Khulna University
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**Title:** Allometric models for prediction of above-ground iomass, carbon and autrients stock in planted *Gmelina arborea* Roxb. of Bangladesh

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**Programme:** Master of Science in Forestry

# Allometric models for prediction of above-ground biomass, carbon and nutrients stock in planted *Gmelina arborea* Roxb. Of Bangladesh

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March, 2018

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Course Title: Thesis Work
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Thesis has been submitted to Forestry and Wood Technology Discipline, Khulna University, Khulna-9208, Bangladesh for the partial fulfillment of the professional Masters degree


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**Dedicated to….**

***My departed mother***

## Declaration

I, Lulu Rayhan Khushi, declare that this thesis submitted for the Degree of Master of Science (MSc) in Forestry and Wood Technology Discipline, Khulna University, Khulna, is my own original research work and have not previously been submitted or it has not been accepted to any other institution.

I, hereby, give consent for my thesis, if accepted, to be available for any kind of photocopying and for inter-library loans.

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## Approval

Thesis has been submitted to Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh, for the partial fulfillment of the requirements for Master of Science (MSc) degree in Forestry. I have approved the style and format of the thesis.

Hossain 11/3/2018

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Lulu Rayhan Khushi

# ABSTRACT

*Gmelina arborea* Roxb. is a fast growing, deciduous tree with a straight trunk. This species is native to Bangladesh. This species has been widely planted and managed at the hilly areas of Southeast part of this country with 12 years of rotation for commercial production of pulp since 1992. The purpose of this study were to derive best fit allometric model for estimating above-ground biomass, carbon and nutrients (N, P, K) stock in *Gmelina arborea* to ensure sustainable production and management of this species. A total of 8 linear models with 64 regression equations were tested for above-ground biomass, carbon and nutrients stock in different parts (leaves, branches, barks and stem) of plant. The best fit allometric models were obtained by considering the values of CV, Rmse, MSerror, AICc, Furnival Index and Regression coefficient ($R^2$). The best fit allometric models were Ln Biomass = -6.89 Ln DBH + 2.661; Ln Biomass = -5.293 Ln DBH + 2.786; Ln Biomass = -5.344 Ln $DBH^2 \times$ Height + 0.907; Ln Biomass = -3.240 Ln $DBH^2 \times$ Height +0.907; Ln Biomass = -3.028 Ln $DBH^2 \times$ Height + 0.925 for leaves, branches, bark, stem without bark and total above-ground biomass respectively. Similarly, the best fit allometric models for Nitrogen, Phosphorous, Potassium and Carbon stock in total above-ground biomass were Ln N = -7.826 Ln $DBH^2 \times$ Height + 0.918; Ln P = -5.763 + Ln $DBH^2 \times$ Height + 0.925; Ln K = -8.070 Ln DBH + 2.594; Ln C = -6.061 Ln $DBH^2 \times$ Height + 0.925 respectively.

**Keywords:** Allometry, Biomass, Carbon, *Gmelina arborea*, Nutrients

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# CHAPTER I

# INTRODUCTION

## 1.1. Introduction

*Gmelina arborea* is native to India, Bangladesh, Sri Lanka, Myanmar, Thailand, Southern China, Laos, Cambodia, and Sumatra in Indonesia. It is fast growing medium sized species and has been introduced in many tropical countries, including the Philippines, Malaysia, Brazil, Gambia, Costa Rica, Burgina Faso, Ivory Coast, Nigeria, and Malawi (Soerianegara and Lammens 1994). It has been widely planted in Southeast Asian countries been planted less widely in tropical African and Latin American countries (Evans 1982) and it is useful for planking, paneling, carriages, furniture, carpentry of all kinds, pulpwood (Khan and Alam 1996). Due to its growth nature, this species has been widely planted and managed with 12 years of rotation for the commercial production of pulp in Bangladesh (KPM, 1992).

Karnaphuli Paper Mills Ltd. (KPM) is the largest and 1$^{st}$ paper mill of Bangladesh which was established during 1953. Bamboo was the main raw material of this mill. With time, bamboo stock in the southeastern hill forest was depleted due to uncontrolled Jhum cultivation and encroachment in bamboo habitat. These incidences result shortage of raw material which was first noticed during mid-eighties (KPM, 1992). Considering this scenario, Pulpwood Division, Kaptai and Pulpwood Division, Bandarban was established in Bangladesh to supplement sustainable supply of pulpwood to KPM (FD, 2015). These two forest divisions contain 37,678 ha of land area. Pulpwood divisions planted some fast growing low density tree species where *G. arborea* was the principal species with 12 year rotation (KPM, 1992). Yearly raw material requirement of KPM is 75,000 tons (air-dry weight) and the first supply of *G. arborea* was started during 1992 with an amount of 7,851 tons (air-dry weight) and the source of rest of raw materials were bamboo and imported pulp. Very recently, supply of *G. arborea* has been decreased to 1,377 tons (air-dry weight) during 2015 (KPM, 2016). This consistent lower supply may be related to encroachment, illegal harvesting, loss of soil productivity and inappropriate stock assessment etc. in the pulpwood Forest Division.

Assessment of stock in terms of volume and biomass is the first step of sustainable management of a forest (Pretzsch, 2009). Biomass estimation has many applications like timber extraction, estimation of productivity, tracking changes in carbon stocks of the forest and global carbon and nutrient cycle (Komiyama et al., 2008, Mahmood et al., 2008b; Mahmood, 2014). Biomass of a stand can be estimated using three methods: the harvest method, the mean tree method and the allometric method. The harvest method requires destructive felling of trees and mean tree method is applicable for the plantation (Golley et al. 1975; Cintro´n and Schaeffer-Novelli 1984; Ketterings et al. 2001). Allometric technique is a non-destructive and commonly used method of biomass estimation where whole or partial weight of a tree can be estimated from measureable tree dimension (stem diameter and height) and allometric equations (Ketterings et al. 2001; Komiyama et al. 2005). Many researchers have tried to develop generalized allometric model for different forests and tree species (Nelson et al. 1999; Monte`s et al. 2000; Komiyama et al. 2002, 2005; Chung-Wang and Ceulemans 2004; Chave et al. 2005; Nava´r 2009; Basuki et al. 2009). But, it is preferable to use species and site-specific allometric model for accurate estimation of biomass (Ketterings et al. 2001; Khan et al. 2005; Soares and Schaeffer-Novelli 2005; Smith and Whelan 2006; Kairo et al. 2009).

