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# TREE-SPECIFIC EQUATIONS FOR ACCURATE CARBON ESTIMATION OF MAJOR FRUIT TREES IN BANGLADESH

**Mohammed Solaiman Talukder[1], Md. Main Uddin Miah[2*], Md. Giasuddin Miah[2]**
**Md. Mizanur Rahman[3] and Sohag Ahammed[4]**

[1]Bangladesh Agricultural Development Corporation, Dhaka, Bangladesh; [2]Department of Agroforestry and Environment, [3]Department of Soil Science, [4]Department of Forest Policy and Management, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh

***Corresponding e-mail:** mmumiahbsmrau@gmail.com

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## ABSTRACT

Tropical fruit trees play an important role in mitigating climate change by sequestering carbon from the atmosphere. However, estimating their carbon sequestration potential requires tree-specific equations. This study aimed to develop such equations for five major fruit tree species in Bangladesh *i.e.* Jackfruit (*Artocarpus heterophyllus*), Mango (*Mangifera indica*), Litchi (*Litchi chinensis*), Guava (*Psidium guajava*), and Jujube (*Ziziphus jujuba*). The study was conducted in four major ecosystems of Bangladesh namely, the Coastal ecosystem, Barind ecosystem, Terrace ecosystem, and Hill ecosystem. Vegetation data were randomly collected from each ecosystem. The equations were derived for Jackfruit $W\ (lb) = 0.26 \times D^2 \times H$ (for diameter <11 inches) and $W\ (lb) = 0.14 \times D^2 \times H$ (for diameter >11 inches); for Mango $W\ (lb) = 0.26 \times D^2 \times H$ (for diameter <11 inches) and $W\ (lb) = 0.13 \times D^2 \times H$ (for diameter >11 inches); for Litchi $W\ (lb) = 0.23 \times D^2 \times H$ (for diameter <11 inches) and $W\ (lb) = 0.13 \times D^2 \times H$ (for diameter >11 inches); for Guava $W\ (lb) = 0.22 \times D^2 \times H$ (for diameter <11 inches), and for Jujube $W\ (lb) = 0.22 \times D^2 \times H$ (for diameter <11 inches) and $W\ (lb) = 0.12 \times D^2 \times H$ (for diameter >11 inches). The equations will help in developing effective carbon management and climate change mitigation strategies in tropical agroforestry systems, aiding researchers, land managers, and policymakers in understanding tree growth and carbon sequestration.

**Keywords:** Agroforestry system, carbon estimation, tree-specific equation, and ecosystems.

## Introduction

Tropical fruit trees, when integrated into agroforestry systems, play a vital role in mitigating climate change by effectively capturing and storing carbon dioxide from the atmosphere. The significance of agroforestry systems, which involve the integration of tree growing with agricultural practices, is increasingly recognized as a crucial approach to addressing the issue of global climate change (Smith *et al.* 2014, Griscom *et al.* 2019). Within these ecological systems, fruit trees have a multifaceted role by serving as an important source of income for the local population and as significant carbon sinks, contributing to both environmental sustainability and the economic well-being of rural people.

The process of carbon sequestration, in which carbon dioxide is assimilated from the atmosphere and retained in plant life, is a fundamental aspect of efforts to mitigate climate change (IPCC, 2018). The pressing necessity to address climate change, considering its extensive impacts on ecosystems, economies, and human civilizations, highlights the significance of assessing and enhancing carbon sequestration in many ecological contexts. Tropical regions are very potential owing to their substantial capacity for carbon sequestration.

The process of carbon sequestration in trees and forests is primarily influenced by the growth patterns that are distinctive to each species, as well as other environmental conditions (Le Quéré *et al.* 2018, Lewis *et al.* 2019). The development of robust allometric equations that account for fluctuations is necessary to accurately estimate carbon sequestration in tropical fruit plants. These equations serve as a tool for connecting various attributes of trees, such as diameter at breast height (DBH) and height (H), with tree biomass. Through this approach, researchers establish a scientific foundation for the estimation of carbon stocks and fluxes, thereby enhancing the development of climate change mitigation plans.

However, tropical fruit trees play a significant role in Bangladesh, a nation where agriculture serves as the foundation of the economy and agroforestry systems are closely interconnected with rural livelihoods (Sultana *et al.* 2021). The fruit tree species that hold significant prominence in Bangladesh include Jackfruit (*Artocarpus heterophyllus*), Mango (*Mangifera indica*), Litchi (*Litchi chinensis*), Guava (*Psidium guajava*), and Jujube (*Ziziphus jujuba*). These species collectively play a crucial role in ensuring food security, nutrient sufficiency, generating income and conserving biodiversity within the country (Khan *et al.* 2017).

