drop, and the culm bottom has been invaded by mold and turns dark green. In 4-year-old bamboo, the sheath has disappeared from the surface of the culm, which is moldy and has become yellowish green in color. In bamboo 5 years old or greater, the culm surface is coarse, covered with mold and moss, and turns brownish green (Lin, 1961; Yen 2010). Huang (2014) disagrees with this method of age determination and argues that the information on properties such as morphology or physical characteristics at different ages of wild bamboo is very limited and could not be the only way to determine the age of bamboo.

However, the writers did not also provide the alternative way to determine the age of bamboo but used the same method to propose 2-4 years to be the matured age for harvesting bamboo. The 4-year old culm is the right mature age where the culms are normally use for panels, parquet, furniture and construction purposes. Bamboo shoots in tropical countries grow up to 30 meters within six months. The record growth speed measured for a bamboo stem is 1.20 meters per day which directly shows the potential of bamboo to substitute slower growing wood species in terms of annual yield (Majundar, et al, 2016). The physical characteristic such as culm height, number of internodes per culm, internode length, internode diameter, culm wall thickness girth, moisture content, and basic density are considered to be important factor in determining the suitability of bamboo for various application and chemical treatment.

The length of the internodes increases from the basal region to the middle portion of the culms and decreases towards the top. Unlike timber, bamboo does not show any secondary thickening and thus attains its final diameter during the final sprouting stage (Liese, 1985, Huong, 2014).

Nutrient contribution of parent trees to new shoots decreases with age due to declining physiological function after age 3–4 years. Culm moisture content also decreases while dry biomass increases with tree age due to cell wall thickening and accumulation of materials like silicon (Liese and Weiner, 1985, Embaye 2004).

2.4 Anatomical Structure of Bamboo

The culms outermost layer, the bark, consists of epidermal cells that contain a waxy layer called cutin. The innermost layer is wrapped by sclerenchyma cells. The tissue of the culm contains parenchyma cells and the vascular bundles. Vascular bundles are a combination of vessels and sieve tubes, with companion cells and fibers (Razak *et al*. 1995). The bamboo node cells are transversely inter-connected, whilst the cell at the internodes are axially oriented. Being a monocotyledon, the bamboo culm lacks the secondary thickening, and further not possessing radial cell elements like timber (Grosser et al. 1971). Chew et al. (1992) analyzed the fiber of *Bambusa Vulgaris*, their study shows that the fiber is long and slender, with a narrow lumen. The average fiber length and width was found to be 2.8 mm and 0.013mm, whilst the lumen width and cell-wall thickness was 0.003mm and 0.005mm respectively.

Latif *et al* (1993) found that the frequency of vascular bundles does not significantly vary with age and height of the culm. They observed that the highest mean concentration of vascular bundles was at the top location of the 2-year-old culm, and the lowest mean concentration was in the middle location of the 1-year-old culm. The high density of vascular bundles at the top was due to the decrease in culm wall thickness (Grosser and Liese 1971). The size of vascular bundles was not significantly different with height and age.

Tomalang et al (1980) in their study found that the main constituents of bamboo culms are holocellulose (60-70%), pentosans (20-25%), hemicellulose and lignin (each amounted to about 20-30%) and minor constituents like resins, tannins, waxes and inorganic salts. The main complex organic compounds in biomass are cellulose, hemicellulose and lignin. The hemicellulose, cellulose and starch in the plants are made up of five and six carbon sugars which on combustion release energy for use with carbon and hydrogen being the combustible components. Lignin is a tough, glue-like substance that keeps plant cell walls from falling apart, a cementing material between cell walls with an amorphous chemical composition and structure. Lignin has coniferyl alcohol as the building block and its combustion releases a large amount of energy (Demibras, 2005). The bamboo culm is made up of about 60% parenchyma, 40% fibre and 10% conducting tissue. Bamboo has about 50-70% cellulose, 30% hemicellulose and 20-25% lignin.

It is well established that the chemical composition of bamboo is similar to that of wood with cellulose, hemicellulose and lignin accounting for over 90% of the total mass. They account for more than 90 of the dry weight of the fiber. The content of other chemical components are little, such as protein, fats, pectin, tannin, pigment etc. In general, the ἀ-cellulose content in bamboo is 40-50%, which is comparable with the reported ἀ-cellulose contents of softwoods (40-52%) and hardwoods (38-56%) (Demirbas, 2004).

2.5 Shrinkage and Swelling of Bamboo

Bamboo, like wood, changes its dimension when it loses or gains moisture. Bamboo is a hygroscopic material, thus the moisture content changes with the changes in the relative humidity and temperature of the surrounding environment (Janssen, 1991). As was mentioned in the latter section, bamboo begins to change its dimension as soon as it starts to loose moisture. This characteristic is in contrast to wood, where it will shrink or swell only below the fiber saturation point (FSP). Free water and bound water exists in bamboo, however the amount of free water may be small compare to bound water. This could explain why it starts to shrink as soon as it loses moisture. The shrinkage and swelling of bamboo in the volume (V), longitudinal (L), radial (R) or tangential (T) direction are expressed by the following equation below:

Shrinkage (%) = decrease dimension (V, L, R or T) X100 (2.3) original dimension.

Swelling (%) = increase dimension (V, L, R or T) X100 (2.4) original dimension (Haygreen and Bowyer, 1998).

Unlike wood, bamboo begins to shrink right from the beginning of seasoning. The shrinkage affects both the thickness of the culm walls and the circumference. Seasoning of mature bamboo from green condition to about 20% moisture content leads to a shrinkage of 4 to 14% in the wall thickness and 3 to 12% in diameter. Bamboo tissue shrinks mainly in the radial direction, and the minimum deformation occurs in the axial direction. The tangential shrinkage is higher in the outer parts of the wall than in the inner parts. The shrinkage of the whole wall appears to be governed by the shrinkage of the outermost portion, which possesses also the highest specific gravity. Mature culms shrink less than immature ones.

2.6 Moisture Content of Bamboo

The moisture content of biomass plays an important role when it comes to its conversion to energy. It determines the conversion process to be employed and the end products.

Moisture content of bamboo varies within one culm and is influenced by its age, the season of felling and the species, in the green stage greater differences exist within one culm as well as in relation to age, season and species (Yen et al, 2010). Young, one-year old shoots have a high relative moisture content of about 120 - 130% both at bottom and top (Zhang, 2011). The nodes, however, show lower values than the internodes. These differences can amount to 25% of the water content and are larger at the base than at the top (Zhang, 2011). In culms of 3 - 4 years the base has a higher moisture content than the top, e.g. for *Dendrocalamus strictus* about 100% and 60% relative moisture content respectively.

Moisture content across the culm wall is higher in the inner part than in the outer part. (Liese W, 1985). The moisture content of this species was significantly higher at bottom and decreases significantly from base to top along the culm height.The result is in agreement with the findings of other researchers (Shanmughavel P. et al,.1986). The decrease in moisture content along the culm height might be associated with structural and chemical composition of bamboos (Liese, 1985). Moisture content is likely the most important determinant of the overall biomass heating value during combustion. Air dried biomass typically has about 15-20% moisture whiles oven dry biomass has 0% (Scurlock, 1999; Osarfo, 2008).

Biomass therefore needs to be dried but not beyond a certain level. The lower the moisture content of the biomass, the more desirable it is as a biofuel. As the moisture content increases, the Effective Heating Value (EHV) decreases until the moisture content reaches a critical value of 87% at which the energy of evaporation becomes equal to the EHV. The critical moisture content of the various biomasses is at 50-55% after which an increase in moisture content leads to significant decreases in EHV.

The biomass of bamboo, in terms of productivity, does not differ much from that of woody biomass (Kumar, et al 2002). Woody biomass and bamboo biomass follow similar relationship between moisture content and Effective Heating Value (EHV). Osafo, (2008) has expressed the relationship between moisture content and Effective Heating Value (EHV) of biomass in Figure 1 below.

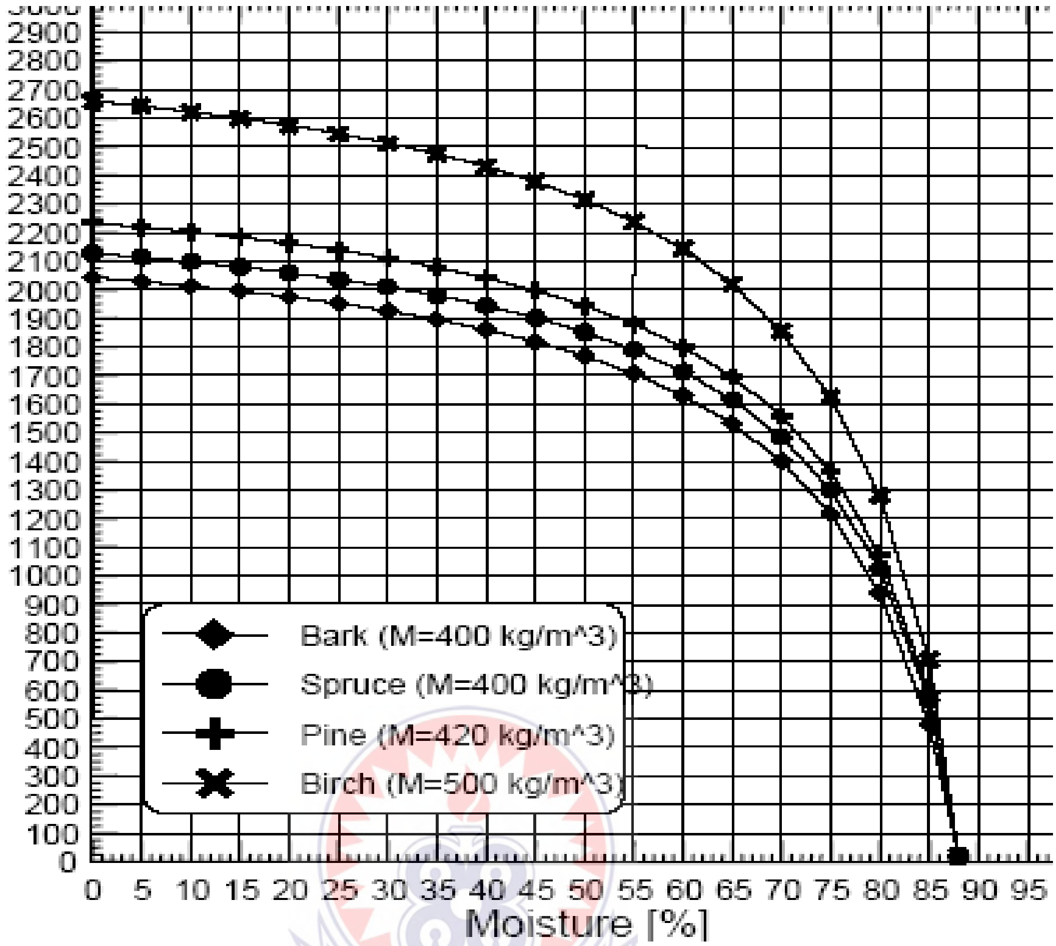

Figure 1: The relationship between moisture content and EHV [kWh/m3]
(Source: Osarfo 2005)

2.7 Bamboo Utilization

Bamboo made its first appearance for the use in floor covering on the international market in the early 1990s to lukewarm reception. The product was undeniably beautiful, but without the perspective of education, it was hardly sold. People in the United States were familiar Only with common local uses, like old-fashioned fishing poles from the slender, flexible varieties of bamboo native to North America, and from imported items like back scratchers and chopsticks. Changing the perception of bamboo as a viable flooring option was hardly rated high compared to most hardwoods and their sustainability factor that makes it a green choice was also a slow process (Haygreen and Bowyer 1998). The bamboo culms have been widely used in building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses and rafters; it is also used in construction as structural materials for bridges, water-transportation facilities and skyscraper scaffoldings. Bamboo houses (or those incorporating bamboo as a structural material) are quite long-lasting when the bamboo is duly treated. In addition, social housing, school buildings, etc. can be built, as well as, doors, windows, trusses, frames, roofing, and small bridges. Due to its fast growth rates and perennial nature, promoting bamboo for energy could therefore play a major role in reducing deforestation (Appiah, 2007). The causes and effect of deforestation are inspiring a search for an alternative sources of raw materials for furniture products and other wooden products so that the natural forest can be preserved (Osarfo, 2005). Ghana has experienced indiscriminate cutting of trees which has resulted in devastating depletion of the forest about 3% per annum (Appiah 2007)

In addition, bamboo has been also processed into an extended diversity of products ranging from domestic household products such as food containers, skewers, chopsticks, handicrafts, toys, furniture, flooring, boats, charcoal, musical instruments and weapons. In rural areas, bamboo is called the poor man's timber due to the entire aspects of bamboo utilization in the human life. The fast growth of bamboo is an incentive for its utilization (Pannipa, 2013).

Effective utilization of bamboo for various uses can minimize the devastating effect of deforestation. Bamboo ashes are used to polish jewels and manufacture electrical batteries. It has been used in bicycles, dirigibles, windmills, scales, retaining walls, ropes, cables and filament in the first light bulb. Janssen (1991), investigated how much strength and how much stiffness (resistance against deformation) does concrete, steel, timber or bamboo give? The result showed that as far as strength is concerned, concrete is the worst, followed by timber. Steel is the best and bamboo the second best. In terms of stiffness, the fourth place is for concrete, third for timber, second for steel and the first place is for bamboo.

Ghana is at the 13th position in comparison with countries with worse forest depletion (Kajir 2006). Ghana's forest cover at the beginning of the century was about 8.2million hectors but now it about 1.6 million hectors. Sixty-five hectors are depleted every year (Appiah 2007). It is estimated that some of these depletion of the forest are caused by the use of trees for Bamboo utilization as alternative wood materials may be divided up into following broad categories: Bamboo is a major building material in many countries, particularly in Asia, Africa and South America, because of its strong characteristics, light weight and flexible properties.

Currently, over one billion people are estimated to be living in traditional bamboo houses (Lobovikov *et al*., 2009). While bamboo continues to be used in these traditional ways, it has also become an important raw material for production of modern building products. It can be used for almost all parts of houses, including posts, roofs, walls, floors, beams and trusses. There are other uses of bamboo; these include agricultural instruments, fishing tools, handicrafts, musical instruments, furniture, crafts and woven mats. About 200 species of bamboo, a well-known feature of Chinese and other Asian cuisines can provide suitable shoots for eating. Fresh bamboo shoots are delicious and healthy, with high fiber content. Bamboo charcoal is traditionally used as a substitute for wood charcoal or mineral coal. It is one the biofuels which are generated from biomass. The biofuels that are currently being derived from biomass are in gaseous, liquid and solid forms. They include pyrolysis gas, methane gas, Hydrogen gas, pyrolysis liquid, biodiesel, ethanol, methanol, fuel wood, charcoal and briquettes. They are used as a source of heat, steam, and electricity and transportation fuel (Picchi *et al*, 2007).

Bamboo Charcoal can serve as a fuel, for cleaning drinking water, cooking, bathing, improving soil, regulating room humidity, preserving freshness of vegetables, fruits and flowers, deodorizing, for conducting electricity, etc. Because bamboo fibers are relatively long, thus it can be used for paper production. Bamboo paper has practically the same quality as paper made from wood. Its brightness and optical properties remain stable. The use of bamboo in composite boards overcome differences in quality related to the culms. These allow the 93 fuel wood. Using wood or bamboo for fuel (fire wood) has a lot of health hazards. Bamboo charcoal is alternative product to minimize the hazardous effects of using bamboo or wood as fuel wood.

Bamboo is said to have some desirable fuel characteristics like low ash content and low alkali index with a lower heating value higher than most agricultural residue grasses and straw but lower than many woody biomass (Scurlox *et. al.*, 2000). One must not forget to adequately emphasize bamboo's role as a means for erosion control, riverbank protection, landslide prevention and land rehabilitation. Bamboo's extensive network of rhizomes and roots binds the top one foot of soil, which is critical for land productivity (Janssen, 1991). Bamboo can also be carbonized into bamboo charcoal. Bamboo charcoal has been in existence for thousands of years in the Asian countries. Bamboo charcoal is characterized by a high density, a porous structure, and a huge specific surface area (Zhao, 2006). According to the literature, bamboo charcoal with an excellent adsorption capacity was used as a potential adsorbent for the removal of various kinds of pollutants, including nitrate–nitrogen dibenzothiophene, phenol, heavy metals, ammonia, and dye (Xianghai et al, 2013).

2.8 Aboveground Biomass of Bamboo

Above ground biomass is living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. Forest biomass is classified into above ground biomass and below ground biomass. (FAO, 2012). Biomass is the organic material both above ground and below ground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. FAO, (2012) also defined biomass to be the pool definition for above and below ground biomass. Aboveground biomass plays an important role in the regulation of atmospheric CO_2 and global climate change by significantly determining an ecosystem's potential for carbon storage as well as carbon sinks (Sohel, 2015).

Some researchers have estimated the total standing biomass by multiplying the number of culms with the average total aboveground biomass (Kumar Chandrashekara; 2014 Shanmughavel and Francis, 1986). Knowledge of the aboveground biomass, carbon storage and the heating value of bamboo species is a prerequisite for sustainable management (Nath *et al*, 2009). Information on the biomass potential of bamboo species grown in Ghana would form the basis for justifying investment in the plantation of the species for biomass production.