*Gmelina arborea* has only allometric equation for volume over-bark in Bangladesh (Latif et al. 1984). Unfortunately, this species has no allometric equation for biomass, carbon and nutrient stock in above-ground parts of *G. arborea* of Bangladesh. But, this information may be very important to ensure or cross checking the possibility for the sustainable supply of raw material to KPM as pulpwood. The objectives of the present study were to derive allometric models for estimating above-ground biomass, nutrients (N, P and K) and carbon stock in *Gmelina arborea* to ensure sustainable production and management of this species.

### 1.2 Objectives:

The objective of the study was as follows:

- To determine the best allometric model for estimating and prediction of above-ground biomass, carbon and nutrients (N, P, K) stock in *Gmelina arborea.*

# CHAPTER II

# LLITERATURE REVIEW

## 2.1. Biomass

The biomass or phytomass of plants comprises the oven-dry weight of leaves, buds, flowers, fruits, branches, and stems, above and below-ground roots in a certain time. Quantity and distribution of vegetal biomass provide important information on ecosystem such as forest structure and condition (Westman et al., 1977), forest site productivity and carbon fluxes (Chambers et al., 2001; Specht et al., 2003; Mahmood, 2012).

## 2.2. Allometric Models

Forest ecologists have developed various methods for biomass estimation forests. The harvest method, the mean tree method and the allometric method are quite common methods of biomass estimation. In many natural forests, the total weight of an individual tree often reaches several tons (Komiyama et al. 2005). So, the harvest method cannot be used easily in the mature forest and it is not reproducible because all trees must be destructively harvested. The mean-tree method is utilized only such forests those are appeared with a homogenous tree size distribution, such as plantations. Allometric method is a non-destructive method and it estimates the whole or partial weight of a tree from measurable tree dimensions, such as plantations. Allometric method is a non-destructive method and it estimates the whole or partial weight of a tree from measurable tree dimensions, including trunk diameter and height using allometric equations (Kettering's et al., 2001). Allometric relationships often show site or species- dependency (e.g., clough et al., 1997; Smith and Whelan, 2006). There are various methods to estimate biomass based on allometric relationships. In most studies, Diameter at Breast Height (DBH) was taken as the only independent variable in the allometric equation (Putz and Chan, 1986; Clough and Scott, 1989; Amarasinghe and Balasubrananiam, 1992; Mackey, 1993; Clough et al., 1997; Ong et al., 2004; Mahmood et al., 2004). However, incorporation of the variable H (tree height) (i.e., the use of $D^2H$) may ensure higher accuracy of biomass estimation (Suzuki and Tagawa, 1983; Tamai et al., 1986; Kusmana et al., 1992; Komiyama et al., 2000). Biomass estimation through allometric varied greatly among sites (Komiyama et al., 2008; Clough et al., 1989). It is preferable to use specific and site specific regression models for biomass estimation (Golley et al., 1975; Ketterings et al., 2001). Specific allometric equations for estimating above-ground biomass have not yet developed for this species in Bangladesh. So, it is required to develop site and species specific regression models for biomass estimation for this species.

## 2.3 Plantation History of *Gmelina arborea* in Bangladesh

The forests in the Chittagong Hill Tracts are predominantly tropical semi-evergreen. The predominant trees are Garjan (*Dipterocarpus turbinatus*), Chapalish (*Artocarpus chapalasha*), Telsur (*Hopea odorata*), Boilam (*Anisoptera glabra*), Teak (*Tectona grandis*), Gamar (*Gmelina arborea*), Mehogani (*Swietenia spp*), Koroi (*Albizzia spp*) etc. Bamboos are common here (FD, 2017). Throughout the 19th century, plantation of commercially important species replaced a large portion of natural forests of this region. Along with these, commercial plantations with fast growing species, such as *G. arborea*, used as raw materials in paper and pulp making industry (Hossain, 2016).

## 2.4 Environmental Condition

*Gmelina arborea* is found in rainforest as well as dry deciduous forest and tolerates a wide range of conditions from sea level to 1200 m elevation and annual rainfall from 750 to 5000 mm. It grows best in climates with mean annual temperature of 21-28°C (Jensen 1995). It found to grow best on deep, well drained, base-rich soils with pH between 5.0 and 8.0. Growth is poor on thin, highly leached acid soils (F/FRED 1994).

## 2.5. Uses

Wood of G. arborea is yellowish or grayish-white, even grained, and very useful for planking, paneling, carriages, furniture, and carpentry of all kinds (Khan and Alam 1996). The wood specific gravity found to range from 420 to 640 kg/m3 (Davidson 1985). It is easily worked, readily takes paint or varnish, and is very durable under water (Gamble 1922). The wood is used for light construction and pulp as well as for fuel wood and charcoal production. Fuel wood provides 4400- 4800 Kcal/kg (Davidson 1985).

## 2.6. Other Uses

The leaves and fruits of G. arborea are used as fodder in many parts of India (Mukherjee 1884, Benthal 1933, Laurie 1945). A number of the plant's parts have medicinal value. It also produces good quality honey.