Nevertheless, the precise evaluation of carbon sequestration in these particular kinds of fruit trees has proven to be a formidable task. The applicability of existing equations designed for other areas or ecosystems may be limited due to differences in growth conditions, genetic diversity, and management practices (Chave *et al.* 2014). In order to bridge this gap in knowledge, the present study aims to develop tree-specific allometric equations that are specifically adapted to the five primary agroforestry fruit tree species found in Bangladesh. The utilization of these equations plays a crucial role in quantifying the capacity of carbon sequestration, hence enhancing the accuracy in assessing the extent to which these trees contribute to mitigating climate change, taking into account the specific ecological circumstances of the country.

The study consists of four primary ecosystems in Bangladesh, which are distinguished by unique environmental conditions and land use patterns. The coastal ecology, which encompasses the Khulna and Satkhira districts, has challenges related to saline intrusion and susceptibility to cyclones. The Barind ecosystem, which encompasses the Rajshahi and Dinajpur districts, is confronted with the dual difficulties of water scarcity and land degradation. The Terrace ecosystem, as exemplified by the Gazipur and Narsingdi districts, is currently grappling with challenges associated with the processes of urbanization and agricultural intensification. The Hill ecosystem, which encompasses the Rangamati and Khagrachari districts, is currently confronted with challenges pertaining to the preservation of forests and the sustenance of indigenous communities. The extensive geographic scope of the established allometric equations guarantees their ability to encompass a wide range of development patterns and ecological factors that are unique to each ecosystem.

The main objective of this research is to establish a strong scientific foundation for the estimation of tree biomass and, consequently, carbon sequestration in Jackfruit, Mango, Litchi, Guava, and Jujube plants of different ecosystems in Bangladesh. It is hoped that policymakers can employ the findings to establish policies and strategies with the goal of simultaneously attaining ecological and economic objectives within the framework of climate change mitigation and rural development.

## Materials and Methods

**Site selection:** The research was carried out in four prominent agro-ecosystems in Bangladesh, including Coastal ecosystem, Barind ecosystem, Terrace ecosystem, and Hill ecosystem. The selection of these ecosystems was determined by considering their climatic zones, soil types, topography, and land use patterns (Islam *et al.* 2018). Mangrove trees, low-lying plains, saline soils, and a humid tropical climate are some of the characteristics that set the coastal environment apart. A semi-arid climate, sandy loam soils, undulating topography, and dry deciduous trees are some of the unique characteristics of the Barind ecosystem. The Terrace ecosystem is characterized by damp deciduous forests, clay loam soils, flat plains, and sub-humid tropical temperatures. The Hill environment exhibits a humid subtropical climate, sandy clay loam soils, undulating hills, and evergreen forests. Two districts were chosen within each habitat based on the presence and variety of the desired fruit tree species. The districts chosen for the study encompassed each ecosystem, including Khulna and Satkhira for the coastal environment, Rajshahi and Dinajpur for the Barind ecosystem, Gazipur and Narsingdi for the terrace ecosystem, and Rangamati and Khagrachari for the hill ecosystem. Three villages were chosen at random within each district, taking into consideration the occurrence and quantity of the specific fruit tree species.

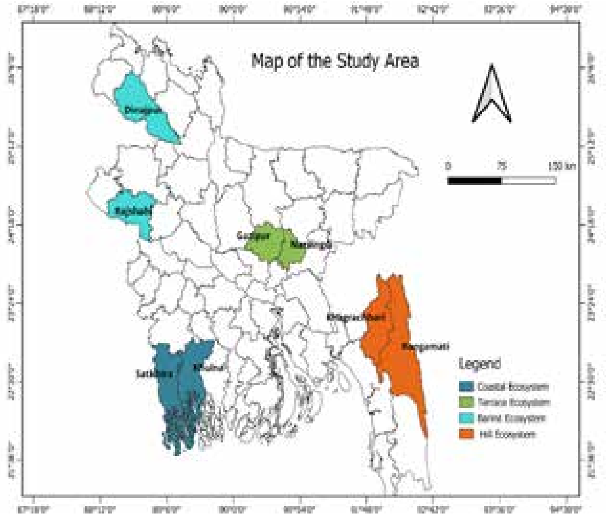

**Figure 1.** Map of the study area.

**Data collection:** The data was collected from January to December 2020. The fruit tree species included in the present study were Jackfruit (*Artocarpus heterophyllus*), Mango (*Mangifera indica*), Litchi (*Litchi chinensis*), Guava (*Psidium guajava*), and Jujube (*Ziziphus jujuba*). The selection of these species was determined by their economic significance, ecological adaptability, and presence in various habitats throughout Bangladesh (Lin 2011). The process of sampling was conducted in accordance with the ethical principles of informed consent and active collaboration, involving the local farmers who either owned or managed the trees.