Bamboo has a huge bio-energy resource potential due to its fast growth (Liu *et al*., 2014; Liu *et al*., 2013; Peng *et al*, 2012). Bamboo is a forests sequester and store more carbon than any other terrestrial ecosystem and are important natural system to mitigate climate change (Peng et al, 2012).

Traditionally, allometric models have been used to estimate aboveground biomass of standing trees (Amoah and Becker, 2009, Zianis and Mencuccini, 2004) as they are non-destructive and provide indirect measurement of biomass in addition to being less time consuming and less expensive compared to direct measurement (St Clair, 1993). The use of allometric models to estimate aboveground biomass of bamboo stands has also been reported in the literature (Yen, 2006; Liu et al, 2014). Nath *et al*. (2009) employed allometric models to estimate the aboveground biomass of *B. cacharensis*, *B. balcooa* and *B. vulgaris* in North East India. Yen and Lee (2011) utilized allometric models to estimate the aboveground biomass of moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamanialanceolata*) in the lower mountain area of central Taiwan.

However, Ganesh (2003) disagree and argues that using generalized allometric models for species such as *O. abbyssinica* can cause over or under estimation as the DBH range is less than 5cm range. They further argue that the difference in climate zone, species type and independent variable used for the regression model make the generalized allomertic model less suitable to estimate the biomass of bamboo species like *O. abbyssinica.*

2.8.1 Pre-Carbonization Seasoning of Bamboo

The cut bamboo should first be dried for at least four weeks preferably standing upright. Lying horizontally almost doubles the drying time. Air seasoning under cover is preferred, but seldom possible. Kiln seasoning under controlled conditions can be performed in about two to three weeks, but is considered to be uneconomical. The bottom part, therefore, takes much longer to season than the top portion. The rate of drying of immature culms is generally faster than that of mature ones, but since the former have a higher moisture content they need longer. In the initial stages drying occurs quite rapidly, but slows down gradually as drying progresses.

Several defects can occur during seasoning. They may be due to the poor initial condition of the culm, due to excessive shrinkage during drying or both. End splitting is not as common or severe as in timber. Surface cracking can occur during drying with all species. Cracks start at the nodes but their extent depends on the species and wall thickness. Thick-walled. Collapse is a most serious seasoning defect. It occurs during artificial as well as natural drying processes and leads to cavities on the outer surface and to wide cracks on the inner part of the culm.

Mature bamboo is especially liable to crack. A deformed surface of the round cross-section of immature bamboo is common. Thick walled species evince an uneven outer surface, and cracks quite often develop on the inner side of the wall. Considerable shrinkage can take place in the middle part of the internodes, which become concave. (Liese, 1985). Bamboo culm must be air seasoned under a cover e.g. a shed before carbonization.

2.8.2 Bamboo Carbonization

Carbonization is the term for the conversion of organic substance into carbon or carbon containing residue through pyrolysis or destructive distillation (Emrich, 1985).

Carbonization is the method of burning wood or other biomass in the absence of air after which it breaks down into liquids, gases and charcoal. It is also said to be a thermochemical decomposition process that takes place in the absence of oxygen and at a slow heating rate (approximately 10 °C/min) to produce a liquid phase (tar or hydrocarbon liquids and water), a carbon rich solid phase (charcoal) and non-condensable gases (CH_4, CO_2, CO, H_2, etc.), as discussed in Demirbas (2004).

Processing of bamboo as charcoal could make handling and transport them and efficient enough to make it an economically interesting small scale industrial activity. As a CO_2 neutral source of energy it can replace fossil fuels. From the point of view of forest management the harvesting of the fast growing bamboo and the subsequent replacement with higher value trees may be a method to a sustainable increase in the value of the forest, both, in monetary terms and with respect to biodiversity (Ebanyenle et al, 2005).

Charcoal is traditionally produced in earth, brick or steel drum kilns in batches from about 1 to 5 tons (INBA, 2010). Carbonization describe the conversion of organic substance into carbon at an elevated temperature. Bamboo carbonization is the heating in brick kiln or mechanical kiln with little air by means of the heat energy generated by burning firewood to pyrolyse bamboo and produce bamboo charcoal (Shenxue, 2004).

The pyrolysis can be performed at a linear heating rate of 10ºC/min. from room temperature to 600ºC and maintained at 600ºC till no weight loss is observed. The temperature ranges are selected based on the decomposition temperatures of the basic components like cellulose, hemi-cellulose and lignin. The char obtained at 500ºC has a calorific value near to that of commercial charcoal.

Wood and bamboo give about 32% char yield at this temperature. Obtaining charcoal from bamboo requires a temperature of 500ºC. It is only then will the charcoal be of commercial quality. Volatiles released between 320-500C are called Potential Tar Forming Volatiles (PTFV) and is about 30% for bamboo. PTFV in bamboo is lower than most of the wood types and therefore may not need special care (Ganesh, 2003). The substance undergo dehydration followed by condensation reaction.

In bamboo charcoal, the structure of bamboo remains unaltered, because the carbonization temperature is lower than its melting point (Hsieh, 2007). The burning process depends on a number of factors such as diameter and moisture content of the bamboo, wind direction and force (INBAR, 2006). Bamboo charcoal production process is divided into three stages: raw material preparation, carbonization and finishing process (Shenxue, 2004). The bamboo culm should be chopped into segments according to the size of the kiln before drying.

Moisture content of raw bamboo should be 15%-20% by air drying before loading into the kiln (INBAR, 2006). The temperature in the kiln at the pre-carbonization stage should be kept at the auto ignition of the bamboo culm which is 150C-280C. A large quantity of heat is needed to maintain the rising of temperature for thermolysis. The temperature in the stage of carbonization is 280C-450C which exceed the auto ignition point of bamboo (Shenxue, 2004).

Amount of charcoal or yield of char decreases as the temperature gets higher due to increased thermal degradation rate. A maximum bio char yield of 80 % was attained at 300 °C. The bio-oil yield increased until 500 °C, remaining practically constant after that. Secondary reactions of volatile compounds are also favored with the temperature increment resulting in a high gas yield (Huang *et al*., 2014).

Bamboo pyrolysis can be divided four stages. The first stage is the drying stage with temperature below 120C and the speed of pyrolysis is very slow at this stage. The second stage is the pre-carbonization with temperature range 120C-260C and there is a distinct pyrolysis reaction in the bamboo at this stage. The third stage is carbonization. Temperature is in the range of 260C- 250C and the bamboo rapidly decompose into many liquid and gas products. Liquid products contain much acetic acid, methanol and bamboo tar, flammable methane and ethylene in gas product are increasing while carbon dioxide is decreasing gradually during this stage. The fourth stage calcination is the (refining stage): the temperature is over 450C. The bamboo is becoming charcoal by means of providing a mass of heat emitting the volatile substances in the charcoal and to enhance non-volatile carbon of charcoal car is the key stage to upgrade the quality of bamboo charcoal base on the temperature in this stage. Jiang et al, (2012) examined the factors that influence the bamboo pyrolysis process, such as the terminal pyrolysis temperature, carbonization speed, bamboo moisture content, and bamboo dimensions. Among these, the terminal carbonization temperature most significantly affected bamboo charcoal quality and properties. The bamboo charcoal can be divided into three groups; low temperature, middle temperature and high temperature charcoal. (Huang, 2014). Pyrolysis produce three products: they are solid (bamboo charcoal), liquid (bamboo vinegar) and gas (bamboo gas). The bamboo gas can be used as fuel. Bamboo charcoal has the characteristics of high density, porous structure, good wear resistance, higher conductivity, etc. (Chin *et al*., 2017).

Bamboo Charcoal is considered to have higher adsorption capacity than wood charcoal because of the special structure of the micro poles of bamboo stem (Chin *et al*., 2017). Fuel wood is gathered and cut to size, and placed in an underground or above ground kiln. The kiln is fired and the fuel wood heats up and begins to pyrolyse.

The kiln is mostly sealed, although a few air pockets are initially left open for steam and smoke to escape. As the kiln emissions change colour, the charcoal producer may seal some air pockets. The production process may take up to a few weeks. About half of the energy in the bamboo is typically lost in the process (but the charcoal produced has higher energy content per unit mass). When the process has ended, the kilns are opened or dug up and the charcoal is removed. The resulting charcoal resembles smaller, lighter pieces of blackened bamboo. (Shenxue (2004). Bamboo has good calorific content, which makes it a viable source of energy. The carbonization processes has been summarized by Shenxue (2004) in a production process flow chart of bamboo charcoal (Figure 2).

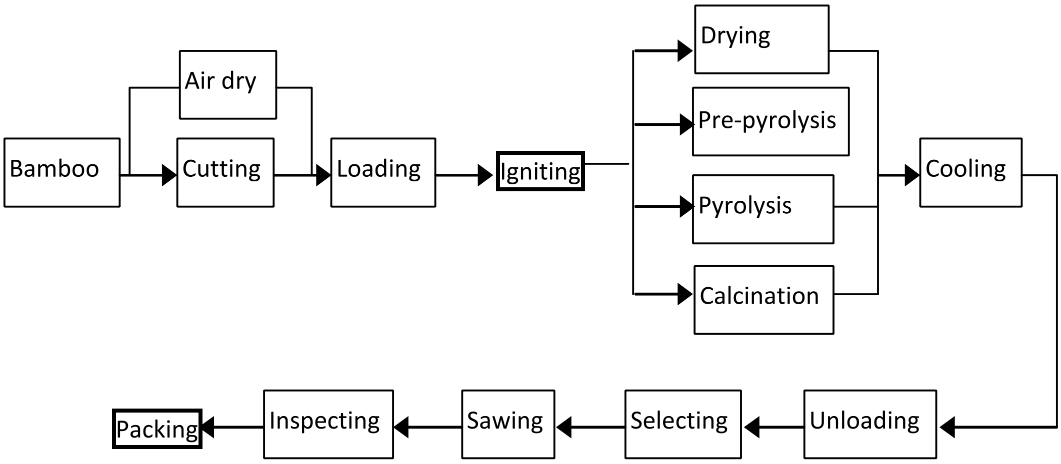

Figure 2: A practical Production process flow chart of bamboo charcoal.
Source: Shenxue (2004); Training Manual of Bamboo Charcoal for Producers and Consumers. p.16.

2.8.3 Bamboo Vinegar

Bamboo vinegar is obtained from the vapor which comes out of the air vent during the pyrolysis process. It is obtained by condensation method and the liquid is made up of organic compounds. Compounds in the vinegar including vapor and gas are collected from the pyrolyzing kettle and condensed into liquid products called bamboo vinegar (Kumar et al, 2002). Crude bamboo vinegar is a kind of brown-black liquid containing more than 300 organic Compound. Huang (2014) identified some of these compounds are as follows;

- Saturated acid: acetic acid, formic acid, propanoic acid, and butanoic acid
- Unsaturated acid: propenoic acid
- Hydroxyl-acetic acid: 2-hydroxyl-acetic acid
- Heterocyclic acid: β -furan-carboxylic acid
- Alcohol: methanol
- Un-alcohol: allyl alcohol

- Ketone: acetone, methyl ethyl-ketone, methyl propyl-ketone, and cyclopentanone
- Aldehyde: formaldehyde, ethyl-aldehyde, and furol
- Ester: methyl formate, methyl acetate
- ArOH: phenol, methyl-phenol, and O-benzene-diol
- Lactone: butyrolactone
- Aromatic substance: benzene, toluene and naphthalene.
- Heterocyclic compounds: furan, and α -methyl furan
- Amine: methylamine

The crude bamboo vinegar can be divided into two layers by setting for two months. The upper layer is clarified bamboo vinegar, which is a light yellow or light brown liquid with special smell, and the lower layer is sediment-bamboo tar (Shenxue, 2004, p11). The content of organic matters in purified bamboo vinegar is 10 ~ 20%. Vinegar can be refined further to produce acetic acid, propionic acid, butyric acid, carbinol and organic solvents. Main use of bamboo vinegar: diminish inflammation, sterilization, deodorization and dermatophytosis treatment ((Kumar et al, 2002).

2.8.4 Ash Content of Bamboo Charcoal

The ash content is made up of the inorganic constituents that do not burn to produce heat (Barbara et al, 2007). Therefore, as the ash content of a biomass increases, the heating value decreases and vice-versa (INBA, 2006).

The ash of bamboo charcoal is its inorganic constituent which is a white or shallow red substance of bamboo charcoal after it has been burned completely at high temperature. The ash element in bamboo charcoal are complex, all the inorganic components in bamboo will remain as ash, among which Si, Mg, Na, Mn etc. are relatively more (Shenxue, 2004). The ash percentage in bamboo charcoal increases from 2.93% - 4.69% with rising pyrolysis temperature while Li et al., (2016) estimated it to be 1.26% (for five years culm) to 1.95% (for one year culm). Li (2004 p.21-22) also estimated it to be 1.5% (for 5years culm) and 2% (1-year culm) (Shenxue 2004). Three and five years had no significant difference in ash content. There was no difference between top and middle portion for ash content, ash content in the bottom portion of the culm was the lowest (Li, 2007 p.7, Shenxue, 2004, Li, 2007 p.21-22). Ash analysis shows potassium levels are higher in the lower part of bamboo than the top portions (Ganesh, 2003).

Fixed carbon content and ash content rather increases with the increase in carbonization temperature. Charcoal obtained at 600C was found to have high calorific value (Kumar and Chandrashekar, 2014). The fixed carbon and volatile matter content are typically about 15% and 80% respectfully. The sulphur content in the fuel is none traceable and therefore poses no problem. Bamboo is classified to be a good fuel for energy conversion and comparable to any other wood. This is particularly so when the percentage of ash is below low 5%. (Ganesh, 2003). To achieve a calorific value near to that of commercial charcoal one must heat the bamboo to about 500C to obtain a clear yield of 3% (Kumar and Chandrashekar, 2014).

The ash content of bamboo as a biomass can reduce the heating value of the charcoal with increases in content. The ash content of biomass is essential for the heating value as it decreases with an increase in ash content (Osarfo, 2008). This is because the ash represents the part of the biomass that does not burn to give energy. The ash from the combustion of the biomass usually consist of the inorganic constituents of the biomass. In ash analysis of biofuels, eight elements are important to ash characterization in the inorganic phase. They are Aluminium, Calcium, Potassium, Phosphorus, Sodium, Iron, Silicon and Magnesium (Paulrud, 2004).

Carbon is the major constituent of biomass and its combustion increases the heating value therefore high carbon content is desirable in biofuels. Cellulose is also the major combustible compound in biomass because it is usually the principal compound in biomass. Cellulose in wood has a high heating value of approximately 19.5 MJ/kg, though lower than those of lignin and extractives. However, because of its higher percentage in terms of its composition, the overall calorific value tends to hinge on the cellulose content. High cellulose content is therefore needed for a species to be a viable energy crop. (Nemesthoty, 2008; Sarfo, 2008).

Nitrogen is also beneficial during combustion. A lower nitrogen content in biomass is desirable. During combustion, the nitrogen present combines with oxygen to form oxides of nitrogen. The problem of nitrous oxides from biomass combustion has been the source of research and worry for both environmental researchers and policy makers.

Nitrous oxides are said to have almost the same climate warming effect as carbon dioxide. Therefore, as we push towards biomass to reduce carbon dioxide released into the atmosphere, we inadvertently introduce another source of environmentally unfriendly gas, which according to scientists is a more powerful greenhouse gas than carbon dioxide. This was a research finding from a group of scientist including Paul Crutzen, a Nobel Prize winner (Smith, 2007; Sarfo, 2008). Bamboo is said to have some desirable fuel characteristics like low ash content and low alkali index with a lower heating value higher than most agricultural residues, grasses and straw but also lower than many woody biomass (Scurlock *et al.*, 2000).

Many literatures about bamboo tend to concentrate on the properties of the bamboo culm (physical, mechanical, anatomical structure of the culm) and carbonization process of the bamboo culm. Much attention has not been given to the impact of the culm properties on the production and the product (charcoal) of the culm.

Determination of bamboo age has been established by many literature using the morphological features (Shupe *et al*, 2005). This does not eliminate guess work completely. Further studies can be conducted to establish further scientific (empirical) way of determining the age of bamboo culm. The use of mechanical kiln for bamboo charcoal is not cost effective because it is expensive to design and use the mechanical kiln. Such research work is difficult to transfer the knowledge because it is expensive for the rural communities. This study is aimed at establishing the relationship between the characteristics of bamboo culm and their impact on the charcoal produced from the culm respectively.

2.8.5 Calorific Value of Bamboo Charcoal.

Calorific value is the total energy released as heat when a substance undergoes complete combustion with oxygen under standard conditions. It can also be said to be the amount of heat produced by the complete combustion of a unit fuel. The calorific value is conventionally measured with a bomb calorimeter (Jiang, et al., 2012).). The calorific value of bamboo is the amount of heat released during the combustion of a specified amount of it and it is an important property for assessing the biomass energy resource (Jiang, et al., 2012). The conclusive combustion characteristics of bamboo in relation to the culm's age was investigated by Huang (2014). Experiments about biomass productivity and fuel characteristics of different *Phyllostachys* species have been carried out by Scurlock *et al*. (2000).