# CHAPTER III

# MATERIALS AND METHODS

## 3.1. Study Area

Present study was conducted at Rowangchhari and Tarachha range of Bandarban Pulpwood Forest Division, Bandarban, Bangladesh. The geographical extent of the study area is in between 22°08' to 22°11' North latitudes and 92°15' to 92°21' East longitudes (Figure 1). About 2528 mm of precipitation falls annually. Mean annual air humidity is 82% and mean annual temperature is 25.9°C. The pulpwood forest division was established during 1985 for supplying the raw materials for the Karnaphuli Paper Mills, Chittagong. Approximately 8720 ha area was vested for pulpwood production. *Gmelina arborea* was the main species planted in this area. There is a conflict between the Forest Department and Local Tribal about the land ownership. So, local people destroy the forest intentionally through illicit felling, encroachment and Jhum cultivation. Now the forest is like a secondary forest dominated by *Gmelina arborea*. There are some *Tectona grandis* plantations by forest department for production forestry.

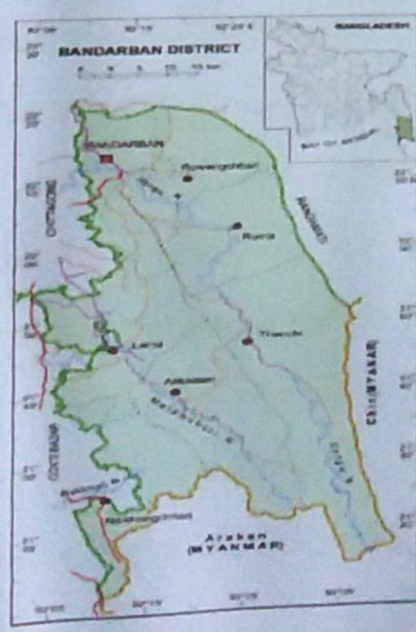



**Figure 1:** Bandarban Pulpwood Forest Division

### 3.2. Sample Collection and Processing

To obtain the representative diameter distribution a reconnaissance survey was taken into account during tree selection. A total of 16 individuals of *G. arborea* were selected to cover the range of DBH from 5 to 30 cm from the studied forest areas. This DBH range was divided into five classes as 5–10, 10–15, 15–20, 20–25 and 25–30 cm. Two to four individuals from each class were selected avoiding deformed and insect or disease infested trees. Destructive sampling was conducted for data collection. Before felling the selected trees DBH was measured. Height of individual samples was measured after felling. Due to difference in moisture content, tree parts were into leaves, small branches (diameter <2 cm), large branches (diameter >2 cm) and stem (Mahmood et al., 2015). The fresh weight of the leaves and branches were weighed in the field using portable digital hanging balance of 100 kg capacity. The stem was divided into suitable sized log section less than 100 kg in mass. The stump was cut carefully using hand saw and weighed and finally added with stem weight. At least 10 sections of log (1 m long) from different position (base, middle and top) of stem were debarked in the field to get fresh weight proportion of stem and bark. Thus stem biomass was divided into bark and stem wood. Ten sub samples (0.25 kg) from each part (leaf, stem, bark, smaller branch and bigger branch) of sampled trees were taken randomly using portable laboratory balance of 0.30 kg. The collected sub-samples were recorded and stored in sealed plastic bags and brought back to laboratory to estimate the fresh to even-dry weight conversion factor or ratio at 80 °C. Conversion factor for each part was derived from oven-dry weight divided by fresh weight of the subsamples (Mahmood et al., 2004, 2012). The respective conversion factor was then multiplied with total fresh weight of each part to get the oven-dry weight. The total oven-dry weight of a sample tree was obtained by summing the oven-dry weight of stem (including stump), bark, branches (sum of small branches and large branches) and leaves. Mean biomass proportion for each part was estimated in accordance with the DBH classes.

## 2.3 Nutrients (N, P and K) and Carbon in Plant Part

Oven-dried sub-samples of tree parts were grounded in a passed through 2 mm sieve and stored in cold place with airtight pots for further chemical analysis. The plant materials were digested and analyzed by using Kjeldhal method (Baethgen and Alley, 1989) to determine Nitrogen in plant samples. Tri acid ($HNO_3$, $H_2SO_4$ and $HClO_3$ in 10:1:3 ratio) digestion was applied to plant samples for determining phosphorus and potassium in sample extract (Allen 1989). Carbon content inn samples was measured by loss of ignition method (Allen, 1989). Nutrient and carbon concentration if plant parts were compared by one-way analysis of variance (ANOVA) followed by Dancan Multiple Range Test using SAS (6.12) statistical software.

## 2.4 Data Analysis and Model Selection

The independent variables include DBH and TH, whereas the dependent variables were the leaves biomass ($B_{leaf}$), branch biomass ($B_{branch}$), stem bark biomass ($B_{bark}$), stem wood biomass ($B_{stem}$) and total biomass ($B_{total}$). Biomass data of different parts were set in scatter plot diagram to see the relationship between independent variable and dependent variables because the data exhibited heteroscedasticity, both the dependent and independent variables was transformed using natural logarithm and square root. A total of 8 linear models ($y = aX + b$, $\sqrt{y} = a\sqrt{X} + b$, $y = aLogX + b$, $Logy = aX + b$, $Logy = aLogX + b$, $y = alnX + b$, $Lny = aX + b$ and $Lny = alnX + b$) with 64 regression equations were tested to derive the allometric model for biomass of each plant part; and nutrients and carbon stock in total above ground biomass (Table 1) (Mahmood et al., 2015). Significance test of regression equations were tested by using SAS (6.12) statistical software. The best fit regression equations were selected considering the higest Coefficient of determination (R2) and F-value, with the lowest value of Coefficient of variation (CV), Root mean square error (Rmse), Mean square error (MSerror), Akaike's information criterion corrected (AICc), Furnival Index (FI) and readily measureable independent variables (Furnival 1961; Chave et al., 2005; Soares et al., 2005; Siddique et al., 2012; Mahmood et al., 2015). Here, we compared a number of statistical models commonly used to estimate above-ground biomass published in forestry literature and mathematically simple in applied relevance (Segura and Kanninen, 2005; Mahmood et al., 2004, 2012, 2015; Basuki et al., 2009; Vahedi et al., 2014; Zewdie et al., 2009). The logarithmic transformation of variables introduces a systematic bias in the calculation which was corrected using a correction factor (CF=exp ($SEE^2$/2), where SEE is the standard error of the estimate) when back-transforming the calculation into biomass (Sprugel, 1983; chave et al., 2005; Basuki et al., 2009). The average deviation was calculated after the prediction was back-transformed and corrected using a CF as follows:

$$\bar{S}(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{|\hat{Y}_i - Y_i|}{Y_i}$$

Where $\bar{S}$ is the average deviation, $Y_i$ is the observed dry weight, $\hat{Y}_i$ is the predicted dry weight, n is the number of observations.