Data was collected for each tree sample, including measurements of height (H) in feet (ft), diameter at breast height (D) in inches (in), as well as weights for the stem (SW), branches (BW), leaves (LW), roots (RW), fruits (FW), and seeds (SW), all measured in pounds (lb). The height of the tree was determined by using a measuring tape, which was extended from the tree's base to its highest point. The diameter was determined by employing a caliper positioned at a height of 4.5 feet above the ground. For the calculation of total stem weight, a sample (a short portion of the stem) weight for a particular volume was measured first then unit volume weight was calculated. Accordingly, total weight of the stem was calculated by multiplying unit volume weight and whole volume of the stem. The estimation of branch weight was conducted by removing all branches from the tree and thereafter measuring their weight on a digital scale. The estimation of leaf weight was conducted by gathering all the leaves from the tree and measuring their mass using a digital scale. The determination of root weight involved the extraction of all roots from the soil, followed by a thorough rinsing with water to eliminate any extraneous matter or soil particles. The roots were afterward measured in terms of weight on a digital scale. The estimation of fruit weight was conducted by harvesting all the fruits from the tree and afterward measuring their weight using a digital scale. The estimation of seed weight was conducted by extracting all seeds from the fruits and afterward measuring their mass with the use of a digital scale.

**Development of tree-specific equations:** The destructive method (clear-cut) was used for developing species-specific equations. For this, the model equation, $W = K \times D^2 \times H$ was used. Where W is above-ground biomass (lb), D is the diameter at breast height (inch), H is the total height of the tree (ft), and K is the factor. The biomass equations were developed on the basis of diameter class $D < 11$ inches and $D > 11$ inches (Chavan and Rasal, 2010; Chavan and Rasal, 2012). From the above equation, the K value was determined species-wise. The above-ground materials of the trees were sorted into stems, branches, and leaves. The roots of sampled trees were dug out and examined. Fresh weight for each component of the sample tree was measured separately on-site. Then, randomly selected representative samples of stems, branches, leaves, and roots were taken back to the laboratory and oven-dried at 75°C to constant weight after recording their fresh weight in the field (Baishya *et al.* 2009, Chen *et al.* 2015). The dry weight for each component was calculated according to the total fresh weight of the corresponding component. Above-ground dry biomass refers to the sum of the dry weight of stems, branches, and leaves; below-ground dry biomass refers to dry root weight and the total carbon storage refers to the sum of the tree›s total carbon storage in this study. The bark was not removed from stems or branches, and all branches were included in above-ground biomass. The amount of carbon in the plant was calculated as 50 percent of the plant›s dry weight (Poorter *et al.* 1990).

**Data analysis:** The data analysis was performed using Microsoft Excel and software R. The data were analyzed using correlation analysis, regression analysis, and analysis of variance (ANOVA). The regression analysis was used to develop the tree-specific equations for estimating the weight (W) in pounds (lb) of the trees based on the diameter (D) in inches (in) and height (H) in feet (ft) of the trees. The regression coefficients were estimated using the nonlinear least squares method. The equation development was done separately for each species and each diameter class (<11 inches and >11 inches). The equation performance was evaluated using the coefficient of determination ($R^2$), root mean square error (RMSE), and mean absolute error (MAE). The study area map was constructed by using QGIS software.

## Results and Discussion

The height and diameter of the trunk of a tree influence the carbon stock of the species. The maximum height and diameter of a tree represent the maximum amount of carbon stock by the species. Carbon stock by different trees varied significantly with respect to plant height, the diameter of the trees, and years after plantation. Among the five species, the tallest plant height was recorded in mango followed by jackfruit, Litchi, guava, and jujube, whereas the average shortest plant height was recorded in guava (Table 1). However, the diameter of the trees was significantly different from each other where the highest diameter was recorded in mango, whereas a tree with minimum diameter was observed in guava (Table 1).