Micro-structural and chemical changes with increasing age and their effects on generation of energy from bamboo are less well described (Li 2004, Van der Lugt *et al*. 2009, Janssen, 1991). The chemical composition of bamboo is similar to that of wood. Cellulose, Hemicellulose and lignin form most bamboo biomass, while minor constituent are resins, tannins waxes and inorganic salts (Fu *et al*. 2007). The high lignin content contributes to the high heating value of biomass. The holocellulose (cellulose and hemicellulose) is reported to have high heating value of 18.6 MJkg-1, whereas lignin heating value of 23.3 to 25.6KJg-1 (Demirbas, 2003). Biomass fuel has properties like heating value, moisture content, particle size, bulk density and ash temperature for microscopic analysis (Demirbas, 2000).

2.8.6 Uses of Bamboo Charcoal Products

The processing of Bamboo as charcoal could make handling and transport efficient enough to make an economically interesting small scale industry activity (Barbara, *et al* 2007). Charcoal is a carbon fuel derived from partial burning of wood or other carbon containing materials. It is used basically for cooking, deodorizing in refrigerators and as substrate in growing orchid, anthurium and other plants. It has been used effectively in the healing arts for centuries. Doctors still use it today as a healing agent, an antidote for poisons and an effective treatment for indigestion and gas. Charcoal can remove ammonia from diluted sulfuric acid Bamboo charcoal absorb bad odour and toxic substances and emit negative ions (Yen, 2005). Some bamboo charcoal are used for the preparation of bamboo briquette and the rest are used as raw bamboo charcoal for fuel.

Bamboo vinegar is extracted during production of bamboo charcoal. It contains about 400 chemical compounds and has many applications, including in cosmetics, insecticides, deodorants, food processing, and agriculture. Activated bamboo charcoal can create a soothing, relaxing hot spring-water like effect due to the release of minerals such as calcium, potassium and magnesium.

Charcoal is harmless when swallowed or breathed in, or when it comes in touch with the skin. It can mildly irritate bowels in sensitive persons but has no side effect or allergenic reaction to the person ingested it. For the past centuries, charcoal has been used effectively in healing arts (Kumar and Chandnashekar. 2014). Activate bamboo charcoal works great to regulate humidity, which is important for the health of the human hair body. Activated Bamboo Charcoal can absorb minerals, toxins, impurities, and other harmful substances from the skin and make the body to have stronger and healthier skin.

Bamboo charcoal soap has also been used in many Asian countries for centuries. It is known as the “black diamond” of healers (Kumar, 2002). Another use for activated bamboo charcoal soap is to treat eczema, psoriasis and dry cracked skin. Bamboo kills bacteria and bamboo charcoal cleans the skin thoroughly and allows the body's natural moisturizers to work effectively on eczema and psoriasis. Purify drinking water - Drop a small piece or bag into a glass or pitcher (Huang, 2014). Bamboo charcoal is also used as additives to many foods in many Asian countries (Figure 3).

Figure **.3:).** Utilization of Bamboo Charcoal in everyday life Source: (a) and (b) www.https://food-hacks.wonderhowto.com, (c) and (d):(Meinjie, 2004).(e) and (f) www.https://food-hacks.wonderhowto.com, (g= personal picture) and (h): INBAR (2010).

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Material and Methods

Study site

The samples for the study was collected from Bobiri Forest Reserve (BFR) (60° 40'-60°44'N) and 10° 15'- 10°22'W). BFR is located approximately 30 km east of Kumasi, Ghana and covers an area of 54.6 km^2. BFR is divided into 73 compartments with four designations, namely, research, butterfly sanctuary, strict nature reserve and production forest. These blocks are under two separate management regimes. The production forest is managed by the Forest Services Division of the Forestry Commission of Ghana while the research, butterfly sanctuary and strict nature reserve designated compartments are managed by the Forestry Research Institute of Ghana (FORIG).

BFR is a mega biodiversity reserve with many flora and fauna species (Figure 4). Floral composition belong to the moist semi-deciduous tree species and the soil type is the Forest Ochrosol (Hall and Swaine, 1981). The reserve experiences a long rainy season from March to June and a short rainy season from September to November. The dry season occurs between December and March with a relatively shorter dry season in August. The mean annual precipitation of the reserve is between 1200 and 1750 mm with the mean annual temperature of 25°C.

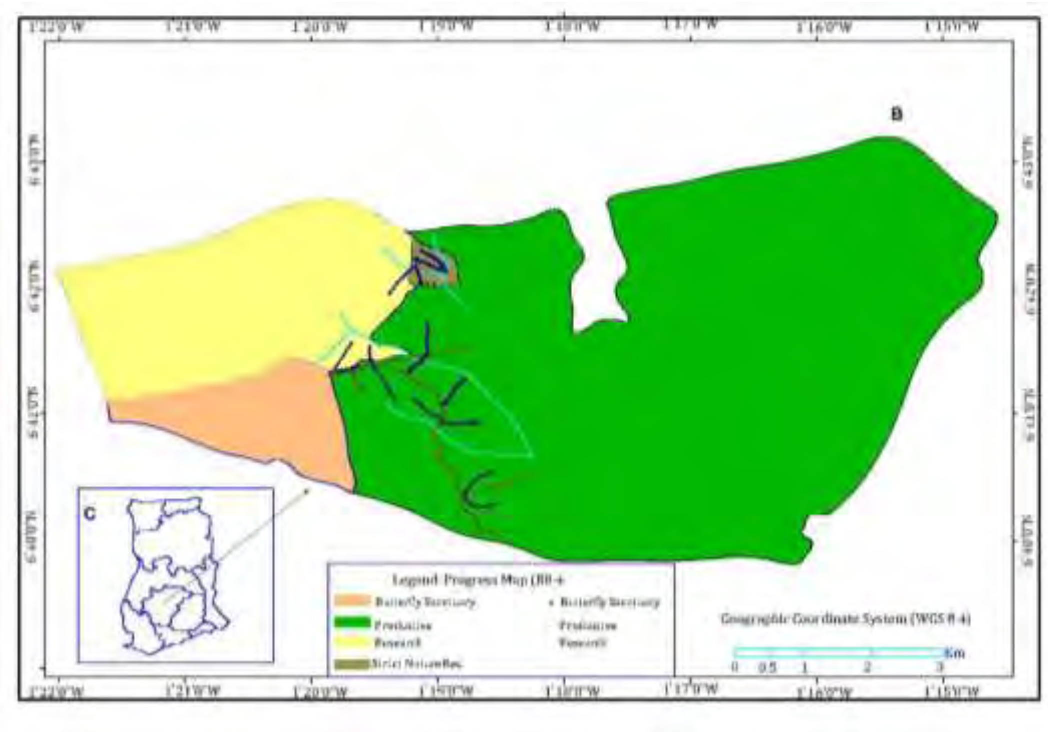

Figure 4: Map of Ghana showing location of Bobiri forest and butterfly sanctuary. Source of map: (Resource Management Support Centre (RMSC) of the Forestry Commission; Djagbletey, (2014).

3.2 Sampling of Bamboo Species

B. vulgaris, *B. var. vitata* and *O. abbyssinica* bamboos were sampled from Bambusetum at the Forestry Research Institute of Ghana's research station at Bobiri forest reserve. In April, 2016, five 0.01ha (10m × 10m) sub-plots were randomly selected each for *B. vulgaris*, *B. var. vitata* and *O. abbyssinica*, making a total of 15 sub-plots (Figure 5). Culms in each sampled plot were counted (Figure 6). The determination of the culm age was based on the features of culm sheath, the development of branches and leaves, and the external colour of the culm (Yen *et al.*, 2010). The culm ages were determined as follows: One-year-old bamboo had sheath still on the culm and the culm surface was covered a white powder. The two-year old bamboos had the culm sheaths on but were beginning to rot; the white powder on the culm surface also beginning to disappear while the culm turning green. For the 3-year old bamboo, the culm sheath had begun to drop and the culm bottom had turned dark green. The 4-year old bamboo had the sheath disappeared from the surface of the culm, which was covered with mold and had become yellowish green in colour. For bamboos that were 5 years old and above, the culm surface was covered with mold or moss and had turned brownish green (Lin, 1961).

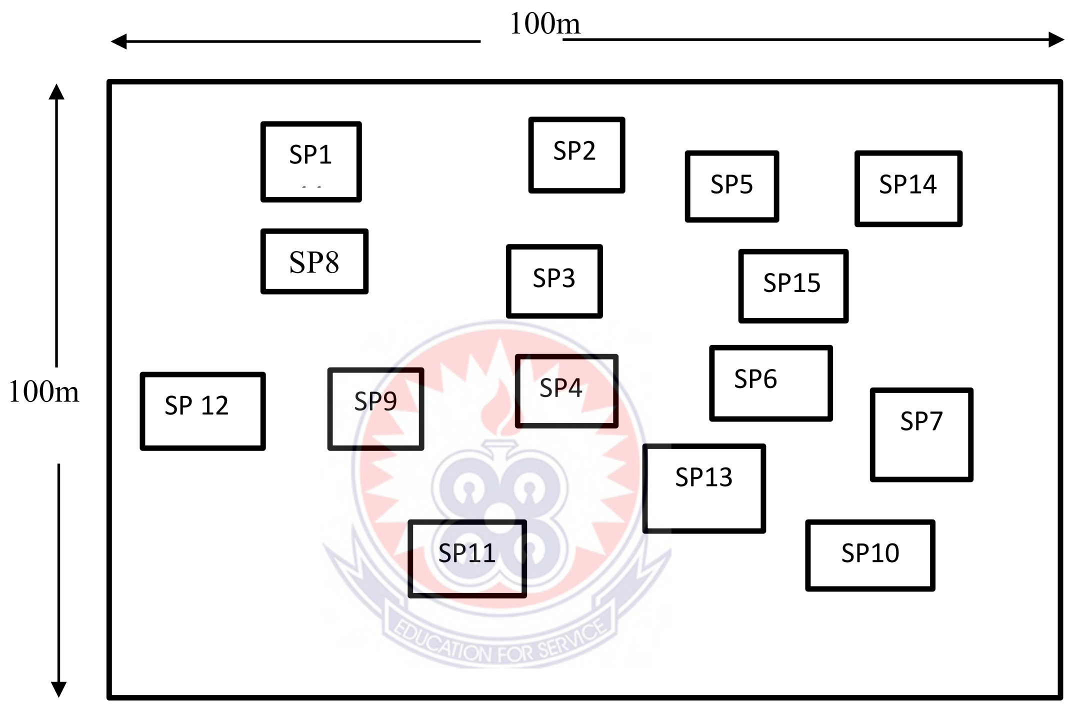

Figure 5. Plot layout for bamboo species and sample collection SP= Sample Plot (10m×10m)


Figure 6. Counting Bamboo Clumps and Culms in the Bobiri Forest Reserve.

3.3 Estimation of Aboveground Biomass of Bamboo Species

Aboveground of bamboo biomass was estimated by harvesting randomly selected 1-2, 3-4, and 5-6-year-old culms of *B. vulgaris*, *B. var. vitata* and *O. abbyssinica*. Five culms per age class were harvested for each of the species (i.e. young = 5 culms, matured = 5 culms and dead = 5 culms for B. vulgaris, B. vulgaris vitata and O. abbyssinica respectively): thus a total of forty-five bamboo culms were harvested from the five sub-plots based on age and diameter class (Figure 7). Harvested culms of the three species on each bamboo clump in all the five sampled plots were also counted recorded.

After harvesting, the total culm height and diameter at breast height (DBH) were measured and the culm samples were separated into leaf, branch and culm components. The culms were further divided into 1 meter intervals and the respective fresh weights of leaf, branch and the culm pieces were taken immediately (Figure 7). Representative sub-samples of the leaves, branches and culms were collected and their fresh weights were taken after which they were oven-dried at 103 ± 2° C to get their oven-dried weights. The total dry weight or biomass for each component of the sampled bamboos was calculated as proposed by FAO (2012).

$$TDW = TFW\frac{SDW}{SFW}$$

Where *TDW* = total dry weight or biomass; *TFW* = total fresh weight; *SDW* = sub-sample dry weight; *SFW* = sample fresh weight.

The sum of the entire components represents oven-dried weight or biomass of that bamboo species. The total stand biomass for *B. vulgaris*, *B. var. vitata* and *O. abbyssinica* was determined and then computed on a hectare basis.

Figure 7. Harvesting and weighing of bamboo culms, branches and leaves in the Bobiri Forest Reserve and Butterfly Sanctuary.

Allometric models to estimate the AGB of the bamboo species

Allometric models ($Y = a \times DBH^b$) were developed to predict biomass of culms, branches and foliage at different ages for the three species (Yen et al., 2010). *Y*= biomass, *a* and *b* = parameters of the allometric equation, *DBH* = diameter at breast height. The quality of the allometric models was evaluated by utilizing both internal and external model validation techniques. For the internal validation, the original data used to develop the models were utilized whereas fresh data were collected from the same study area for the purpose of evaluating the external validity of the models. R^2, RMSE and MAPE were used for the evaluation of the internal validity of the models.

In addition, plots of predicted versus observed biomass values with their associated correlation coefficient values (Pearson r) were used as a basis for evaluating the quality of the models. Regarding the external validity, the percent prediction error (PPE) based on observed and predicted biomass was utilized (Table 4). The percentage Prediction Error was utilized to evaluate the external validity of the model. PPE = (*O*-*P*)/*O*×100 where *O* and *P* are observed and predicted biomasses.

3.4 Sampling Bamboo for Fuel Property Analysis

The samples of bamboo parts (culms, branches and leaves) were put into poly bags, labeled and tightly tied to prevent evaporation. The samples were weighed immediately and carefully using a digital scale (off-site, but within the same day) to determine the exact weight of each sample taken in the field (Figure 8). Fresh weights of the samples were recorded using the field data forms. Samples were sent to laboratory for the analysis of dry mass. Samples which were oven-dried at 103 ± 2° C was weighed and the total dry weight or biomass for each component of the sampled bamboos was calculated. (Figure 9). Two groups of samples were utilized in the analysis of the fuel properties of the bamboo species. The first group was the control group made up of raw (untreated) bamboo culms whereas the second group was the treatment group made up of bamboo culms carbonized at 300° C. For each of the bamboo species, samples of bamboo were assigned to the control and treatment groups at random.

Figure 8: Sample culms, branches and leaves of bamboo species before oven drying.

Figure 9. Sample culms, branches and leaves of bamboo species after oven drying.

3.5 Determination of Gross Calorific Value, Proximate and Ultimate Analysis of Bamboo Species

Gross calorific values (GCV) of the bamboo samples were determined on the basis of thermal energy generated by complete combustion of the samples in a constant pressure chamber. GCV of the bamboo samples was measured using a C6000 bomb calorimeter analyzer manufactured by IKA-Werke GmbH & Co.KG, Stauffen, Germany and in accordance with DIN EN 14918 standard. A proximate analysis was conducted to determine the fraction of ash and volatile matter (VM). The fixed carbon (FC) content was obtained by difference. Proximate analyses of the biomass samples were performed according to ASTM D 5142-04 standard test method. The ultimate analysis provides the percent weight of carbon, hydrogen and oxygen as well as sulphur and nitrogen. Ultimate analyses of the samples were performed according to ASTM D 5373-02 (for carbon, hydrogen and nitrogen contents) and ASTM D 4239-05 for Sulphur content).

3.6 Determination of Cellulose, Hemicelluloses and Lignin Contents

The bamboo samples (control and carbonized groups) for the chemical analysis were air-dried and conditioned to moisture content between 15% - 20% (INBAR, 2006). Samples were placed in a Wiley mill and ground. Each material was then placed in a shaker with sieves to pass through a 40 mesh sieve (425µm) yet retained on a 60 mesh sieve (250µm) and stored for chemical analyses.

About 10g air-dried of the ground samples that passed through a number 60 (250µm) sieve and retained by number 80 (180µm) sieve was placed in an extraction thimble ensuring that it did not extend above the level of the top of the siphon tube. Samples were extracted for 8 hours using a mixture of alcohol-acetone, 1:2 (v/v) in the Soxhlet extraction apparatus -TAPPI, T204 cm-88.

The sample in the thimble was returned to the extractor and extraction continued with 95% alcohol (about 200ml) for 4 hours until the alcohol siphoned over colorless. The samples were removed from the thimble and spread out on a thin layer and allowed to dry in the air until they were free of alcohol. The dried alcohol-free samples were placed in the thimble and extracted with 200ml of hot water for 8 hours. The extracted materials were air dried thoroughly. The samples after hot water extraction were air-dried and used as extractive free samples for the determination of cellulose, hemicelluloses and lignin and were determined according to TAPPI standard methods T203 cm-74, T203 cm- 74 and T222 cm-88, respectively.