**Table 1:** Regression equations for allometric relationship

| Models | Independent variables |
|---|---|
| $y= aX + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $\sqrt{y}= a\sqrt{X} + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $y= a \text{ Log } X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $\text{Log } y = a X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $\text{Log } y = a \text{ Log } X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $y= a \ln X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $\text{Ln } y= a X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |
| $\text{Ln } y= a \ln X + b$ | DBH; $DBH^2$; DBH x TH; $DBH^2$ x TH; DBH x $TH^2$; $DBH^2$ x $TH^2$ |

DBH=Diameter at Breast Height; TH= Total Height

# CHAPTER IV

# RESULT AND DISCUSSION

## 4.1. Results

The mean biomass proportion of different parts of *G. arborea* found to vary with DBH classes. Comparatively higher proportion of leaf (4.53±0.07%) was observed at the DBH class of 15 to 20 cm while higher proportion of branch biomass (22.94±0.64%) was observed for the same DBH class (15-20 cm). But almost similar proportion of stem (71.53± 3.46-74.84±2.53%) and bark (8.73±0.42-9.14±0.31%) biomass was observed for all DBH classes (Table 2).

**Table 2:** Biomass proportions (mean±SE) in plant parts according to DBH classes of *Gmelina arborea*

| | **Biomass proportion percentage** | | | |
|---|---|---|---|---|
| **DBH (cm)** | **Leaf** | **Branch** | **Bark** | **stem** |
| 05-10 | 2.75±0.95 | 13.27±1.89 | 9.14±0.31 | 74.84±2.53 |
| 10-15 | 2.55±1.91 | 16.20±3.85 | 8.84±0.62 | 72.41±5.10 |
| 15-20 | 4.53±0.07 | 22.94±0.64 | 7.89±0.08 | 64.64±0.64 |
| 20-25 | 3.74±0.80 | 22.47±3.31 | 8.03±0.39 | 65.76±3.18 |
| 25-30 | 2.43±0.67 | 17.31±3.45 | 8.73±0.42 | 71.53±3.46 |

Nutrients (N, P and K) and carbon concentration in plant parts varied significantly ($p <$ 0.05). Comparatively highest concentration of nitrogen (26.85mg/g) phosphorus (0.12 mg/g) and potassium (16.08) were observed in leaf. Higher concentration (48.86) of carbon was observed in bigger branch followed by stem (48.35) (Table 3).

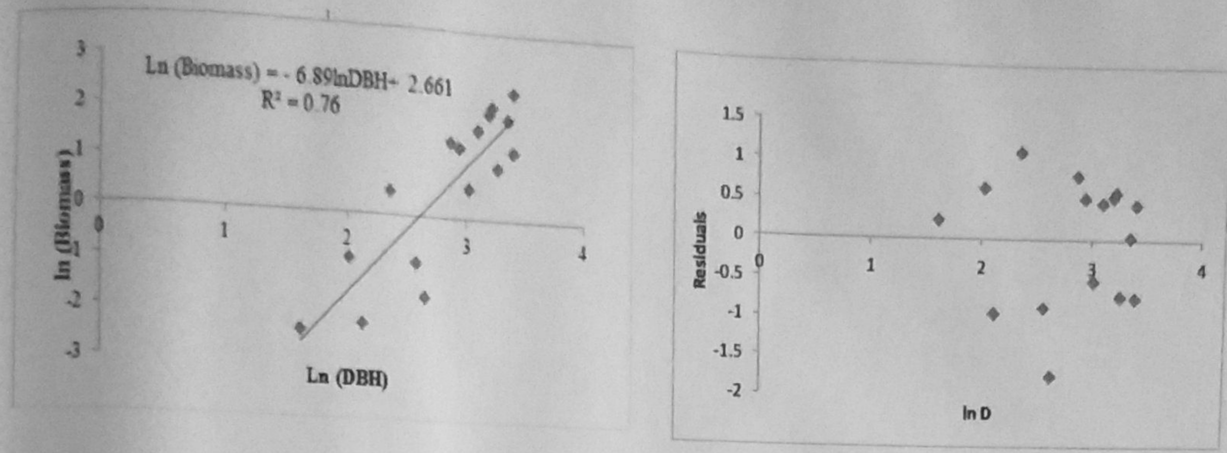
This study tested a total of 8 linear models along with 64 regression equations in combination with DBH and TH as independent variables, which yield a total of 240 equations for leaves, bark, branch, stem and total above-ground biomass. Most of the equations were significant ($p<0.05$) but 217 regression equations were excluded considering the value of co-efficient of determination ($R^2$) less than 0.70 for leaves, 0.80 for branch, 0.97 for bark, stem without bark and total above-ground biomass. The preliminary selected equations were compared to get the best fit allometric equation or model considering the parameters of estimation such as CV, Rmse, MSerror, F value, AICc and furnival index (Table 4). The selected allometric models were Ln Biomass = -6.89 Ln DBH + 2.661; Ln Biomass = -5.293 Ln DBH + 2.786; Ln Biomass = -5.344 Ln $DBH^2$ ×Height + 0.907; Ln Biomass = -3.240 Ln $DBH^2$ × Height +0.907; Ln Biomass = -3.028 Ln $DBH^2$ × Height + 0.925 for leaves, branches, bark, stem without bark and total above-ground biomass respectively (Table 4 and Figure 2). Irrespectively, allometric models for nutrients (N, P and K) and carbon stock in the above-ground biomass were also selected by considering the same principle as followed for the biomass equations. The selected allometric models for Nitrogen, Phosphorous, Potassium and Carbon were Ln N = -7.826 Ln $DBH^2$ × Height + 0.918; Ln P = -5.763 + Ln $DBH^2$ × Height + 0.925; Ln K = -8.070 Ln DBH + 2.594; Ln C = -6.061 Ln $DBH^2$ × Height + 0.925 respectively (Table 4 and Figure 3).