The fresh weights of the stem of a tree influence the carbon stock of the species. The maximum fresh weight of the stem of a tree represents the maximum amount of carbon stock by the species. Among the five species, the highest fresh weight of stem was recorded in mango followed by jackfruit, Litchi, and jujube, whereas the average shortest plant height was recorded in jujube (Table 2) in case of above 11-inch diameter. Accordingly, the highest fresh weight of stem was recorded in mango followed by jackfruit, Litchi, and jujube, whereas the average shortest plant height was recorded in guava (Table 2) in case of the below 11-inch diameter of stem.

Among the agroforestry species, the highest fresh weight of the branch was recorded in mango followed by jackfruit, litchi, and jujube, whereas the average shortest plant height was recorded in jujube (Table 3) in case of above 11-inch diameter. Accordingly, the highest fresh weight of the branch was recorded in mango followed by jackfruit, litchi, and jujube, whereas the average shortest plant height was recorded in guava (Table 3) in case of the below 11-inch diameter of stem.

The highest fresh leaf weight was recorded in mango followed by jackfruit, litchi, and jujube, whereas the average shortest plant height was recorded in jujube (Table 4) in case of above 11-inch diameter. Accordingly, the highest fresh leaf weight was recorded in mango followed by jackfruit, litchi, and jujube, whereas the average shortest plant height was recorded in guava (Table 4) in case of the below 11-inch diameter of stem.

**Table 2. Fresh weight of stem based on diameter class**

| Species name | Stem (kg) | |
|---|---|---|
| | >11 inch | <11 inch |
| Jackfruit | 938.43b | 201.37b |
| Mango | 1143.30a | 215.60a |
| Litchi | 467.36c | 132.44c |
| Guava | - | 16.08e |
| Jujube | 72.51d | 47.12d |
| CV (%) | 1.57 | 2.22 |

**Table 1. Plant height and diameter of fruit tree species**

| Species name | Height class (ft) | | Diameter class (inch) | |
|---|---|---|---|---|
| | Tall | Short | >11 | <11 |
| Jackfruit | 40.65 | 35.72 | 28.45 | 10.89 |
| Mango | 42.48 | 38.75 | 31.12 | 10.96 |
| Litchi | 26.22 | 23.67 | 24.84 | 10.78 |
| Guava | - | 8.13 | - | 6.18 |
| Jujube | 14.33 | 11.85 | 12.99 | 8.92 |

The highest fresh root weight was recorded in mango (806.01 kg plant$^{-1}$) followed by jackfruit, litchi, and jujube, whereas the average lowest root was recorded in jujube (Table 5) in case of above 11-inch diameter. Accordingly, the highest fresh root weight was recorded in mango followed by jackfruit, litchi, and jujube, whereas the average shortest plant height was recorded in guava (Table 5) in case of the below 11-inch diameter of stem.

Among the following species, factors were calculated. In the case of jackfruit and mango, the factors were found same in diameter (<11 inches). But in the case of a diameter of above 11 inches, the factors were found 0.14 and 0.13 in jackfruit and mango, respectively. On the other hand, the factors of litchi were found 0.13 (> 11-inch diameter) and 0.23 (< 11-inch diameter), respectively. But in the case of guava, a diameter above 11 inch was not found and for below 11 inch diameter 0.22 factor was determined. Lastly, 0.12 (> 11-inch diameter) and 0.22 (< 11-inch diameter) factors were calculated for jujube (Table 6).

The relationship between biomass and the diameter and height of the tree is expressed by biomass equations. The model $W = K \times D^2 \times H$ is used to examine how height and diameter affect the tree›s above-ground biomass. Where W is above-ground biomass (lb), D is the diameter at breast height (inch), H is the total height of the tree (ft), and K is the factor that was identified before. For jackfruit, the biomass equations developed on the basis of diameter class < 11 inches and >11 inches (Table 7). The biomass equations were developed for aboveground biomass with height and diameter of jackfruit tree on the diameter class viz. diameter below 11 inches, diameter above 11 inches (Table 7). The developed biomass equations for total above-ground biomass (AGB) of jackfruit as a function of diameter at breast height and height showed a high correlation for the equation for < 11 inches (95.3%), equation > 11 inches (93.6%). Comparison and application of the proposed pan-tropic general models (Chave *et al.* 2014) with observed biomass data sets for each forest type revealed the significance of site-specific equations for precise biomass estimation in both primary and secondary forests in Southeast Asia (Basuki *et al.* 2009, Kenzo *et al.* 2009). The previously examined species-specific formulas