3.7 Determination of Ash Content

The ash content of biomass is essential for the heating value as it decreases with an increase in ash content (INBAR, 2006). This is because the ash represents the part of the biomass that does not burn to give energy. The ash content (g/g) of the sample bamboo culms was determined according to the TAPPI standard T 2II. Oven-dried bamboo pellets were weighed before being place in a muffle furnace and ignited at 550ºC for 3 h. The ash percentage was estimated according to equation below:

Ash content (%) = Mass of ash ×100/Total mass of oven-dried pellet samples (Amoah and Cremer, 2017).

3.8 Carbonization of the Samples

Carbonization describes the conversion of organic substance into carbon at an elevated temperature. Bamboo carbonization is the heating in brick kiln or mechanical kiln with little air by means of the heat energy generated by burning firewood to pyrolyse bamboo and produce bamboo charcoal (Shenxue, 2004). Culms of all the three species under study were carbonized into charcoal through traditional method of producing charcoal in an earth kiln in a single batch (UNDP, 2010).

Culm samples underwent series of pre-carbonization preparation ranging from cutting, labelling, weighing and air-drying of culms. Samples of raw bamboo were air dried to moisture content of 15%-20% before loading into the kiln as stated by INBAR (2006). Sample culms of all the three species were sawn into segments with lengths of 61cm each and labelled in an ascending order; young culm, matured culm and dead culm. The labelling was to aid in the arrangement of the sample culms and for easy identification before and after carbonization.

Traditional Kiln model for making charcoal was used for the carbonization of the culms. Samples were arranged in a shallow rectangular dug trench on the ground (Figure 10.a). Samples were arranged according to species using metallic plates to separate one species from the other. The purpose of the metallic plates were to aid the identification of charcoals of each species after carbonization. The well-arranged bamboo samples were covered with fresh weeds to separate the bamboo from the cover soil (Figure 10.b).

Weeds covered bamboo culms in the shallow trench were also covered with semi wet soil dug from the shallow rectangular trench. The purpose for covering the sample culms with weeds in this type of kiln is for the weeds to serve as a barrier between the sample bamboo culms to be carbonized and the cover soil so that the cover soil will not quench the fire in the kiln. The thickness of the cover soil used for the covering of the sample bamboo before carbonization was about 10cm to 15cm. The kiln size was 70cm x 60cm with a height of 40cm.

Two small vertical pipes were put through the cover soil and the cover weeds to serve as vents to supply oxygen to aid the pyrolysis. Pyrolysis of the charcoal took about 24 and a half hours to complete. Charcoals of the three species were carefully removed and cooled with dry soil and bagged in a transparent polythene bags to prevent absorption of atmospheric moisture. Charcoal Samples of the three species were labeled and sent to the laboratory for analysis.

Figure 10.a: Carbonization of the Bamboo culms (preparation stage).

Figure 10.b: Carbonization of the bamboo culms (pyrolysis and bagging stage)

3.8.1 Determination of Gravimetric Yield for Charcoals of the Three Bamboo Species

Weights of the selected samples of bamboo culms for the carbonization were determined and recorded before the carbonization. Samples were sawn to a uniform length of 61cm according to the size of kiln which was used for the carbonization. Three main sections (top, middle and bottom) of each selected sample culm were sawn and weighed with a digital scale (Table 8). Charcoal obtained from the carbonized culms were sealed and labeled in polybags to prevent absorption of atmospheric moisture.

Weight of culms after carbonization (charcoal) of all the three species were determined on a digital scale. Details of the pre-carbonization weights and post carbonization weights are recorded in Table 8. Gravimetric yield of the three species of the bamboo after the carbonization was determined using the following: Gravimetric yield = Weight of bamboo charcoal/ Weight of raw bamboo ×100. (Yen et al., 2010). Details of the Gravimetric yield of the carbonized culms are displayed in Table 8.

3.9 Data Analysis

The quality of the allometric models was evaluated by utilizing both internal and external model validation techniques. For the internal validation, the original data used to develop the models were utilized whereas fresh data were collected from the same study area for the purpose of evaluating the external validity of the models. The study relied on R^2, RMSE and MAPE for the evaluation of the internal validity of the models. In addition, plots of predicted versus observed biomass values with their associated correlation coefficient values were used as a basis for evaluating the quality of the models. Regarding the external validity, percent prediction error (PPE) based on observed and predicted biomass was utilized (Table 4).

CHAPTER FOUR

RESULTS AND FINDINGS

4.1 Bamboo Culm Density and Culm Type Distribution

Three of the bamboo species (viz. *B. vulgaris vulgaris, O. abbyssinica, and B. vulgaris var. vitata*) planted in the Bobiri Forest Reserve were studied. The density of the stand of the three species totaled 16,763 culms ha^{-1} during May 2016. *B. vulgaris var. vitata* represented 43% (7,171culms ha^{-1}) of the total stand density; *B. vulgaris,* 37% (6,267 culms ha^{-1}) and *O. abyssinica*, 20% (3,325 culms ha^{-1}). Among the culm types, mature bamboo presented the highest stand density (34%; 5,783 culm ha^{-1}), followed by dead culms (23%; 3,849 culms ha^{-1}), young culms (19%; 3,256 culms ha^{-1}) and shoots (2%; 393 culms ha^{-1}). Harvested culms comprised 21% (3,482 culms ha^{-1}) of the total stand. Distribution of culm types for *B. vulgaris* was preponderant towards mature culms; for *O. abyssinica* and *B. vulgaris* var. *vitata*, the distribution was towards harvested and dead culms, respectively (Fig. 11). The Density of the three species presented the matured culm as the culm with the highest density (34%). Dead culm represented (23%), young culm represented (19%), shoot represented (2%) and Harvested culms represented (21%) of the total stand density of Bobiri Forest Reserve in Ghana.

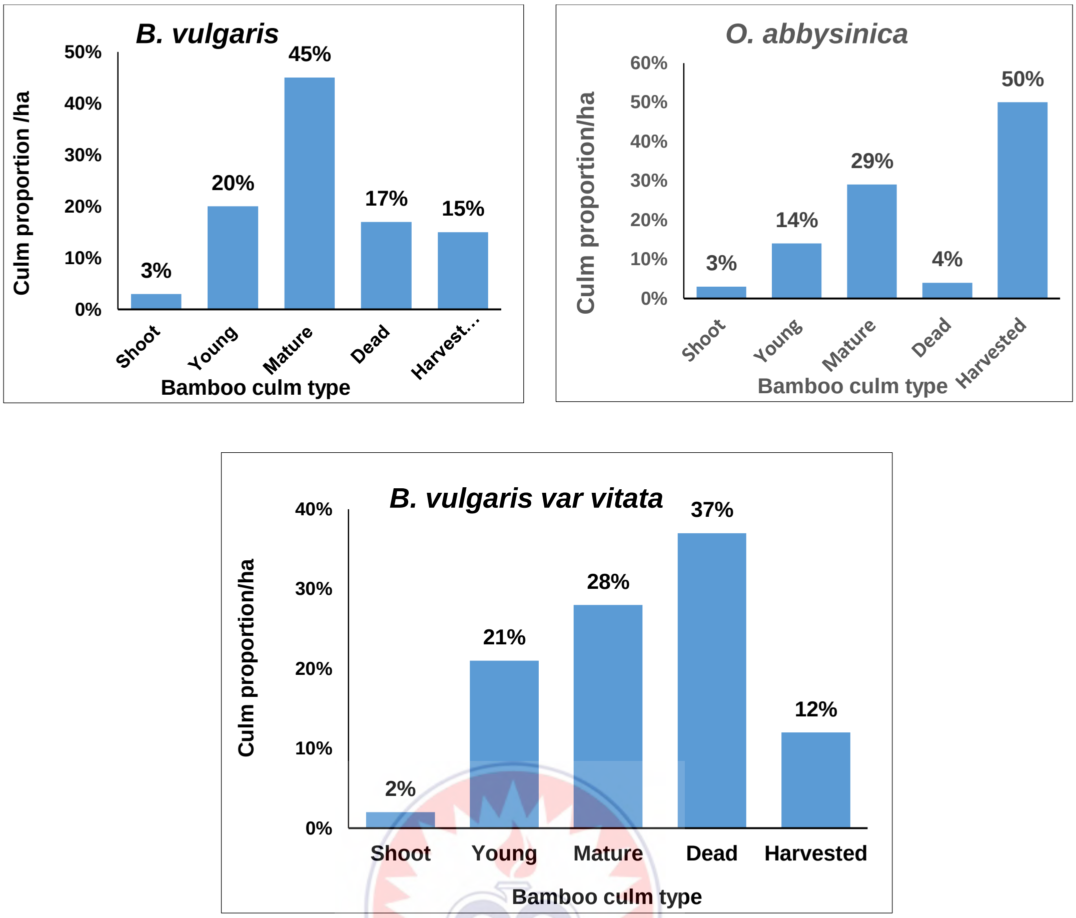

Fig. 11: Culm population distribution of different culm types of the three studied bamboo species

4.2 Biomass Structure and Predicting Biomass

Biomass structure and predicting biomass for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata*. Distribution of biomass across different bamboo components and ages for the three species showed that the culm contributed the highest biomass (80-96%), followed by branches (3-15%) and foliage (1.1-7%). Among the bamboo species, highest culm biomass was observed in *B. vulgaris*, whereas lowest and the intermediary was found in *O. abbyssinica* and *B. vulgaris var. vitata,* respectively (Fig. 12).

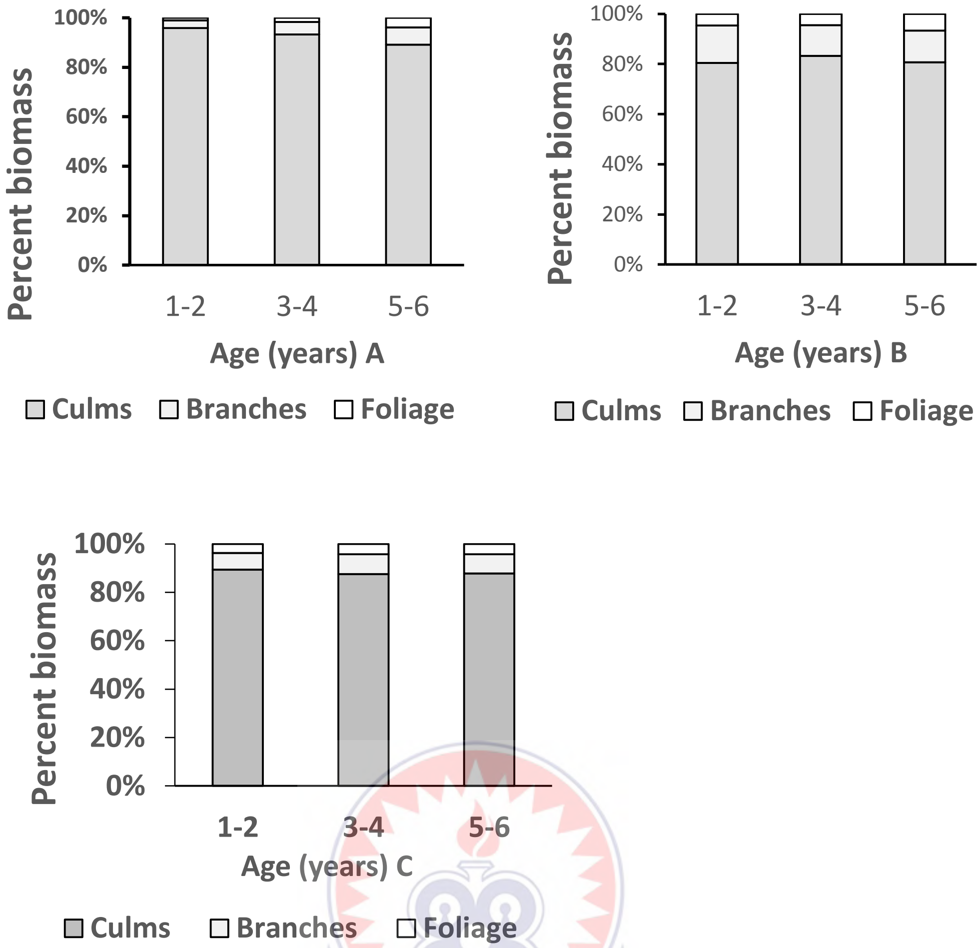

Fig 12: Proportion of foliage, branches and culms to aboveground biomass for different age classes of (a) *B. vulgaris*, (b) *O. abbyssinica* and *(c) B. vulgaris var. vitata*

The DBH, H and biomass of the foliage, branches and culms as well as the total aboveground biomass for *B. vulgaris, O. abbyssinica* and *B. vulgaris var. vitata* are reported in Table 1. Mean DBH (7.80 cm) and H (19.77cm) for *B. vulgaris* and 7.36 cm and 19.03m for *B. vulgaris var. vitata* were comparable. Low mean DBH (2.85cm) and H value (10.94m) were observed for *O. abbyssinica*. No statistically significant differences in H and DBH were observed for *B. vulgaris* in respect of culm age ($p > 0.05$) whereas for *O. abbyssinica* and *B. vulgaris var. vitata*, significant differences in mean DBH were found in respect of culm age ($p < 0.05$). Aboveground biomass across different ages of bamboo showed significant difference for *B. vulgaris* ($F = 8.035$, $p < 0.001$) and *B. vulgaris var. vitata* ($F = 5.211$, $p < 0.05$) but non-significant difference was observed for *O. abbyssinica* ($F = 2.648$, $p > 0.05$). Across the bamboo of *O. abbyssinica*, allocation of aboveground biomass was highest in juvenile (1-2 years) bamboo whereas mature (3-4years) and dead (5-6years) presented the highest aboveground biomass for *B. vulgaris* and *B. vulgaris var. vitata*, respectively (Table 1).

Table 1

Diameter, height and biomass distribution of *Bambusa vulgaris, Oxynanteria abbyssinica and B. vulgaris var. vitata*

Age (years)	N	DBH (cm)	H (m)	Biomass (kg)			
				Foliage	Branch	Culm	Aboveground
B. vulgaris							
1-2	5	8.17 ± 1.50	17.87 ± 4.41	0.43 ± 0.25	1.18 ± 0.55	35.72 ± 11.73	37.32 ± 12.81
3-4	5	8.54 ± 0.86	20.33 ± 4.16	0.60 ± 0.14	1.92 ± 0.44	35.13 ± 8.79	37.65 ± 9.54
5-6	5	6.99 ± 0.66	21.10 ± 4.29	0.64 ± 0.14	1.19 ± 0.41	15.08 ± 4.00	16.91 ± 4.50
Oxynanteria abbyssinica							
1-2	5	1.60 ± 0.42	13.00 ± 1.00	0.31 ± 0.15	0.98 ± 0.44	5.50 ± 3.09	6.79 ± 3.57
3-4	5	1.54 ± 0.29	13.40 ± 1.41	0.27 ± 0.15	0.70 ± 0.37	4.72 ± 2.20	5.69 ± 2.69
5-6	5	1.14 ± 0.08	13.43 ± 3.66	0.21 ± 0.04	0.39 ± 0.06	2.51 ± 0.41	3.11 ± 0.48
B. vulgaris var. vitata							
1-2	5	5.14 ± 0.63	17.76 ± 2.40	0.65 ± 0.45	1.11 ± 0.49	14.11 ± 5.26	20.36 ± 6.32
3-4	5	7.31 ± 1.73	22.00 ± 2.64	1.41 ± 0.91	2.53 ± 0.97	26.78 ± 9.99	36.62 ± 12.65
5-6	5	8.85 ± 1.75	22.33 ± 1.154	1.74 ± 1.00	2.90 ± 0.93	32.90 ± 11.49	44.65 ± 14.03

Mean ± standard deviation

Total aboveground biomass (AGB) of *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* in the Bobiri Forest Reserve was estimated at 190.61Mgha^{-1}. Of this, culm, branch and foliage components contributed 90.3%, 5.7% and 4.0%, respectively (Table 2). At the species level, *B. vulgaris* made up to 60.3% of the total AGB, followed by *B. vulgaris var. vitata* (37.5%) and *O. abbyssinica* (2.2%). Three-to-four-year-old culm age classes contributed the highest proportion of stand biomass for *B. vulgaris* and *O. abbyssinica* whereas for *B. vulgaris var. vitata,* it was the 5-6-year-old culm age class that represented the highest proportion of stand biomass.

Table 2

Biomass of foliage, branches, culm and aboveground per ha among different bamboo species

Bamboo species		Biomass Mg/ha			
	Age (years)	Foliage	Branch	Culm	Aboveground
B. vulgaris					
	1-2	0.54	0.98	30.55	32.08
	3-4	1.69	3.53	59.36	64.59
	5-6	0.64	0.77	16.89	18.29
	Total	**2.87**	**5.29**	**106.80**	**114.97**
O. abbyssinica					
	1-2	0.13	0.27	1.03	1.43
	3-4	0.23	0.39	0.93	1.55
	5-6	0.02	0.03	0.22	0.27
	Total	**0.38**	**0.68**	**3.18**	**4.24**
B. vulgaris var. vitata					
	1-2	0.54	0.60	7.79	8.93
	3-4	1.48	1.73	19.26	22.47
	5-6	2.38	2.59	35.04	40.01
	Total	**4.41**	**4.92**	**62.08**	**71.41**
Grand Total		**7.66**	**10.89**	**172.06**	**190.61**

Allometric models ($Y = a \times DBH^b$) were developed to predict biomass of culms, branches and foliage at different ages for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* (Table 3).