**Table 3:** Nutrients and carbon concentration (mean ± SE) in different parts of *Gmelina arborea*

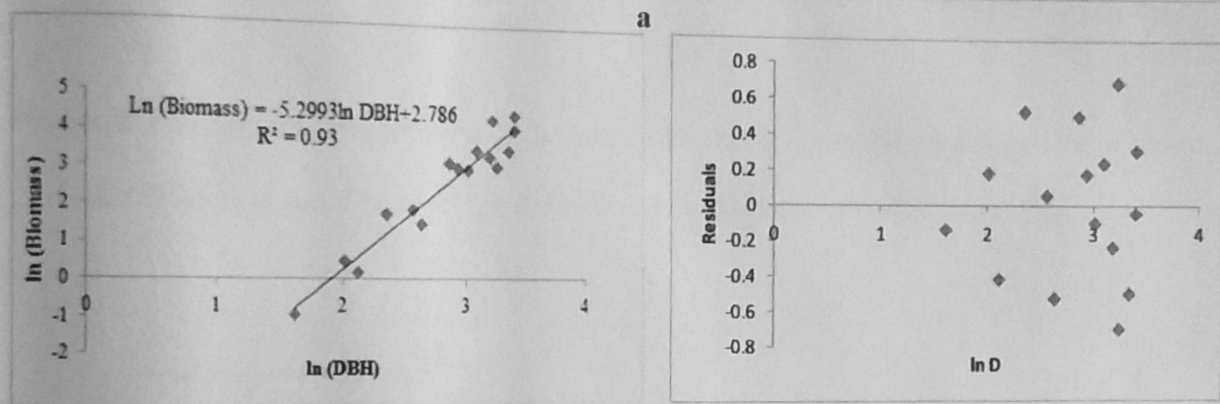
| **Plant parts** | **N (mg/g)** | **P (mg/g)** | **K (mg/g)** | **C %** |
|---|---|---|---|---|
| Leaf | 26.85±1.61 | 0.12±0.01 | 16.08±0.39 | 46.12±0.11 |
| Stem | 6.64±0.38 | 0.01±0.00 | 4.51±0.10 | 48.35±0.43 |
| Bark | 18.15±5.38 | 0.50±0.07 | 9.51±0.10 | 45.74±0.03 |
| Bigger Branch | 7.08±0.35 | 0.08±0.01 | 6.86±0.26 | 48.86±0.01 |
| Smaller Branch | 11.67±1.77 | 0.04±0.01 | 12.94±0.20 | 47.13±0.50 |