**Table 3. Fresh weight of branch based on diameter class**

| Species name | Fresh weight of Branch (kg) | |
|---|---|---|
| | >11 inch | <11 inch |
| Jackfruit | 841.22b | 180.51b |
| Mango | 1024.87a | 193.26a |
| Litchi | 418.94c | 118.71c |
| Guava | - | 14.42e |
| Jujube | 64.99d | 42.24d |
| CV (%) | 0.96 | 3.42 |

**Table 4. Fresh leaves weight based on diameter class**

| Selected species | Fresh leaves weight (kg) | |
|---|---|---|
| | >11 inch | <11 inch |
| Jackfruit | 315.35b | 67.67b |
| Mango | 384.19a | 72.44a |
| Litchi | 157.05c | 44.51c |
| Guava | - | 5.42e |
| Jujube | 24.36d | 15.83d |
| CV (%) | 3.18 | 4.22 |

**Table 5. Fresh-weight roots based on diameter class**

| Selected species | Roots (kg plant$^{-1}$) | |
|---|---|---|
| | >11 inch | <11 inch |
| Jackfruit | 590.89b | 126.79b |
| Mango | 806.01a | 151.99a |
| Litchi | 277.34c | 78.59c |
| Guava | - | 6.34e |
| Jujube | 35.53d | 23.09d |
| CV (%) | 2.86 | 1.95 |

**Table 6. Determination of k values for tree-specific equation based on height and diameter**

| Selected species | Diameter (>11 inch) | Diameter (<11 inch) |
|---|---|---|
| Jackfruit | 0.14 | 0.26 |
| Mango | 0.13 | 0.26 |
| Litchi | 0.13 | 0.23 |
| Guava | - | 0.22 |
| Jujube | 0.12 | 0.22 |
| CV (%) | 1.78 | 2.16 |

are helpful in precisely estimating the above-ground biomass of jackfruit (Nam *et al.* 2016, Manuri *et al.* 2014).

Mango trees are modeled using $W = K \times D^2 \times H$ to examine the impact of height and diameter on the tree›s aboveground biomass. where W stands for aboveground biomass (pounds), D for breast height diameter (inches), H for tree height (feet), and K for the previously determined factor. The biomass equations for mango were created based on two diameter classes: less than 11 inches and more than 11 inches (Table 8). The biomass equations were developed for aboveground biomass with height and diameter of a mango tree on the diameter class viz. diameter below 11 inches, diameter above 11 inches (Table 8). The developed biomass equations for total above-ground biomass (AGB) of mango as a function of diameter at breast height and height showed a high correlation for the equation for < 11 inches (92.4%), equation > 11 inches (98.6%). The significance of site-specific equations for precise biomass estimation based on application and/or comparison of the suggested pan-tropic general models (Chave *et al.* 2014) and observed biomass data sets for each forest type was highlighted by studies conducted in both primary and secondary forests in Southeast Asia (Basuki *et al.* 2009, Kenzo *et al.* 2009).

The model $W = K \times D^2 \times H$ is used to examine how height and diameter affect the tree›s above-ground biomass for litchi. where W stands for above-ground biomass (pounds), D for breast height diameter (inches), H for tree height (feet), and K for the previously determined factor. The biomass equations for litchi were derived based on two diameter classes: <11 inches and >11 inches (Table 9). The diameter class of litchi trees—diameter below 11 inches and diameter above 11 inches—was taken into consideration when developing the biomass equations for above-ground biomass (Table 9). The total above-ground biomass (AGB) of litchi as a function of height and breast height was calculated using biomass equations. The results indicated a strong correlation for the equations for < 11 inches (88.98%) and > 11 inches (92.2%).

The model $W = K \times D^2 \times H$ is used to examine how height and diameter affect the tree›s aboveground biomass for guava. where W stands for aboveground biomass (pounds), D for breast height diameter (inches), H for tree height (feet), and K for the previously determined factor. The biomass equations for guava were created based on the diameter classes of less than 11 inches and more than 11 inches (Table 10). The diameter class of guava trees—diameter below 11 inches and diameter above 11 inches—was taken into consideration when developing the biomass equations for aboveground biomass (Table 10). The developed biomass equations for the total above-ground biomass (AGB) of guava as a function of height and diameter at breast height revealed a strong correlation (86.78%) for the equation for diameters less than 11 inches.