In general, DBH of the bamboos explained the variation in the biomass of the culms, branches and foliage fairly well with R^2 values ranging from 0.596 to 0.999. Among the allometric models, those for the culms presented the highest predictive power with r-squared in the range 0.930-0.972, 0.868-0.916, and 0.870-0.988, respectively, for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata*. Similarly, relatively higher r-squared values were obtained for models involving the total AGB whereas those that predicted foliage biomass presented the lowest predictive power. The percentage Prediction Error was utilized to evaluate the external validity of the model. $PPE = (O-P)/O \times 100$ where O and P are observed and predicted biomasses. The PPEs provided the directional difference between the observed biomass and predicted biomass. A positive PPE value indicated that the observed biomass was larger than the predicted biomass and the model underestimated the biomass. A negative PPE value indicated that the observed biomass was smaller than the predicted biomass and the biomass model overestimated the biomass. In order to assess the magnitude of the difference between the observed and predicted bamboo biomass, the absolute percentage differences (*PPE*) were also calculated.

Table 3

The parameters of allometric models for predicting bamboo biomass with DBH indicating a, b, R^2 mean absolute error (MAE) and root mean square error (RMSE)

Type of bamboo	Section/Age	$Y = a \times DBH^b$				
		a	b	R^2	RMSE	MAPE
B. vulgaris	Stem					
	1-2 years	0.786	1.806	0.972	1.861	5.27
	3-4 years	0.257	2.286	0.930	1.833	5.12
	5-6 years	0.058	2.850	0.939	0.929	5.76
	Branch					
	1-2 years	0.005	2.604	0.950	0.159	8.26
	3-4 years	0.028	1.964	0.793	0.160	7.65
	5-6 years	0.001	3.680	0.898	0.123	9.13
	Foliage					
	1-2 years	0.001	2.826	0.874	0.114	15.71
	3-4 years	0.015	1.727	0.596	0.073	11.41
	5-6 years	0.008	2.218	0.813	0.064	8.04
	Total aboveground biomass					
	1-2 years	0.763	1.840	0.971	2.062	5.47
	3-4 years	0.291	2.260	0.926	1.995	5.20
	5-6 years	0.061	2.883	0.955	0.995	4.82
O. abbyssinica	Stem					
	1-2 years	2.105	1.890	0.916	0.927	13.41
	3-4 years	1.590	2.408	0.868	0.610	10.92
	5-6 years	1.853	2.256	0.887	0.126	4.46
	Branch					
	1-2 years	0.415	1.722	0.935	0.117	10.59
	3-4 years	0.242	2.309	0.709	0.164	18.78
	5-6 years	0.293	2.169	0.881	0.021	4.02
	Foliage					
	1-2 years	0.100	2.211	0.795	0.096	21.98
	3-4 years	0.072	2.796	0.691	0.077	21.13
	5-6 years	0.158	2.014	0.598	0.022	8.82
	Total aboveground					
	1-2 years	2.632	1.881	0.955	0.771	9.53
	3-4 years	1.910	2.410	0.855	0.808	11.63
	5-6 years	2.304	2.233	0.919	0.126	3.38
B. vulgaris var. vitata	Stem					
	1-2 years	0.140	2.795	0.870	1.916	11.06
	3-4 years	0.842	1.725	0.974	1.928	5.47
	5-6 years	0.614	1.815	0.998	0.466	1.22
	Branch					
	1-2 years	0.004	3.473	0.900	0.173	11.26
	3-4 years	0.085	1.687	0.900	0.326	9.20
	5-6 years	0.114	1.475	0.636	0.458	14.85
	Foliage					
	1-2 years	004	5.907	0.859	0.187	25.52
	3-4 years	0.004	2.858	0.961	0.120	10.52
	5-6 years	0.002	3.111	0.969	0.127	8.93
	Total aboveground					
	1-2 years	0.412	2.369	0.902	2.181	10.17
	3-4 years	1.606	1.562	0.977	2.226	5.65
	5-6 years	1.292	1.618	0.999	0.516	1.39

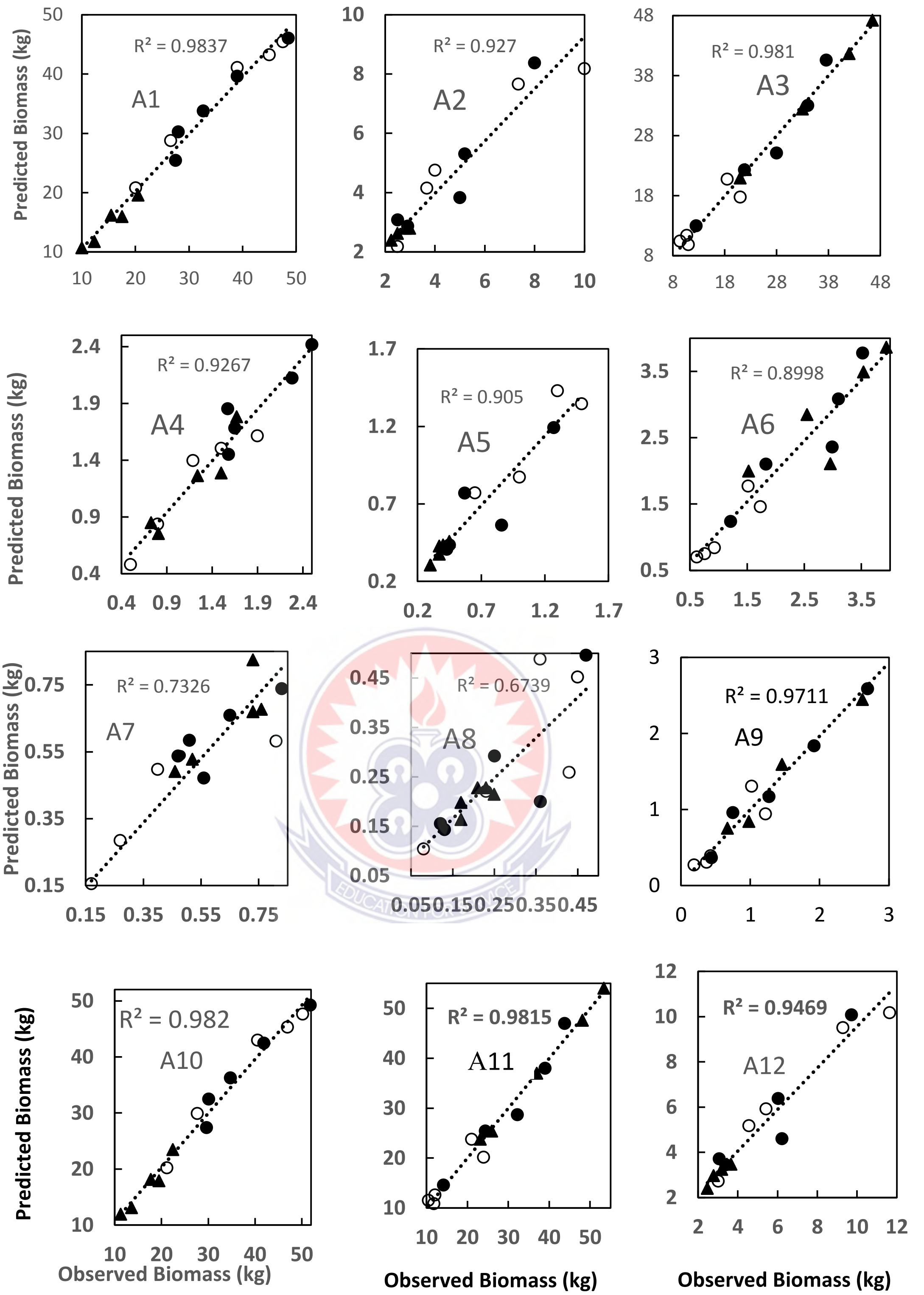

Fig. 13: Observed vs. predicted bamboo culm biomass for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* (A1-A3, respectively), branches (A4-A6), foliage (A7-A9) and AGB (A10-A12). "●", "○" and "▲" represent 1-2, 3-4 and 5-6 years bamboos, respectively.

Table 4

Percentage prediction error (PPE) based on observed and predicted biomass of bamboo samples used for external validity

Bamboo species	DBH (cm)	Observed Biomass (kg)	Predicted Biomass (kg)	PPE
B. vulgaris				
Culm				
1-2 years	8.01	34.5	33.67	2.42
3-4 years	9.00	45.5	39.03	14.21
5-6 years	7.50	20.1	18.05	10.01
Branches				
1-2 years	8.01	1.35	1.13	16.68
3-4 years	9.00	2.40	2.10	12.67
5-6 years	7.50	1.62	1.66	2.25
Foliage				
1-2 years	8.01	0.34	0.36	5.17
3-4 years	9.00	0.61	0.67	9.35
5-6 years	7.50	0.69	0.70	1.63
O. abbyssinica				
Culm				
1-2 years	1.92	6.31	7.22	14.46
3-4 years	1.84	7.89	6.90	12.50
5-6 years	1.10	2.49	2.29	6.98
Branches				
1-2 years	1.92	1.43	1.27	10.76
3-4 years	1.84	1.26	0.98	21.49
5-6 years	1.10	0.35	0.36	2.93
Foliage				
1-2 years	1.92	0.49	0.42	13.66
3-4 years	1.84	0.52	0.39	23.83
5-6 years	1.10	0.18	0.19	6.35
B. vulgaris var. vitata				
Culm				
1-2 years	4.42	10.96	8.91	18.66
3-4 years	5.67	15.28	16.79	9.93
5-6 years	7.02	20.34	21.09	3.73
Branches				
1-2 years	4.42	0.73	0.69	4.43
3-4 years	5.67	1.42	1.58	11.79
5-6 years	7.02	2.06	2.01	1.96
Foliage				
1-2 years	4.42	0.14	0.12	18.11
3-4 years	5.67	0.07	0.06	14.08
5-6 years	7.02	0.05	0.04	6.36

4.3 Carbon Storage in Culms, Branches and Foliage

Carbon storage in culms, branches and foliage of *B. vulgaris, O. abbyssinica and B. vulgaris var. vitata* on average, Carbon concentration was highest in culms of *B. vulgaris, O. abbyssinica and B. vulgaris var. vitata* (43.31%) and lowest in foliage (38.58%) with branches having intermediate Carbon concentration (42.58%). At the species level, the average Carbon concentrations were 42.38%, 41.06% and 41.04% for *B. vulgaris, O. abbyssinica and B. vulgaris var. vitata,* respectively (Table 5). The differences in Carbon concentration across the species were non-significant ($p > 0.05$). Similarly, the effect of bamboo age on Carbon concentration was found to be non-significant ($p > 0.05$). Carbon storage in aboveground biomass (AGB) was 50.76Mgha^{-1}, 1.98Mgha^{-1} and 33.87Mgha^{-1} for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata*, respectively (Table 6). For all the bamboo species, the allocation of Carbon storage in AGB was highest in the culm, followed by branches and foliage. The culms of *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* respectively, contributed 93%, 78% and 89% of the total Carbon storage in AGB. Carbon storage in culms, branches and leaves were determine by using the following formula:

- Carbon storage = AGB × Percentage Carbon Content.
- PCC = the ratio of the carbon weight to the dry weight in plant bodies (Yen et al., 2009).

Details of the carbon storage components (culms, branches and leaves) of *B. vulgaris, O. abbyssinica and B. vulgaris var. vittata* are represented in Table 6.

Table 5

Carbon concentration (% dry matter) in bamboo components (culm, branch and foliage) of different age classes for *B. vulgaris, O. abbyssinica and B. vulgaris var. vitata*

Culm age class	*B. vulgaris*			*O. abbyssinica*			*B. vulgaris var. vitata*		
	Culm	Branch	Foliage	Culm	Branch	Foliage	Culm	Branch	Foliage
1-2 years	44.02	43.74	38.34	43.87	42.36	37.97	41.89	42.26	39.18
3-4 years	44.45	43.56	39.04	43.00	42.05	38.25	42.70	41.89	39.02
5-6 years	44.36	44.01	39.86	43.09	41.89	37.08	42.44	41.43	38.52

Table 6

Carbon storage (Mg/ha) of foliage, branches, culm and aboveground per ha for *B. vulgaris, O. abbyssinica and B. vulgaris var. vitata*

Bamboo species	Age (years)	Foliage	Branch	Culm	Aboveground
B. vulgaris					
	1-2	0.21	0.43	13.45	14.09
	3-4	0.66	1.54	26.39	28.59
	5-6	0.25	0.34	7.49	8.09
	Total	**1.12**	**2.31**	**47.33**	**50.76**
O. abbyssinica					
	1-2	0.05	0.11	0.45	0.61
	3-4	0.09	0.16	0.83	1.08
	5-6	0.01	0.01	0.09	0.12
	Total	**0.15**	**0.29**	**1.54**	**1.98**
B. vulgaris var. vitata					
	1-2	0.21	0.26	3.26	3.73
	3-4	0.58	0.72	8.22	9.52
	5-6	0.92	1.07	14.87	16.86
	Total	**1.71**	**2.05**	**30.11**	**33.87**
Grand Total		**2.98**	**4.65**	**75.06**	**82.68**

4.4 Chemical Composition of the Bamboo Culms

Chemical composition of bamboo is similar to that of wood. Cellulose, Hemicellulose and lignin form most of bamboo biomass, whiles minor constituents are resins, tannins, waxes and inorganic salts (Yen et al. 2011; Zhou, G. M., 2006). Cellulose presented the highest percentage in *O. abbyssinica* young culms (41.08%) matured culms (39.94 %) branches (47.55%) and leaves (28.93%). High percentages of cellulose contents were recorded in the culms of the two species, *B. vulgaris var. vitata* and *B. vulgaris*. Matured culms of *B. vulgaris* recorded the highest Cellulose content (48.99%) among all the culms (Table 7). Leaves of *O. abbyssinica* presented the lowest cellulose content (28.93%). Hemicellulose presented the next highest chemical component in all the three bamboo species with dead culms of *B. vulgaris* recording the lowest percentage (16.11%) whiles matured culm and leaves of *B. vulgaris var. vitata* presented the highest content 26.95% and 28.25% respectively. The holocellulose (Cellulose and Hemicellulose) is reported to have a high heating value of 18.6MJKg^{-1} (Demirbas 2005). Matured and dead culms of *B. vulgaris* presented a high calorific value of 17.01 MJkg-^{1} and 17.23MJkg-^{1} respectively may be due to the high content of lignin and holocellulose in them. High lignin contents contributes to high heating value of biomass (Kumar and Chandrashekar 2014). Matured and dead culms of *B. vulgaris* which have high lignin contents of (19.00%) and (19.03%) respectively in comparison with the rest of the culms might have contributed to the high calorific value of *B. vulgaris* matured and dead culms (Fig. 1.4).

High ash percentage in *B. vulgaris* leaves (15.23%) may be the reason for its lowest calorific value compare to the culms and branches (Fig. 8). The high ash content in bamboo biomass can be attributed to the presence of high silica content in bamboo. High ash content negatively affect the heating value of materials (Kumar and Chandrashekar 2014). Ash content of *O. abbyssinica* branches was the lowest (1.89%) as compared to the branches of *B. vulgaris* (2.01%) and *B. vulgaris var. vitata* (3.78%) (Table 7). The study points to the fact that the dead culms of *B. vulgaris* presented the highest calorific value (17.23MJkg-^{1}), the second highest was *O. abbyssinica* (17.08MJkg-^{1}) with the third highest culm being *B. vulgaris* young (17.01MJkg-^{1}). *B. vulgaris var. vitata* matured culm presented the least calorific value (16.22 MJkg-^{1}) among the other two species (Fig. 1.4). The lignin content (19.03%) was highest in *B. vulgaris* and lowest in *B. vulgaris var. vitata* leaves (6.84%). There was significant difference between cellulose and Hemicellulose but there was also a significant difference between the ash content and the moisture content with mean values of 5% and 8% for ash content and moisture content respectively (Table 7).