**Table 4:** Selected allometric models for different parts of *Gmelina arborea*. * indicated the best fit equation

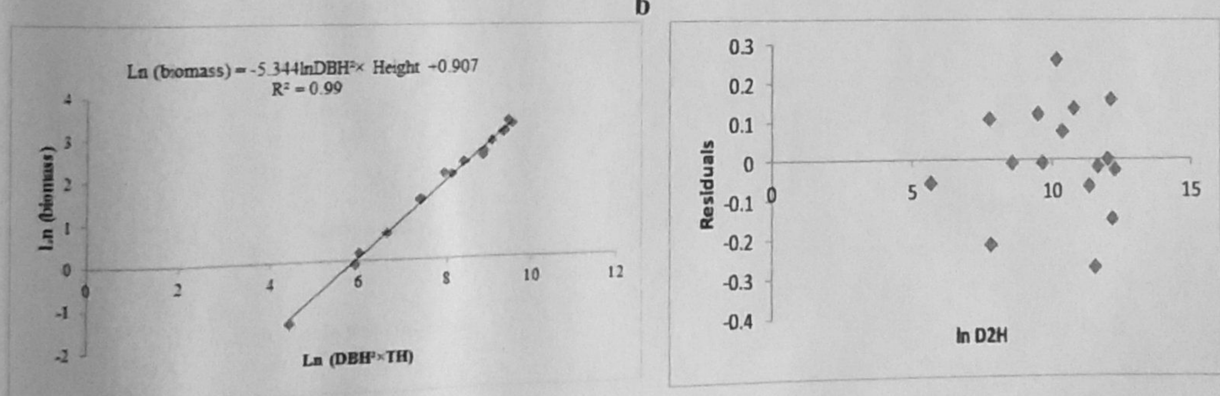
| Leaf | Equation | $R^2$ | a | b | Sa | Sb | Cv | Rmse | Mserror | F | AICc | FI | CF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ln Y=a+b ln(D)* | 0.763 | -6.896 | 2.661 | 1.134 | 0.396 | 141.768 | 0.841 | 0.707 | 45.157 | 0.305 | 2.261 | 1.283 |
| | ln Y=a+bln (D2H) | 0.755 | -6.975 | 0.955 | 1.174 | 0.146 | 144.398 | 0.856 | 0.733 | 43.022 | 0.893 | 2.303 | 1.366 |
| | ln Y= a+b ln (DH) | 0.745 | -6.976 | 1.482 | 1.203 | 0.232 | 147.075 | 0.872 | 0.760 | 40.965 | 1.481 | 2.346 | 1.398 |
| | ln Y= a+bD | 0.742 | -2.663 | 0.173 | 0.558 | 0.027 | 148.049 | 0.878 | 0.770 | 40.244 | 1.692 | 2.361 | 1.346 |
| | SQRT Y=a+bD | 0.721 | -0.344 | 0.111 | 0.379 | 0.018 | 34.014 | 0.596 | 0.355 | 36.215 | -10.717 | 1.602 | |
| Branch | | | | | | | | | | | | | |
| | ln Y=a+b ln(D)* | 0.933 | -5.293 | 2.786 | 0.572 | 0.200 | 16.643 | 0.424 | 0.180 | 194.388 | -21.578 | 3.034 | 1.016 |
| | ln Y=a+bln (D2H) | 0.927 | -5.399 | 1.003 | 0.605 | 0.075 | 17.306 | 0.441 | 0.195 | 178.736 | -20.329 | 3.155 | 1.022 |
| | ln Y= a+b ln (DH) | 0.919 | -5.413 | 1.559 | 0.642 | 0.124 | 18.263 | 0.466 | 0.217 | 159.051 | -18.605 | 3.330 | 1.028 |
| | SQRT Y=a+b D | 0.836 | -1.096 | 0.298 | 0.724 | 0.035 | 25.184 | 1.139 | 1.297 | 71.193 | 10.029 | 8.148 | |
| | SQRT Y=a+bSQRT (D) | 0.820 | -5.477 | 2.369 | 1.286 | 0.296 | 26.343 | 1.191 | 1.420 | 63.861 | 11.468 | 8.523 | |
| Bark | | | | | | | | | | | | | |
| | ln Y=a+bln (D2H)* | 0.994 | -5.344 | 0.907 | 0.153 | 0.019 | 6.082 | 0.112 | 0.013 | 2271.685 | -64.249 | 0.561 | 1.000 |
| | ln Y=a+b ln(D) | 0.992 | -5.220 | 2.507 | 0.176 | 0.061 | 7.081 | 0.130 | 0.017 | 1672.537 | -59.385 | 0.653 | 1.000 |
| | ln Y= a+b ln (DH) | 0.990 | -5.373 | 1.412 | 0.202 | 0.039 | 7.954 | 0.146 | 0.021 | 1322.458 | -55.663 | 0.733 | 1.000 |
| | SQRT Y=a+b D | 0.989 | -0.485 | 0.185 | 0.105 | 0.005 | 5.500 | 0.165 | 0.027 | 1305.254 | -51.820 | 0.827 | |
| | SQRT Y=a+bSQRT (D2H) | 0.988 | 0.272 | 0.042 | 0.092 | 0.001 | 5.881 | 0.176 | 0.031 | 1139.918 | -49.677 | 0.884 | |
| Stem | | | | | | | | | | | | | |
| | ln Y=a+bln (D2H)* | 0.994 | -3.240 | 0.907 | 0.153 | 0.019 | 2.837 | 0.112 | 0.013 | 2271.685 | -64.249 | 1.605 | 1.000 |
| | ln Y=a+b ln(D) | 0.992 | -3.116 | 2.507 | 0.176 | 0.061 | 3.302 | 0.130 | 0.017 | 1672.537 | -59.385 | 1.868 | 1.000 |
| | ln Y= a+b ln (DH) | 0.990 | -3.270 | 1.412 | 0.202 | 0.039 | 3.710 | 0.146 | 0.021 | 1322.458 | -55.663 | 2.098 | 1.000 |
| | SQRT Y=a+b D | 0.989 | -1.388 | 0.529 | 0.300 | 0.015 | 5.500 | 0.472 | 0.223 | 1305.254 | -18.167 | 6.773 | |
| | SQRT Y=a+bSQRT (D2H) | 0.988 | 0.777 | 0.120 | 0.263 | 0.004 | 5.881 | 0.505 | 0.255 | 1139.918 | -16.025 | 7.242 | |
| Total above ground biomass | | | | | | | | | | | | | |
| | ln Y=a+bln (D2H)* | 0.991 | -3.028 | 0.925 | 0.185 | 0.023 | 3.138 | 0.135 | 0.018 | 1622.476 | -58.2109 | 2.321 | 1.000 |
| | ln Y=a+b ln(D) | 0.991 | -2.907 | 2.561 | 0.188 | 0.066 | 3.233 | 0.139 | 0.019 | 1527.862 | -57.2575 | 2.391 | 1.000 |
| | ln Y= a+b ln (DH) | 0.986 | -3.054 | 1.441 | 0.237 | 0.046 | 3.989 | 0.172 | 0.029 | 998.953 | -50.5359 | 2.950 | 1.001 |
| | SQRT Y=a+b D | 0.984 | -1.832 | 0.647 | 0.456 | 0.022 | 6.935 | 0.718 | 0.515 | 842.731 | -4.74309 | 12.340 | |
| | SQRT Y=a+bSQRT (D2H) | 0.978 | 0.834 | 0.146 | 0.434 | 0.006 | 8.039 | 0.832 | 0.692 | 623.590 | -0.01623 | 14.305 | |