For jujube, the model $W = K \times D^2 \times H$ is used to examine how height and diameter affect the tree›s aboveground biomass. Where W represents aboveground biomass (pounds), D is the diameter at breast height (inches), H is the tree›s total height (feet), and K is the previously identified factor. Based on diameter classes of less than 11 inches and more than 11 inches, the biomass equations

**Table 7. Regression analysis of the variables**

| Diameter class | Biomass equations | $R^2$ | RMSE | MAE |
|---|---|---|---|---|
| <11 inch | $W (lb) = 0.26 \times D^2 \times H$ | 95.3% | 23.6 | 18.4 |
| >11 inch | $W (lb) = 0.14 \times D^2 \times H$ | 93.6% | 36.7 | 28.9 |

**Table 8. Regression analysis of the variables**

| Diameter class | Biomass equations | $R^2$ | RMSE | MAE |
|---|---|---|---|---|
| <11 inch | $W (lb) = 0.26 \times D^2 \times H$ | 92.4% | 14.6 | 10.5 |
| >11 inch | $W (lb) = 0.13 \times D^2 \times H$ | 98.6% | 18.3 | 13.2 |

**Table 9. Regression analysis of the variables**

| Diameter class | Biomass equations | $R^2$ | RMSE | MAE |
|---|---|---|---|---|
| <11 inch | W (lb) = 0.23 × $D^2$ × H | 88.98% | 22.6 | 14.3 |
| >11 inch | W (lb) = 0.13 × $D^2$ × H | 92.2% | 24.6 | 16.8 |

for jujube were developed (Table 11). The height and diameter of jujube trees on the diameter class—diameter below 11 inches, diameter above 11 inches—were used to develop the biomass equations for aboveground biomass (Table 11). The total above-ground biomass (AGB) of jujube as a function of height and breast height was calculated using biomass equations. The results showed a strong correlation between equations for < 11 inches (95.66%) and equations for> 11 inches (92.98%).

The presence of precise and tree-specific allometric equations holds considerable implications for the management of carbon and the mitigation of climate change in tropical agroforestry systems (Van Breugel *et al.* 2011). The utilization of these equations enables more accurate evaluations of the potential for carbon sequestration, hence assisting in the formulation of efficient approaches for carbon accounting and monitoring (Tabal *et al.* 2020). These equations can be employed by researchers to enhance the accuracy of carbon cycling models in agroforestry landscapes, hence facilitating more precise forecasts of carbon stocks and fluxes (Chave *et al.* 2014).

According to Hairiah *et al.* (2006), the utilization of these equations provides local communities and land managers with valuable tools to enhance the optimization of agroforestry practices. Farmers and landowners can make well-informed decisions regarding tree planting, trimming, and harvesting by acquiring knowledge about the correlation between tree dimensions and biomass (Ashraf *et al.* 2015). The acquisition of this knowledge has the potential to enhance livelihoods and augment carbon sequestration in these ecologically significant habitats (Nunes *et al.* 2020).

## Conclusion

Tropical fruit trees heavily integrated into the agroforestry systems of Bangladesh can sequestrate carbon from the atmosphere and contribute to reducing global warming. Five tree-specific allometric equations were developed for major fruit tree species to precisely evaluate their carbon sequestration capacity in Bangladesh's unique ecological contexts. Our findings show that correct biomass predictions must encompass both diameter categories, i.e., trees with a DBH of less than 11 inches and those with a DBH of more than 11 inches. These equations can help researchers refine carbon models in agroforestry systems to anticipate carbon stocks and fluxes. The accuracy and adaptability of these equations allow researchers, land managers, policymakers, and local populations to make educated decisions. It also supports sustainable carbon management and climate change mitigation approaches for Bangladesh.

**Table 10. Regression analysis of the variables**

| Diameter class | Biomass equations | $R^2$ | RMSE | MAE |
|---|---|---|---|---|
| <11 inch | W (lb) = 0.22 × $D^2$ × H | 86.78% | 10.3 | 9.4 |
| >11 inch | - | - | | |

**Table 11.** Regression analysis of the variables

| Diameter class | Biomass equations | $R^2$ | RMSE | MAE |
|---|---|---|---|---|
| <11 inch | W (lb) = 0.22 × $D^2$ × H | 95.66% | 16.3 | 10.5 |
| >11 inch | W (lb) = 0.12 × $D^2$ × H | 92.98% | 17.4 | 15.3 |

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