Table 7

Frequency variables of lignin, cellulose, hemicellulose, ash and moisture content of *O. abbyssinica, B. vulgaris and B. vulgaris var. vitata.*

Bamboo Species	Biomass type	Lignin	Cellulose	Hemicelluloses	Ash	MC
O. abbyssinica	Young	14.36±0.80	41.08±1.95	19.09±1.93	2.63±0.69	8.33±1.78
	Matured	15.69±5.63	39.94±1.42	21.48±4.21	2.92±0.72	8.95±1.33
	Dead	16.23±4.06	38.73±2.56	18.46±3.67	1.75±0.62	7.42±1.36
	Branches	10.46±0.64	47.55±0.34	16.71±0.16	1.89±0.05	10.00±0.00
	Leaves	10.46±0.64	28.93±0.35	24.98±0.18	11.12±0.16	9.41±0.00
B. v. vitata	Young	12.32±2.79	38.85±2.38	25.06±1.49	2.29±1.01	9.06±0.35
	Matured	10.99±0.48	38.85±2.38	26.95±5.76	4.71±0.52	9.50±1.12
	Dead	15.02±3.57	36.73±1.99	22.42±2.80	2.56±0.56	8.79±1.02
	Branches	8.88±0.24	43.35±0.32	24.12±0.06	3.78±0.50	9.71±0.00
	Leaves	6.84±0.43	30.38±0.13	28.25±0.23	12.83±0.13	10.13±0.00
B. vulgaris	Young	15.04±0.09	42.83±0.21	20.54±0.30	1.98±0.07	7.40±0.00
	Matured	19.00±0.33	48.99±0.22	18.35±0.36	2.44±0.36	8.15±0.00
	Dead	19.03±0.60	47.53±0.29	16.11±2.89	4.34±0.07	7.90±0.00
	Branches	17.12±0.23	32.83±0.47	21.35±0.35	2.01±0.11	2.01±0.11
	Leaves	13.61±0.85	30.67±0.44	16.73±0.01	15.23±0.35	9.57±0.00

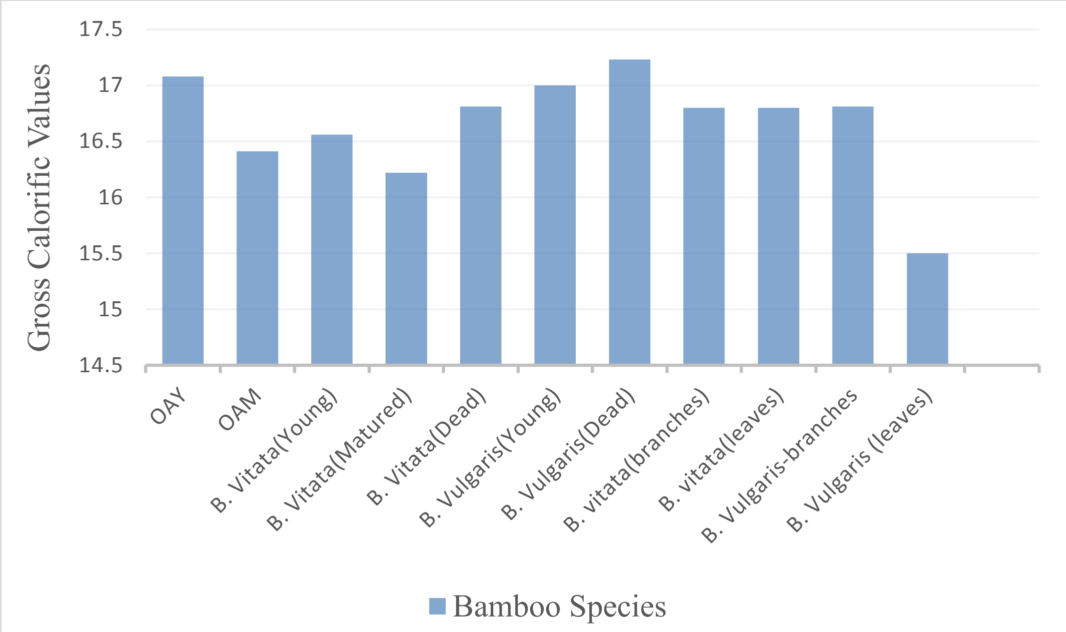

Fig. 14: Gross Calorific Values (MJkg^{-1}) of the three bamboo species*; O. abbyssinica, B. vulgaris var. vitata and B. vulgaris.*

4.5 Gravimetric Yield of Bamboo Culms after Carbonization

Weights of pre-carbonized and post carbonized culms of all the three species were recorded and their Gravimetric yields were also determined (Table 8). According to Jiang (2004) during carbonization bamboo decompose into many liquid and gas products. Liquid products contain much acetic acid, methanol and bamboo tar. These liquid and gas products which evaporated out of the bamboo during the pyrolysis gave the weight differences after the carbonization of the samples. The carbonization causes the gases in the bamboo to diffuse into the atmosphere with various liquids which evaporated reduced the weight of the carbonized bamboo (charcoal). Weight of the raw bamboo culms and weight of carbonized bamboo culms (charcoal) were measured to determine the Gravimetric Yield of the culms.

Gravimetric yield is the ratio of bamboo charcoal (*M*carb) to initial raw bamboo mass (*M*count), dry at 0%. Gravimetric yield of the three species of the bamboo after the carbonization was determined by the following formula: It is expressed in percentage by the equation *n*m = (*M*carb/ Mcount) ×100. Mass losses of the middle culm of young *B. vulgaris var vitata* and the bottom of the matured culm of *B. vulgaris var vitata* were the lowest (8.5% and 17%, respectively). *B. vulgaris* matured culm (bottom) recorded the highest gravimetric yield (83.0%). *B. vulgaris var. vitata* recorded the second highest gravimetric yield (81.5%) *and O. abbyssinica* recorded 68.0% which was lower than *B. vulgaris* and *B. vulgaris var. vitata* culms. The highest gravimetric yield for the top culms was recorded in *O. abbyssinica* (67.5%), with matured culms of *B. vulgaris* representing the lowest gravimetric yield of 50.2%. Middle culms of matured *B. vulgaris*, *B. vulgaris vitata matured*, and *O. abbyssinica* matured showed increase of gravimetric yield from bottom to the top. However middle culms *O. abbyssinica* matured and *B. vulgaris vitata* matured did not follow this trend. *O. abbyssinica* matured middle recorded 50.2% while the top recorded 67.5%, similarly matured *B. vulgaris* vitata middle also recorded 54.9% while the top recorded 57.9%. This trend is an indication that there were more charcoal yield from the bottom and middle parts of the culms than tops (Table 8).

Mass losses in the young culms of *B. vulgaris* were relatively lower; 37.9%, 42.1%, and 40.5% respectively for bottom, middle and top than the matured culm with mass losses of 44.8%, 45.1% and 49.8% in that order. For *O. abbyssinica*, higher mass losses occurred in the whole of the young culms (50.8%). On the average, mass losses in *O. abbyssinica* were the highest compared to the two other species. Culms of *O. abbyssinica* were smaller in volume and the diameters were also smaller than the culms of *B. vulgaris* and *B. vulgaris var vitata* so the mass losses occurred during the temperature ramping stage worsened at isothermal period. Highest gravimetric yield were observed for samples obtained from the bottom of the culms for all the three species under study (Table 8). Gravimetric yield of the young culms for all the three species were relatively higher than those of the matured culms but bottom culm of *O. abbyssinica* matured did not relate to this trend.

Table 8:
Gravimetric yield of *B. vulgaris, B. vulgaris var. vitata* and *O. abbyssinica* before and after carbonization.

Bamboo Species L = 61cm	Section	Weight of bamboo before carbonization	Weight of Bamboo after carbonization	Gravimetric yield (%)
B. vulgaris young	Top	152.7g	884.7g	57.9
	Middle	501.5g	298.4g	59.5
	Bottom	3510g	2178.4g	62.1
B. vulgaris Matured	Top	435.8g	218.8g	50.2
	Middle	1927.1g	1063.3g	55.2
	Bottom	811.1g	673.4g	83.0
O. abbyssinica Young	Top	253.2g	128.6g	50.8
	Middle	310.8g	211.4g	65.1
	Bottom	628.9g	409.7g	68.0
O. abbyssinica Matured	Top	521.8g	352.2g	67.5
	Middle	664.5g	428.2g	53.0
	Bottom	945.2g	687.6g	72.7
B.v. vitata Young	Top	327.5g	205.2g	62.7
	Middle	810.1g	601.8g	74.3
	Bottom	1188.2g	968.7g	81.5
B.v. vitata Matured	Top	427.8g	247.8g	57.9
	Middle	742.1g	407.4g	54.9
	Bottom	1402g	989.8g	70.6

4.6 Heating Value of the Bamboo Culms after Carbonization

Heating Value of the three species under study were determined using a bomb calorimeter. The result was expressed as the energy unit per dry matter units of substances e.g. MJkg-1 (CEN/TS14918, 2000). The heating value also called calorific value or heat of combustion is defined as the energy content of a biomass fuel. It is one of the most important characteristic parameters for design calculations and numerical simulations of thermal systems no matter how biomass is used for direct combustion or co-firing with other fuel e.g. coals (Wang, 2015).

Heating value of a fuel may be reported on two bases, the higher heating value (HHV) or gross calorific value (GCV) and lower heating value (LHV) or net calorific value. The Gross Calorific Value also known as higher heating value explicates the total amount of heat released from the fuel during combustion under constant volume. The laboratory results of the three carbonized bamboo species under study were compared in this discussion. The calorific value of *O. abbyssinica, B. vulgaris vulgaris* and *B. vulgaris var vitatta* are presented in (Table 9).

The laboratory analysis shows that *B. vulgaris vulgaris* recorded the highest heating value of 30.7214 MJ.kg-^{1}, *B. vulgaris var vittata* recorded intermediary heating value of 29.7559 MJ.kg-^{1} whiles *O. abbyssinica* recorded the lowest heating value of 23.2264 MJkg-^{1}. High ash content negatively affect the heating value of materials (Kumar and Chandrashekar 2014). The high lignin content contributes to the high heating value of biomass (Demirbas 2005; Kumar and Chandrasher 2014). Among the three species the charcoal of the *B. vulgaris vulgaris* had the highest gross calorific value (30.7214MJ.kg-^{1}), however there was a significant difference (0.97 MJk-1) between *B. vulgaris vulgaris* (30.7214MJk-^{1}) and *B. vulgaris var vitata* (29.7559 MJk-^{1}). B. vulgaris var vitata also had a heating value closer to *B. vulgaris* and thus making it a good species for charcoal production, however its weight before carbonization was found to be lighter than *B. vulgaris* which could be a draw back to the quantity of charcoal yield.

Table 9

Gross calorific values (MKg^{-1}) from the charcoal of the three bamboo species; *O. abbyssinica, B. vulgaris var. vittata and B. vulgaris vulgaris.* (Standard-Benzoic Acid 26.1912)

Bamboo Charcoal	Gross Calorific value, MJ/kg
Oxynanteria abbyssnica	23.2264
Bambusa vulgaris var. vitata	29.7559
Bambusa vulgaris	30.7214

CHAPTER FIVE

DISCUSSION

5.1 Bamboo Culm Density and Culm Type Distribution

Like most of the forest reserves in Ghana, harvesting of bamboo for commercial purposes is prohibited and in the case of Bobiri forest reserve, bamboo cutting is allowed only for research purposes. Thus, most of the bamboo clumps have been in their natural stands since the establishment of the bamboo plantation in the reserve. The study found that the total culms per hectare was 7,171, 6,267 and 3,325 respectively for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* compared to 21,191culmsha^{-1} reported for moso bamboo in China (Yen and Lee, 2011).

On average, mature and dead culms in the Bobiri forest reserve represent more than half (57%) of the total stand. It is also worthy of note that compared to the moso bamboo forest in China which is under management, the bamboo plantation in the Bobiri forest reserve is not managed and the combined effect is that there is lack of rigor in respect of sprouting. Harvesting of mature culms is necessary to increase in shoot production, stimulate growth of rhizomes and roots (Van der Lugt et al., 2018). Other studies have shown that harvesting of mature culms could promote the production of young culms (Nath et al., 2009; Yen et al., 2010; Yen and Lee, 2011).

Predictive models are important for estimating biomass of standing plant species. However, the performance of such models is overestimated when simply determined on the samples that were used to construct the model (Steyerberg et al., 2001). Model validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model (AIAA, 1998; ASME, 2006) and it is a mandatory step in regression model development (Consonni et al., 2010). External validation has been reported to be the most effective way of evaluating a model's predictive power (Consonni et al., 2010) and is the most used methods in recent times (OECD, 2007).

5.2 Biomass and Carbon Stock Potential of Bamboo Species, Components and Age Classes

The 21% harvested bamboo compared to the 23% dead bamboo culms found in this present study appears not to be good enough since they suggest that matured culms which are allowed to decay are more than those harvested and utilized. This situation is not in the best interest of carbon sink or sequestration which is one of the main reasons for the bamboo plantation.

It is reported that when matured bamboo deteriorates, they release carbon from the aboveground biomass into the atmosphere (Liese, 2009 in Tekpetey, 2011). Therefore, if this trend of relatively higher percentage of the bamboo dyeing is allowed to continue, the purpose of establishing the plantation might then be defeated since almost all the sequestered and stored carbon may eventually be released and returned to the atmosphere through decomposition and burning to subsequently contributes to global warming. In this light, in order for the bamboo to continue to supplement net carbon sink, more need to be harvested and utilized for the requested carbon to be stored in other forms such as fibre fabric, furniture, laptop computers, handicrafts etc. so that the total accumulation of carbon in a solid state will exceed the carbon released to the atmosphere.

It was also generally found that culms and foliage provide the highest and lowest biomass respectively across all three bamboo species and age classes in this study. This appears to corroborate the findings of Chiayo et. al (2012) who also found culms of bamboo to have as high as 34.981 ± 25.148 tons/ha compared to branches and foliage together of 7.625 ± 5.197 tons/ha AGB. Similar trends were also observed in Wang and Chen (2015) who studied different bamboo species from different site conditions in Taiwan and Shohel *et al*. (2015) who also carried out their studies on *Bambusa vulgaris*.

Wang and Chen (2015) reported biomass of culm to range from 14.9 ± 1.76Mg/ha to 63.45 ± 4.88Mg/ha compared to that of leaves that ranged from 3.37 ± 0.62Mg/ha to 8.07 ± 0.52Mg/ha. Again, Yen (2016) found culms to have the highest AGB (41.94 Kg/culm) compared to foliage (0.73 Kg/culm) and branches (4.87 Kg/culm) and this trend was throughout five different DBH classes of *Moso bamboo.* But it is interesting to report some apparent contrary findings of Pathak et. al. (2016) that there is significant difference ($P < 0.05$) in biomass among bamboo components (culm, branch and leaves) but changes in biomass concentration do not significantly ($P > 0.05$) correlate with bamboo species and different culm age classes.

Furthermore, the findings in this study revealed that for 1-6 yrs old bamboo, culm, branch and foliage respectively contributed average biomass of 75-92.89%, 4.6-16.04% and 2.5-8.96% also appear to agree with the findings of some researchers. Yen (2016) found 1-5 yrs old *Moso bamboo* to have AGB in the range of 83-92%, 7-14% and 1-3% respectively for culms, branches and foliage. Also, Yen and Lee (2011) found 1-5 years old *Moso bamboo* to possess 83-85%, 12-17% and 3-4% AGB respectively for culms, branches and foliage. In their study, Nath et al. (2009) also found the proportions of aboveground biomass for culms, branches and foliage of the studied bamboo species to be 80-95%, 1-14% and 0.13-7%, respectively. Other study (Yen & Lee, 2011) reported similar proportion of 83-85%, 12-17% and 3-5%, in that order.

In addition, the proportion of each component's AGB appears generally similar among the different age groups for the three species studied in this present research. This also appears to corroborate the findings by Yen and Lee (2011). Moreover, in this study, higher heights were generally associated with lower biomass for foliage, culm and branch, except for *B. vulgaris var. vitata* whose components' biomass behaved contrary to this trend. Lower DBH was also found to be associated with higher heights but lower biomass for culm, foliage and branches. These however appear to be at variance with Yen (2016) who found that biomass of almost all components increase with increasing DBH class. This appears confirmed by Majundar et al (2016) that bamboo with DBH ≤30cm has biomass of about 69.38% whereas those with DBH of ≥70cm had biomass of only about 23%. These authors further found biomass distribution to vary among 10 DBH classes significantly ($F=74.13$, $df=1.9$; $p < .001$) and this is reported to show relatively higher coefficient for allometric relationships between density and AGB in different DBH classes (equation= $Y = 0.56x – 0.23$; $R^2=0.90$) Majundar et al. 2016).

Bambusa vulgaris was found to exhibit the highest AGB of $114.97 Mgha^{-1}$ is also affirmed by Sohel et al. (2015). It is possible that the leaf area index of *B. vulgaris* stand is comparatively higher than the other two species which provides a leverage for it to absorb much more of the solar radiations that incidence on it just as has been reported on *Mosso bamboo* stands (Yen and Lee, 2011; Wang et al. 2013). It is however, important to note that, though report indicates that most bamboo species accumulates about three-fourth of their biomass for the entire growth in just 40 days after propagation, from this present study, it appears that the three species in Ghana attain higher biomass by the 4th year. This finding appears to be positive since bamboo reaches maturity after 4 years and therefore they must necessarily be allowed to grow up to ≥ 4 years to attain the needed strength before harvesting (Li *et al,* 2016). This therefore implies that the bamboos will be harvested at a time that they had accumulated the maximum carbon or biomass and therefore utilization will amount to storing more carbon and helping to mitigate climate change.

5.3 Predicting Biomass for the Three Bamboo Species.

Allometric models are important for estimating volume, biomass and carbon storage of standing plant species (Zianis & Mencuccini, 2004; Yen *et al*. 2010). However, the performance of such models is overestimated when simply determined on the samples that were used to construct the model (Steyerberg *et al*., 2001). Thus model validation (a process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use) has apparently become a mandatory step in regression model development (AIAA, 1998; ASME, 2006; Consonni *et al.,* 2010).