Ln (Biomass) = - 6.89lnDBH+ 2.661
R² = 0.76
ln (Biomass)
Ln (DBH)
ln D

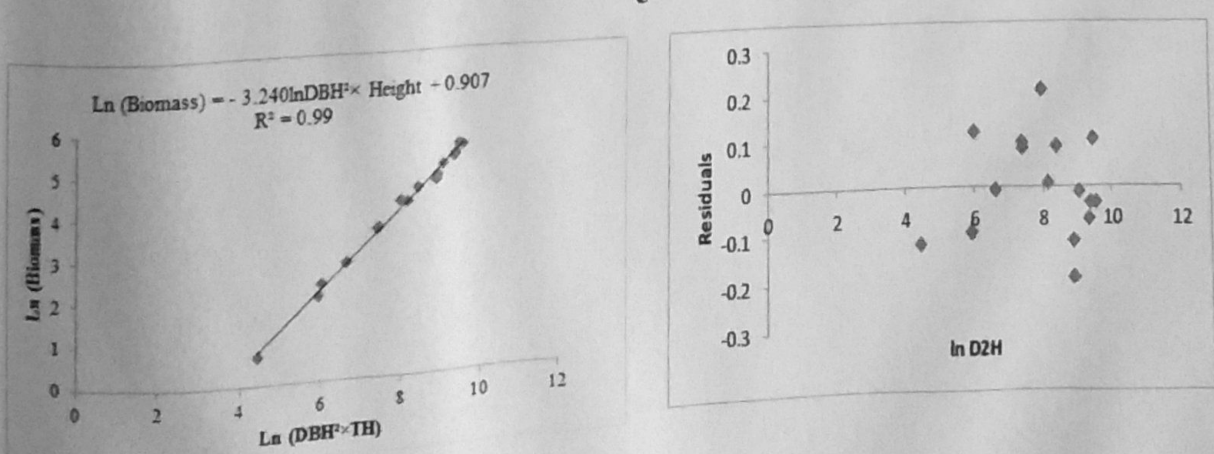
a


Ln (Biomass) = -5.2993ln DBH+2.786
R² = 0.93
ln (Biomass)
ln (DBH)
ln D

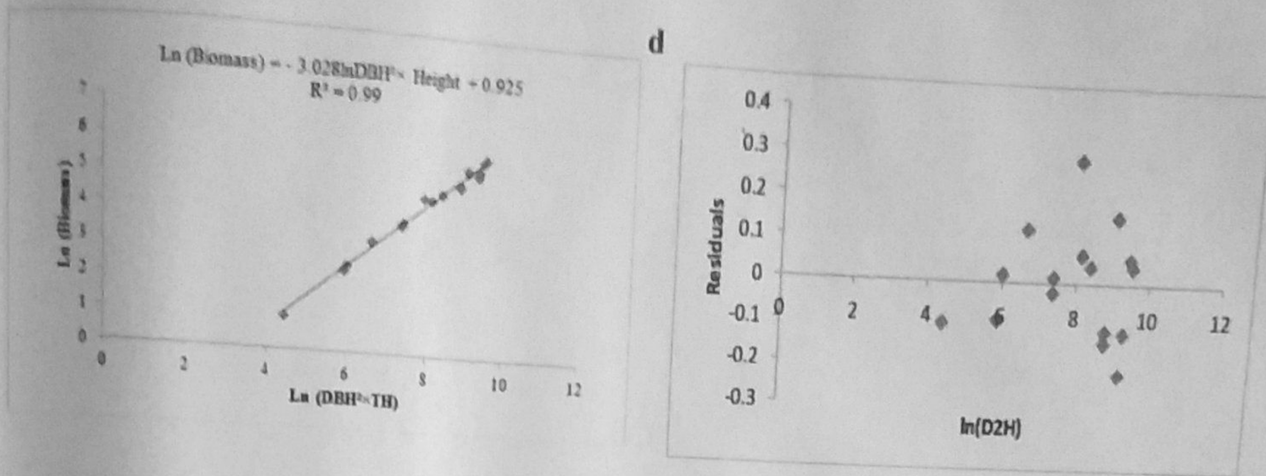
b


Ln (biomass) = -5.344lnDBH²× Height +0.907
R² = 0.99
Ln (biomass)
Ln (DBH²×TH)
ln D2H

c

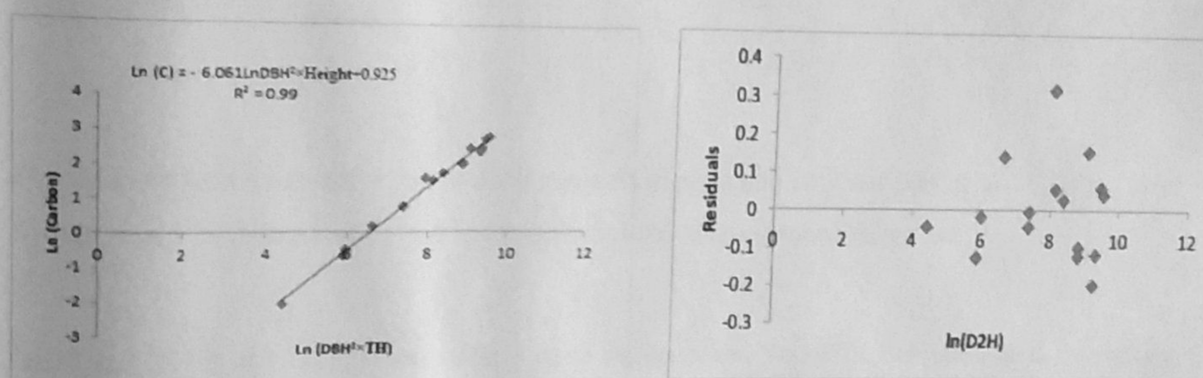

Ln (Biomass) = - 3.240lnDBH²× Height + 0.907
R² = 0.99
Ln (Biomass)
Ln (DBH²×TH)
ln D2H

d

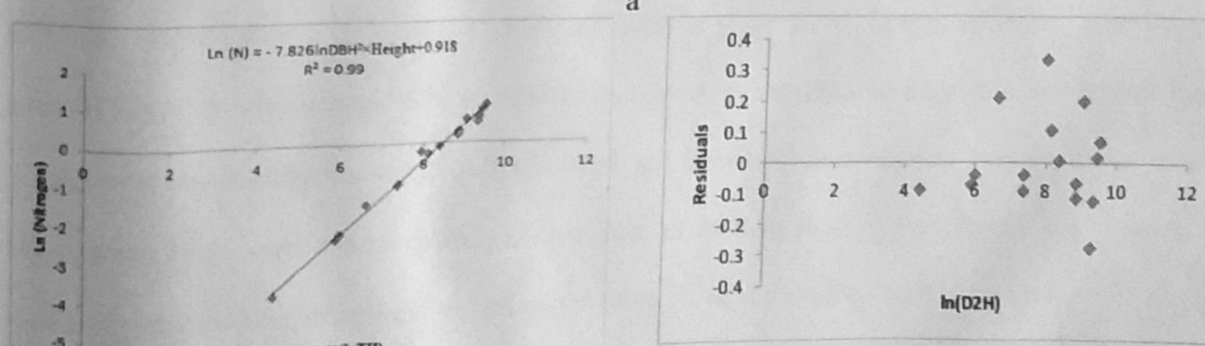



e

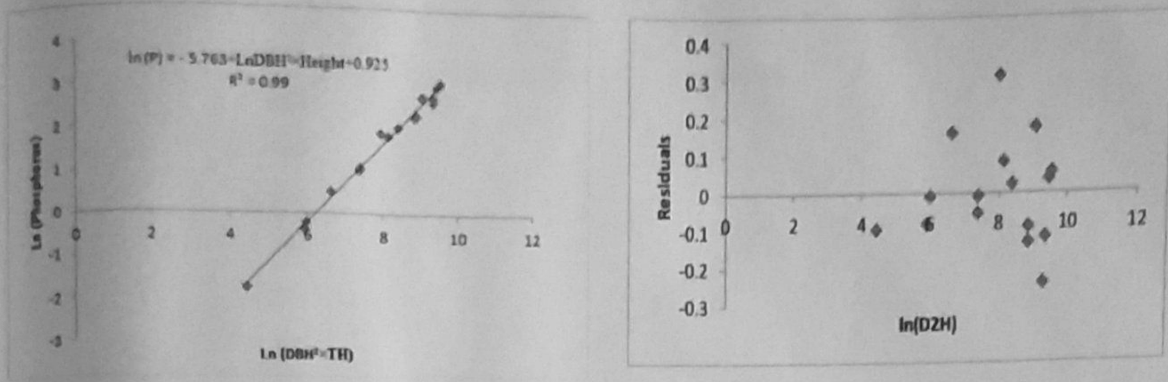
**Figure 2**: Graphical representation of the best fit models and residual plot of (a) leaf (b) branch (c) bark (d) stem without bark (e) total above-ground biomass of *Gmelina arborea*.



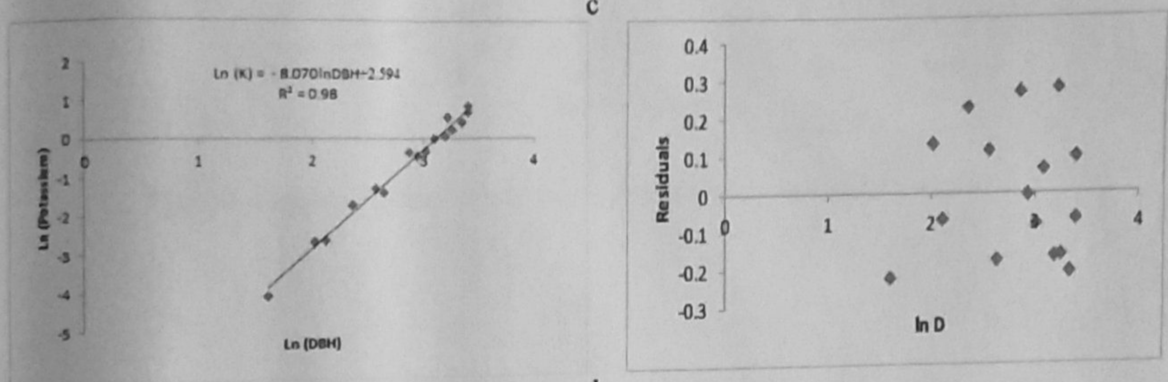

a




b




c




d

**Figure 3:** Graphical representation of the best fit models and residual plot of (a) Carbon, (b) Nitrogen, (c) Phosphorus, (d) and Potassium in total above-ground biomass.

DBH and TH (total height) are widely used independent variables for allometric equations to estimate above-ground biomass of different species (Lee 1990, Saintilan 1997). Therefore, present study recommended DBH and TH as independent variables for allometric models for the *G. arborea* considering the scope of application and different statistical test. In comparison with the present study, common allometric biomass model of Nam et al. (2016) showed no variation. Therefore, the derived allometric models seem to be valided with the common models

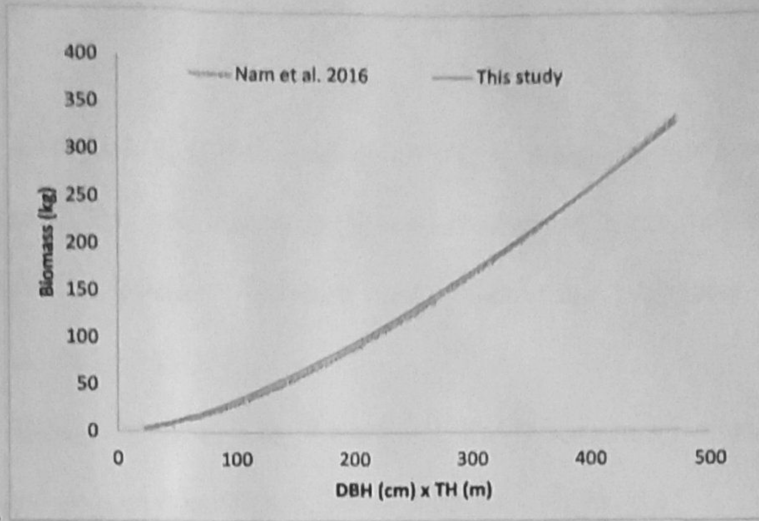



**Fig:** comparison of estimated total above ground biomass of *Gmelina arborea*

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