External validation has been reported to be the most effective way of evaluating a model's predictive power (Consonni *et al.*, 2010) and it is the most used methods in recent times (OECD, 2007). In the present study, DBH of bamboo culm was utilized as a predictor of bamboo biomass based on the quality of the predictive power of DBH in previous studies. The use of DBH to predict volume, biomass and Carbon storage of standing tree and bamboo has been common (Segura & Kanninen 2005; Nath et al. 2009; Yen & Lee 2011). Also, because there is a strong correlation between diameter and height of standing trees and bamboo, the inclusion of height in addition to diameter as a predictor of biomass and C storage does not significantly improve the utility of the model very much (Hofstad & Norway 2005; Yen *et al.* 2010).

This present study also appears to have confirmed the efficiency and reliability of using DBH alone in allometric models to predict biomass and Carbon storage. DBH was found to appreciably explain variations in biomass distributions across components and age classes in total. In culms, branches and foliage biomass, R^2 values ranged from 0.596 (foliage of 3-4 yr. *B. vulgaris*) to 0.998 (stem of 5-6 yr. *B. vulgaris var. vitata*). In total, DBH predicted bamboo biomass to accuracies ranging from 85.5% (for 3-4 yr. *O. abbyssinica*) to 99.9% (5-6 yr. *B. vulgaris var. vitata* - Table 4). These findings appear consistent with others reported in literature. For instance, Yen (2016) has reported R^2 of 0.97 while Yen and Lee (2011) have also reported R^2 of 0.96 in using DBH to predict aboveground biomass of *Moso bamboo*.

In using Weibull distribution model, DBH predicted ABC wit R^2 value of 0.937 and prediction accuracy of 96.4% for *Moso bamboo* (Zhou 2006 in Xiaojun et al 2011). Xiaojun et al (2011) also found R^2 values of 0.497 to 0.995 upon using three different models (Linear, PLS and Erf-BP) to predict ABC from DBH of *Mosso bamboo*. Moreover, whereas Li et al (2016) found the distribution of leaf and branch biomass with DBH to be dispersed and not showing any clear trend, Lesungnoen (2016) found DBH to predict culm biomass with R^2 ranging from 0.705 to 0.952, and leaf biomass with 0.618 to .797. These imply that DBH can be used to estimate AGB of bamboo to an appreciably higher level of accuracy.

The R^2 values (Pearson r) that range from 0. 6739 for foliage to 0.9837 for branches are indications that the model used in this study is of relatively higher accuracy and can be relied on especially also because the distribution of observed and predicted biomass were scarcely dispersed (as can be observed in Figure 1.3). The range of RMSE values (from 0.021 to 1.928) reported in this current study appear to be far below the range (from 1.998 to 4.848) found by Xiaojun et al (2011) but appear to be closer to the 0.869 found by Yen (2016) all of whom studied on *Mosso bamboo.*

Again, the MAPE values (1.2% to 25.52%) and the RMSE obtained in the present study fall far below those found by Li et al (2016) on *Thorny bamboo* (RMSE of 0.3018 to 5.4160 and MAPE of 11.54% to 71.01%). This favourable comparison of the RMSE and MAPE values of our study and those of the previous one is highly positive, especially for the MAPE values since all the values in our studies are less than 50% and pointing to relatively higher accuracy of forecast of our model fit as asserted by Lewis 1982 in Li et al (2016). These lower MAPE values also appear to be a reflection of the strong relationship between DBH and biomass as well as observed and predicted biomass for the various components and species of bamboo in this study as observed in Figure 1.3 and Table 4 all of which might have led to relatively minimal prediction errors of between 1.63 to 23.83% -Table 4.

It is worthy to report however that there is lower correlation between DBH and height for some bamboo species and therefore allometric models that incorporate H as variable, will in such instances obviously improves the prediction ability though insignificantly by producing lower RME and MAPE values. But Xiao Jun et al. (2011) also cautions against the use of large number of variables in a model to predict AGB and AGC. Therefore, it is suggested that to predict AGB of culms for some bamboo species using DBH and H as variables or Parameters in allometric models should be enough if possible.

5.4 Characterization of Bamboo Culms before and After Carbonization

According to Jiang (2004) during carbonization bamboo decompose into many liquid and gas products. Liquid products contain compounds such as acetic acid, methanol and bamboo tar, flammable methane and ethylene in gas products. Carbon dioxide decreases during this stage. Bamboo pyrolysis produces three products: they are solid (bamboo charcoal) liquid (bamboo vinegar) and gas (bamboo gas). These liquid and gas products (i.e. volatile substances) which evaporated out of the bamboo during the pyrolysis and combustion gave the weight differences after the carbonization of the samples as described by Munir et al. (2009) and Haykiri-Acma (2003). Most of the weight lost occurred in the degradation zone (point) called the active pyrolysis zone. The temperatures of the active pyrolysis zone is around 180-370 °C. Another weight lost zone during pyrolysis occurred at the temperatures of 390-490 °C and it is called passive pyrolysis zone. The weight lost at the active pyrolysis zone can be attributed to the evolution of the volatile compounds generated during the decomposition of hemicellulose and cellulose. The weight lost in the passive pyrolysis zone is mainly due to lignin conversion (Garcia-Ibanez et al. 2006). Culm weights of all the three species under study were found to increase along the culm from the top to the bottom (Table 4).

Charcoal weights recorded after carbonization also decreases along the culms from bottom to the top. This trend of weight reduction along the culm from bottom to the top was similar for all the eighteen samples of the three species under study thus weights of charcoal from the bottom and the middle culms were far heavier than their respective charcoal from the top culms (Table 8). Comparing the charcoal of the three species *B. vulgaris* was found to be the heaviest among them while *B. vulgaris var vitata* was found to be heavier than *O. abbyssinica*. The extent of weight lost in these two combustion steps (active pyrolysis and passive pyrolysis) differed by species. The difference in the profile can be attributed to differences in the physical and chemical properties of biomass. The volatile constituents are CO, CO_2, H_2, H_2O, tar and light hydrocarbons (Kumar et al. 1992). Charcoal yields from middle and bottom of the culms were higher than the yield from the top section of the culms.

5.5 Heating Value of the Bamboo Culms

B. vulgaris vulgaris recorded the highest heating value, *B. vulgaris var vittata* recorded intermediary heating value whiles *O. abbyssinica* recorded the lowest heating value. According to Kumar and Chandrashekar (2014) high ash content negatively affect the heating value of materials but on the contrary the ash content of *O. abbyssinica* in this study was low compared to the other two species, it recorded low Gross Calorific Value. This means other factors might have contributed to the low heating value and not only ash content. Among the three species the charcoal of the *B. vulgaris* had the highest calorific value however there was little significant difference between *B. vulgaris* and *B. vulgaris var vitata*. *B. vulgaris var vitata* also had a higher heating value compared to *O. abbyssinica*, and thus making it a good species for commercial charcoal production. Charcoal of *B. vulgaris* which recorded the highest heating value of 30.7214 MJ.kg-^{1} among the three species under study was also the heaviest among them thus making it the preferred choice for commercial bamboo charcoal production.

Gravimetric yield of the three species of the bamboo after the carbonization indicated that mass losses of var vitata and the middle culm of young *B. vulgaris* bottom of the matured culm of *B. vulgaris var. vitata* were the lowest (8.5% and 17%, respectively). Mass losses in the young culms of *B. vulgaris* were relatively lower; 37.9%, 42.1%, and 40.5% respectively for bottom, middle and top than the matured culm with mass losses of 44.8%, 45.1% and 49.8% in that order. For *O. abbyssinica*, higher mass losses occurred in the whole of the matured culms. This in agreement with findings of other studies (Rousset et al., 2011).

On the average, mass losses in *O. abbyssinica* were the highest compared to the two other species. Culms of *O. abbyssinica* were smaller in volume and the diameters were also smaller than the culms of *B. vulgaris* and *B. vulgaris var. vitata* and this contributed to the mass losses occurred during the temperature ramping stage and the isothermal period. Highest gravimetric yield were observed for samples obtained from the bottom of the stem for all the three species under study (Table 8). These results are in agreement with those of previous studies. (Sridhar et al., 2007; Rouset et. al., 2011). Gravimetric yield of the young culms for all the three species were relatively higher than those of the matured culms but bottom culm of *O. abbyssinica* matured did not relate to this trend.

CHAPTER SIX

SUMMARY OF FINDINGS CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of the Findings

Countries are gradually experiencing the environmental effect of global warming as consequential effect of continuous release of carbon into the atmosphere through industrial and other human activities. The drastic depletion and degradation of tree forests that are supposed to sequester the carbon to ameliorate the environment of the effect of global warming has resulted in much interest in bamboo cultivation or forestation across the globe. This study therefore sought to estimate and compare the carbon sequestration potentials of three different bamboo species *(Bambusa vulgaris, Oxynanteria abbyssinica* and *B. vulgaris var. vitata)* in different culm components for different age classes from a bamboo forest in Ghana (Bobiri Forest). Charcoal made from tree forest also remains one of the ways of forest depletion in Ghana. The study also sought to estimate and compare the heating values of charcoal made from the three common species as well as establishing the suitable one for commercial charcoal production in Ghana to mitigate the effects of forest depletion.

6.2 Conclusion

Based on results obtained, the following conclusions were drawn:

1. Bamboo stand density for *B. vulgaris*, *O. abbyssinica* and *B. vulgaris var. vitata* grown in Ghana are very high (7171culms ha^{-1}, 6267 culms ha^{-1} and 3325 culms ha^{-1} respectively). Shoot production of the bamboo species was low and this could be due to high proportions of uncut mature and dead culms. This is positive for carbon sequestration however lack of harvesting is a disadvantage for growth of new shoots for regeneration.

2. The bamboo species differed in AGB accumulation and carbon storage. Among the bamboo species, *B. vulgaris* was the most efficient at AGB accumulation. The amount of AGB stored in the bamboo was 61% higher in *B. vulgaris* (115 t ha−1) than in *B. vulgaris var. vitata* (71 t ha−1); the AGB in B. vulgaris was 27-fold that of *O. abbyssinica*. These differences could be due to differences in culm thickness, diameter and height of the bamboo species. However, the percentage of harvested bamboo (21%) compared to dead ones (23%) found in this present study appears to suggest that matured culms which are allowed to decay are more than those harvested and utilized and this is not in the best interest of carbon sink or sequestration and storage since as bamboo deteriorates, the sequestered carbon is released back into the atmosphere. Lower DBH was also found to be associated with higher heights but lower biomass for culm, foliage and branches.

3. The AGB and carbon storage were influenced by bamboo species, bamboo components and not by bamboo age. Harvesting bamboo at a short rotation cycle of 2 years may therefore not affect the biomass production levels. DBH predicted biomass of bamboo to accuracies ranging from 85.5% to 99.9% and predicted Carbon storage to accuracies from 67.4% to 98.4%. This also means that the model is of relatively higher accuracy and can be relied on especially also because the distribution of observed and predicted biomass were scarcely dispersed (Figure 4.3).

4. Culms of *B. vulgaris* was the heaviest among the three species (2178.4g) with 83.0% gravimetric yield and had the highest Gross Calorific value of 30.7MJk-^{1} (Table 8). Bottom and middle parts of culms of all three species were found to be

heavier than the top parts of the culms. The gravimetric yield of the bottom parts of culms of all the three species under study were found to be higher than the top parts, however the matured culms of *O. abbyssinica* and B. vulgaris var. vitata did not follow this trend (Table 8).

6.3 Recommendations

It is recommended that in order for the bamboo to continue to supplement net carbon sink, more need to be harvested and utilized for the sequestered carbon to be stored in other forms such as fibre fabric, furniture, laptop computers, handicrafts etc. so that the total accumulation of carbon in a solid state will exceed the carbon released to the atmosphere so as to ameliorate the environment from global warming effects. Bamboo can be harvested at a short rotation cycle of 2 years and will therefore not affect the biomass production levels.

It is recommended that Allometric models can be used to predict the aboveground biomass of bamboo culms using the diameter at breast height (DBH) without destroying the culms and also minimize the difficulty in measuring aboveground biomass of bamboo. This is because DBH predicted biomass of bamboo to high percentage accuracies ranging from 85.5% to 99.9%.

Bambusa vulgaris vulgaris is recommended for commercial bamboo charcoal production because it was the heaviest culm with high gravimetric yield (83%) and also recorded the highest Gross Calorific Value among the three species in this study.

It is also recommended that further research work should be carried out by comparing the Gravimetric yield of bottom culms and top parts of culms for all the three species to aid future bamboo charcoal industries. Furthermore, simple technology for producing bamboo charcoal with available materials must be developed and transferred to the producers of bamboo charcoal because the traditional way of producing charcoal is very tedious and has resulted in the low productivity and utilization of bamboo charcoal.

REFERENCES

AIAA. (1998). Guide: Guide for the verification and validation of computational fluid dynamics simulations, American Institute of Aeronautics and Astronautics, U. S. A.

Ammon C. and Baiadi A. (2016). The Benefits of the Bamboo Network in International Trade, Preliminary and Incomplete, University of Warwick, UK.

Amoah, M., & Cremer, T. (2017). Net calorific values and mineral concentration of thirteen tree and shrub species in Ghana. Journal of Sustainable Forestry, 36, 307–716.

Amoah, M., Becker, G. (2009). Assessment of logging efficiency and development of allometric models for predicting stumpage volume of some commercial tree species in Ghana, Int. For. Rev. 11(1), 1-11.

Anon, R. (2010). Guadua Bamboo**.** *Bambusa vulgaris;* Characteristics and Identification. www.guaduabamboo.com/bambusa-vulgaris.html. [Accessed 2010, August, 14].

Appiah M., Blay D., Damnyag L., Dwomoh F.K., Pappinen A., Luukkanen O., (2007) Dependence on forest resources and tropical deforestation in Ghana. Springer Science and Business Media B.V. 2007.

Ayre-Smith, R.A., (1963). The use of bamboo as cattle feed. East African Agric Forest Journal. Ethiopia 29, 50–51.

Balduino Junior, A., Baduino, L., Friederichs, T. Y., Bayestorff, G., Da Cunha, A., & Brand, M. A. (2016). Energetic potential of bamboo culms for industrial and domestic use in Southern Brazil. Ciência Rural, Santa Maria, 46(11), 1963–1968.

Barbara M. E., Choocharoenb, D. C., Spreera, W., Naglea, M., Leisa, H., Neefb, A., Muellera, J. (2007). The Potential of Bamboo as a Source of Renewable Energy in Northern Laos, University of Kassel-Witzenhausen and University of Göttingen, October 9-11, 2007.

Burkhill H.M. (1994). The useful plants of west Tropical Africa, Volume 4, Royal Botanic Gardens, 1985 2nd Edition, Burenhead, England.

Chew, L.T., Rahim, S. and Jamaludin, K. (1992). *Bambusa vulgaris* for urea and Cement-bonded particleboard manufacture. Journal Tropical Forest Science 4(3):

Chin, K. L., Ibrahim, S., Hakeem, K. R., H'ng, P. S., Lee, S. H., & Lila, M. A. M. (2017). Bioenergy production from bamboo: Potential source from Malaysia's perspective. "Bamboo for Bioenergy" Bioresources.Com, 12(3), 6844–6867.

Consonni, V., Ballabio, D., Todeschini, R., (2010). Evaluation of model predictive ability by external validation techniques, Journal of Chemometrics, 24 (3-4); https://doi.org/10.1002/cem.1290.

Demibras A. (2005). Estimation of Structural Components of Wood and Non-Wood Biomass Samples. Abstract. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. 27 (8). 761-767.

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

Dora, S. (2008). Bamboo As A Source Of Bioenergy Feedstock In Ghana, The College Of Agriculture And Natural Resources; Kwame Nkrumah University Of Science And Technology, Ghana.

Ebanyenle, E., K. Ameyaw and E.J. Oware, (2005). Ghana's Bamboo Industry: Country Report, Training course, September 25-25 November, Hangzhou, China, pp: 1-7.

Embayea, K., Weiha, M., Ledinc, S. and Christersson, L. (2004). Biomass and nutrient distribution in a highland bamboo forest in southwest Ethiopia: implications for management. Forest Ecology and Management 204 (2005) 159–169.

Emrich, W. (1985). Charcoal and Carbonization, Mechanical Wood Products Branch Factory. Industries Division FAO Forestry Department Forest and Agriculture Organization of the United Nations, Rome.

FAO (2004). FAO Forestry Department. Unified Bioenergy Terminology – UBET. FAO CORPORATE DOCUMENT REPOSITORY.www.fao.org. Rome.

FAO. (2012). Guidelines on destructive measurement for forest biomass estimation. Rome: Author.

FAOSTAT (2010) Statistical Database of the Food and Agriculture Organization of the United Nations. FAO, Rome.

Farrelly, D. (1984). The book of bamboo. Sierra Club Books, San Francisco, California. Forestry Sciences, Vol.37.

Fayehun O. A. (2010). Household Environmental Health Hazards and Child Survival in Sub-Saharan Africa, ICF Macro Calverton, Maryland, USA.

Fu, M., Xie J., Zhou B., Zhengcai, Li. and Xiantan, X. (2007). Technical Manual on Sympodial Bamboos Cultivation, China Forestry Publishing House No. 7, Liuhaihutong. 249-256.

Fu-Chu, Y. Kuo-Hui, W., Lui, M. J., Lin, W. P., Hui, M. K. (2009). Preparation and Characterization of functional fabrics from bamboo charcoal/Silver titanium dioxide/Silver composite powder and Evaluation of their antibacterial efficacy. Nano technology for Tissue Engineering and Regenerative Medicine, Taoyuan, Taiwan.

Ganesh, A. (2003). Bamboo Characterization For Thermochemical Conversion And Feasibility Study Of Bamboo Based Gasification And Charcoal Making, Energy Systems Engineering of Indian Institute of Technology, Mumbai.

Grosser, D. and Liese, W. (1971). On the anatomy of Asian bamboos, with special reference to their vascular bundles. Wood Sci. & Technol. 5:290 – 312.

Hall, J. B., & Swaine, M. D. (1981). Distribution and ecology of vascular plants in a tropical rainforest: Forest vegetation in Ghana (pp. 383). The Hague: W. Junk.

Haygreen, J.G., and Bowyer, J.L. (1998). Forest products and wood science. An Introduction, Iowa State University Press/Ames. Third Edition.https://food-hacks.wonderhowto.com/news/you-should-be-adding-charcoal-your-food-heres-why-0159772.

Huang, P. H., Jhan, J. W., Cheng, Y. M. (2014). Effects of carbonization parameters of Moso Bamboo-Base Porous Charcoal on Capturing Carbon Dioxide. The scientific

INBAR Media Release, (2010). UNFCCC hears bamboo has a special niche to help climate and development objectives. Cancun 2010, Beijing, China.

INBAR, (2006). The partnership for a better world-strategy to the year 2015. Beijing, China.

Janssen, J.J.A. (1991). Mechanical properties of bamboo. Kluwer Academic Publishers; China.

Jiang, Z., Liu, Z., Fei, B., Cai, Z., Yu, Y., & Liu, X. (2012). The pyrolysis characteristics of moso bamboo. Journal of Analytical and Applied Pyrolysis, 94, 48–52.

Kajir A. (2006) Stopping international logging in Papua New Guinea's Rainforest New internationalist, Journal of Forestry Research, 24(2), 41–464.

Kelecha, W., (1980). The Bamboo Potential of Ethiopia. Forestry and Wildlife Conservation and Development Authority, Addis Ababa, Ethiopia. Monograph, 14pp.

Kemausuor, F, Nygaard, I, & Mackenzie, G. A. (2015). Prospects for bioenergy use in Ghana using long-range energy alternatives planning model. Energy, 93(part 1), 672-682.

Kumar and Chandnashekar. (2014). Fuel properties and combustion characteristics of some promising bamboo species in India. Journal of Forestry Research, 25(2), 471–476.

Kumar, A., Ramanuja R, I.V. and Sastry, C. (2002) Bamboo for sustainable development. *In:* Proceedings of the 5th international bamboo congress and the 6th international bamboo workshop, San José, Costa Rica.

Latif, A. M., Ashaari, A., Jamaludin, K. and Mohammed, Z. J. (1993) Effects of anatomical characteristics on the physical and mechanical properties of *Bambusa bluemeana.* Journal Tropical Forest Science 6(2): 159-170.

Li, L., Lin, Y., & Yen, T. (2016). Using allometric models to predict the aboveground biomass of theory bamboo of thorny bamboo (bambusa stenostachya) and estimate its carbon storage. Taiwan Journal of Forest Science, 31(1), 37–47

Li, S., Xu, S., Liu, S., Yang, C., & Lu., Q. (2004). Fast pyrolysis of biomass in free-fall reactor for hydrogen-rich gas. Fuel Processing Technology, 85, 1201–1211.

Li, X. (2004). Physical, chemical, and mechanical properties of bamboo and its utilization potential for fiberboard manufacturing. Master of Applied Science thesis, Graduate Faculty of the Louisiana State University and Agriculture and Mechanical College.

Liese W. and Kohl M. (2014). Bamboo Plants and its Uses; Springer International Publishing, Switzerland.

Liese, W. (1985). Bamboo Biology Silvic Properties Utilization GTZ Eschborn Germany. McClure, F.A. (1967). The bamboos, A Fresh Perspective. Harvard University Press. Cambridge, Massachusetts.

Lin, W. C., (1961). Studies on the classification of Bambusaceae in Taiwan. Report No. 69. Taiwan Forestry Research Institute, p.145.

Liu, Z., Fei, B., Jiang, Z., & Liu, X. (2014). Combustion characteristics of bamboo-biochars. Bioresource Technology, 167, 94–99. doi:10.1016/j.biortech.2014.05.023

Liu, Z., Jiang, Z., Cai, Z., Fei, B., Yu, Y., & Liu, X. (2013). Effects of carbonization conditions on properties of bamboo pellets. Renewable Energy, 51, 1–6. doi:10.1016/j.renene.2012.07.034

Lobovikov, M., Lou, Y., Schoene, D., & Widenoja, R. (2009). The poor man's carbon sink: Bamboo in climate change and poverty alleviation. Non-Wood Forest Products Working Document Number, 8(FAO), 72pp.

Majundar, K., Choudhary, B. K., & Datta, B. K. (2016). Aboveground woody biomass, carbon stocks potential in selected tropical forest patches of Tripura, Northeast India. Open Journal of Ecology, 6, 598–612.

McClure, F.A. (1967). The bamboos, A fresh perspective. Harvard University Press. Cambridge, Massachusetts.

Nath, A.J., Das, G., Das, A.K., (2009). Above ground standing biomass and Carbon storage in village bamboos in North Eeast India. Biom. And Bioenerg. 33, 1188-1196.

Nemestothy, K.P., (2008) Wood Fuels: Characteristics, Standards, production technology. E.V.A-The Austrian Energy Agency.

Obiri, B. D., & Oteng-Amoako, A. A. (2007). Sustainable development of the bamboo industry in Ghana. Gh. Jurnal of Forensic, 21, 14–27.

Osarfo, Y. B. (2005). Reducing emissions from tropical forest deforestation applying compensated reduction in Ghana. In P. Moutinho & S. Schwartzman (Eds.), Tropical deforestation and climate change (pp. 63–72). Belém, Brazil: IPAM Instituto de Pesquisa Ambiental da Amazônia.

Pannipa, C. (2013). Bamboo an Alternative Raw Material for Wood and Wood-Based Composites. Journal of Material Science Research Vol. 2 No. 2 2013 Pub: Canadian Center of Science and Education.

Pathak, P. K., Kumar, H., Kumari, G., & Bilyaminu, H. (2016). Biomass production potential in different species of bamboo in Central Uttar Pradesh. The Ecoscan, 10(1 & 2), 41–43.

Pauli G. (2010). Utilization of Charcoal to Preserve Wood, the Blue Economy. Journal of Sustainable Forestry, 34, 306–715. USA.

Paulrud, S. (2004). Upgraded Biofuels - Effects of Quality on Processing, Handling Characteristics, Combustion and Ash melting. Doctoral thesis, Swedish University of Agricultural Sciences.

Peng, H., Wang, N., Hu, Z., Yu, Z., Liu, Y., Zhang, J., & Ruan, R. (2012). Physicochemical characterization of hemicelluloses from bamboo (Phyllostachys pubescens Mazel) stem. Industrial Crops and Products, 37, 41–50.

Picchi, G., Gordon, A. and Naresh, T., (2007). Feedstock to Furnace: Bioenergy Systems for the Ontario Greenhouse Industry. Potential in Ontario for the Implementation of Willow Short Rotation Coppice Cultivation for the Greenhouse Industry.

Rao, A. N., Rao, V. R and Williams, J.T. (editors), (1998). Priority Species of Bamboo and Rattan. IPGRI and INBAR.

Razak, A., Latif, A. O. M., Liese, W. and Norini, H. (1995) Planting and Utilization of bamboo in Peninsular Malaysia. Research Pamphlet. Forest Research Institute Malaysia.

Ronald, O., Ocampo & Normalina, Usita P. (2015) Utilization of Bamboo Charcoal as Additives in Cakes, Asia Pacific Journal of Multidisciplinary Research Vol. 3 No.5, 82-86 Part II P-ISSN 2350-7756 E-ISSN 2350-8442 www.apjmr.com

Schmidt-Rohr, K. (2015). "Why Combustions Are Always Exothermic, Yielding About 418 kJ per Mole of O2". J. Chem. Educ. 92: 2094–2099. doi:10.1021/acs.jchemed.5b00333.

Scurlock, J.M.O., Dayton, B.C. and Hames, B. (2000). Bamboo: An overlooked biomass resource? Oak Ridge National Laboratory, U.S.A. Oak Ridge, TN 37831-6407.

Segura, M., Kanninen M., (2005). Allometric models for tree volume and total aboveground biomass in tropical humid forest in Costa Rica. Biotroica. 37: 2-8.

Shanmughavel, P., Francis, K. (1986). Aboveground biomass production and nutrient distribution in growing bamboo (Bambusa bambos (L.) Voss). Biom. Bioenerg.10, 383-391.plantation in the degraded tropical forests: Implications for policy development. Land Use Policy, 49, 142-151.

Shenxue J. (2004). Training Manual of Bamboo Charcoal for Producers and Consumers. Bamboo Engineering Research Center, Nanjing Forestry University, China.

Shupe, U. X. B., Peter, T.F., HSE, G. F., Eberhardt, C. Y. and Eberhardt, T. L. (2007). Chemical changes with maturation of the bamboo species *P h y U M y s pubesaar*. Journal of Troprca1 Forest Science 19(1): 612.

Smajgl A. Geoff C., Pambudhi F., Bohensky E, House A, Butler J., Prananingtyas S.D, Fadillah R, Khan A, Gunawan A.B., Rusdianto S, Armundito E, Palupiningtyas S,. (2009) Assessing impacts of fuel subsidy decisions on poverty and forest depletion in East Kalimantan, Indonesia: An agent-based analysis CSIRO 2009 (Rep. No .2).

Smith, L. (2007). Rapeseed biofuel 'produces more greenhouse gas than oil or petrol'. The Times. September 22, 2007.

Sohel, M.S.I., Alamgir, M., Akhter, S. (2015). Carbon storage in a bamboo (Bambusa vulgaris) plantation in the degraded tropical forests: Implications for policy development. Land Use Policy, 49, 142-151

St. Clair, J. B. (1993). Family differences in equations for predicting biomass and leaf area in Douglas fir (Pseudotsuga menziesii var. menziesii), For. Sci. 39: 743-750.

Steyerberg, E.W., Harrel Jnr, F. E., Borsboom, G.J.M., Eijkemans (René), M. J. C., Vergouwe, Y., Habbema, J. D. F., (2001). Internal validation of predictive models: Efficiency of some procedures for logistic regression analysis, J. of Clin. Epidem. 54, 774-781.

Tomalang, F. N., Lopez, A.R., Semara, J.A., Casin, R. F. and Espiloy Z.B. (1980). Properties and utilization of Philippine erect bamboo. In International Seminar on Bamboo Research in Asia held in Singapore, May 28-30, 1980: proceedings edited by Lessard, G. and Chouinard, A. Singapore: International Development.

Van der Lugt, P., ThangLong, T., & King, C. (2018). Carbon sequestration and carbon emissions reduction though bamboo forests and products. INBAR Working Paper. INBAR: Beijing, China.

Wang, D. and Shen, S.J. (1987). Bamboos of China. Timber Press, Portland, Oregon. . Journal Tropical Forest Science 4.S795 -62

Wang, D. F., & Chen, T.-H. (2015). Bamboo resources and carbon storage in Taiwan. Ecology and Environmental Concerns, 10th World Bamboo Congress, Korea. World Journal Vol. 2014 Article ID 937867 page 2014.

Weisse, M., & Goldman, E. D. (2017). Global Tree cover loss rose 51 percent in 2016; In: World Resource Institute, Indonesia. Retrieved April 9th, 2019, from https://wri-indonesia.org/en/blogtags/ 9896?page=1..

World Book Inc. (2001). World Book Encyclopedia, Chicago: World Book ©2010, Edition: Juvenile Audience; English volume 2.

Xianghai, M., Yihe, Z., Jinbo, L., Zhilei, Z., Leipeng, L., and Chu, P. K. (2013). Effect of Bamboo Charcoal Powder on the Curing Characteristics, Mechanical Properties, and Thermal Properties of Styrene–Butadiene Rubber with Bamboo Charcoal Powder. China University of Geosciences, Beijing 100083, China.

Xiong, S., Zhang, S., Wu, Q., Dong, A., & Chen, C. (2014). Investigation on cotton stalk and bamboo sawdust carbonization for barbecue charcoal preparation. Bioresource Technology, 152, 86–92.

Yen G. (2005). Technology in Nature greenyen.com/benefit.html about bamboo growth-habith.html.

Yen, T. M. (2016). Culm height development, biomass accumulation and carbon and carbon storage in an initial growth stage for a fast-growing moso bamboo (Phllostachy pubescens). Botanical Studies, 57, 10.

Yen, T. M., & Lee, J. S. (2011). Comparing aboveground carbon sequestration between moso bamboo (Phyllostachys makinoi) and China fir (Cunninghamia lanceolata) forests based on the allometric model. Forest Ecology and Management, 261, 995–1002.

Yen, T.M., Ji, Y.J., Lee, J.S., (2010). Estimating biomass production and carbon storage for a fast-growing makino bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. For. Ecol. and Manag, 260, 339-344.

Zhang, H., Zhuang, S., Sun, B. O., Ji, H., Li, C., & Zhou, S. (2014). Estimation of biomass and carbon storage of moso bamboo (Phyllostachys pubescens Mazel ex Houz.) in Southern China using a diameter-age bivariate distribution model. Forestry, 87, 674–682.

Zhang, Q. S., Jiang, S. X., & Tang, Y. Y. (2002). *Industrial utilization on bamboo: Technical report No. 26*. The International Network for Bamboo and Rattan (INBAR), People's Republic of China.

Zhang, Y. (2011). Bambusoideae-Cultivation-Technical manual-English Xicheng District Beijing 100009, 4.S795 -62.

Zhou, F.C. (1981). Studies on physical and mechanical properties of bamboo woods. Journal of the Nanjing Technological College of Forest Products 2: 1-32.

Zhou, G. M., 2006 Carbon storage, fixation and distribution in Moso bamboo (Phllostachys pubescens) stands ecosystem. PhD thesis, Zhejiang University, Zhejiang, China.

Zianis, D., Mencuccini, M., 2004. On simplifying allometric analysis of forest biomass. For. Ecol. and Mang. 187, 311-332.

APPENDIX I

Field data form for plot measurement of bamboo forests

Survey date: ______ Plot code: ______

Name of survey team members: ______

Administration location of plot: ______

Coordinates of plot centre Longtitude: ______ Latitude: ______

Altitude (m) ______ Average slope: ______

Plot area ______ Plot size: ______

Forest types: ______

Sub-plot measurement ID ______ **Sub-plot code:** ______

Number of clump in sub-plot ______

Average stem per clump ______

ID	Bamboo name	Bamboo age	Total height (m)	DBH (cm)	Remarks
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
etc					

APPENDIX II

Field data form for destructive measurement of bamboo biomass

Survey date		Sample plot code:	
Name of survey team			
Starting time		Ending time	

ID of sampe bamboo	Age class	Size of sample bamboo		Fresh weight of sample bamboo by parts (kg)			Fresh weight of sample taken for analysis (kg)					
		H (m)	DBH (cm)	Stem	Branh	Foliage	Stem (0.0m)	Stem 1/4)	Stem (1/2)	Stem (3/4)	Branch	Foliage
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
....												

APPENDIX III

Synthesis of destructive measurement data of bamboo forests

Forest type:				
Administration location of survey area:				
Coordinates at centre of sample plot:	Latitude		Logitude:	
Date of survey:				
Name of implementing organization:				
Name of person responsible for data:				

#	**Sample bamboo ID/name**	**Age**	**Size of sample bamboo**		**Fresh AGB biomass (kg/bamboo) by parts (data measured in the field)**				**Remarks on sample bamboo (note any irregular charater)**
			DBH (cm)	H (m)	Stem	Branch	Foliage	Total	
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									
41									
42									
43									
44									
45									
46									
47									
48									
49									
50									
51									
52									
53									
54									
55									
56									
57									
58									
59									
etc									

APPENDIX IV

Analytical data record on oven dry mass of sample bamboos

Name of laboratory:	
Date of data report:	
Name of person in charge:	

#	Sample bamboo ID/name	Age of bamboo	Sample part	Fresh weigh with out tare (gram)	Oven dry weight of sample with tare (gram)	Weight of tare (gram)	Ratio of oven dry weight to fresh weight
1			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
2			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
3			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
4			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
5			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
6			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
7			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
8			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
9			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
10			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
11			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				
etc			Stem (0.0 m)				
			Stem (1/4 m)				
			Stem (1/2 m)				
			Stem (3/4 m)				
			Branch				
			Foliage				