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THE RELATIONSHIP BETWEEN DIAMETER AT BREAST HEIGHT, HEIGHT, AND CROWN VOLUME OF TEAK PLANTATIONS IN GHANA: IMPLICATIONS FOR BIOMASS CARBON STOCK ESTIMATION

BY

ADZAGBRE EDMUND

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KNOWLEDGE INTEGRITY IMPACT

DECLARATION

I hereby declare that the work embodied in this thesis is my original work and has not been previously presented, either wholly or partially, for the award of any degree or diploma at any university or institution.

I have acknowledged all sources of information used in the preparation of this thesis by appropriate citations and references. Any help received in the work has been acknowledged.

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DEDICATION

I dedicate this work to God Almighty, whose boundless grace, wisdom, and strength have carried me through this journey. Without His presence, none of this would have been possible. I also honour the memory of my late father, whose spirit and wisdom remain a guiding light in my life. This is for you, thank you for always believing in my dreams.

ABSTRACT

Plantation forests are essential in mitigating climate change due to their high carbon sequestration and biomass accumulation potential. *Tectona grandis* (Teak) is a widely cultivated, fast-growing hardwood in Ghana, valued for its economic benefits, role in afforestation, biodiversity conservation, and contribution to national carbon accounting. However, accurate biomass and carbon estimation in Ghanaian Teak plantations remains limited by reliance on generalized allometric models developed under different ecological conditions, leading to potential errors in carbon assessments. This study aimed to improve understanding of allometric relationships between diameter at breast height (DBH), total height, and crown volume across Teak age classes (5, 10, 15, and 25 years). It also examined the influence of field-measured versus allometrically estimated heights on carbon stocks and evaluated Teak's carbon sequestration potential. Data were collected in Form Ghana Limited plantations in Ghana using simple random sampling design, with measurements of DBH, height, and crown dimensions. Biomass and carbon stocks were derived using published allometric equations for Teak. Regression and one-sample T-tests was done to assessed the conformity to geometric and elastic similarity theories.

Findings showed a strong DBH – height relationship but DBH – crown volume showed weak and inconsistent relationships with crown volume. highlighting the influence of competition and light availability on crown and DBH development. Carbon accumulation peaked at 15 years, followed by 25, 10, and 5 years. Field Measured height-based estimates were consistently higher than model-derived height values. The study recommends age-specific, locally calibrated allometric equations and the integration of direct crown measurements or remote sensing tools like LiDAR to improve carbon estimation precision.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Teak (*Tectona grandis*), a tropical hardwood species, is widely recognized for its adaptability, commercial viability, and high carbon sequestration potential (Singh et.,2020). Due to its rapid growth and economic significance, Teak has been extensively planted beyond its natural range with extensive plantations found in countries such as Indonesia, Ghana, Nigeria, Côte d'Ivoire, Panama, Costa Rica, and Brazil (Ghimire et al., 2024). These plantations serve a number of purposes, like timber harvesting, ecosystem restoration, and carbon sequestration, as part of more extensive climate change mitigation actions.

Forests, both plantations and natural forests, play an essential role in the global carbon cycle and are giant sinks for carbon in the atmosphere, capturing carbon dioxide (CO_2) in biomass and soils. This ecosystem service positions forests as a fundamental natural solution to climate change through sequestering concentrations of greenhouse gases (United Nations, 2016; Liang & Liu, 2017). Among all the forest types, plantation forests are particularly noteworthy due to their productivity and carbon-sequestration potential. Combined, tropical plantation forests cover approximately 56.8 million hectares of land globally and account for a significant share of forest product production and timber (Payn et al., 2015). Their rapid growth enhances their effectiveness in trapping atmospheric CO_2, thereby furthering their mission in mitigating global climate change (FAO, 2015). In Ghana, Teak plantations form a major component of national afforestation and reforestation efforts. These efforts are designed to offset deforestation, increase biodiversity, promote rural livelihood, and address international climate commitments like those established under the Paris Agreement. Besides, Teak plantations also play an important role in reclaiming degraded landscapes, sustaining ecological processes, and addressing climate change (Asigbaase et al., 2024).

Accurate estimation of Teak plantations' climate value demands the development of robust methodologies to quantify carbon stock. Allometric equations, which entail quantitative correspondence among measurable tree parameters such as diameter at breast height (DBH), height, and crown volume and biomass, play a crucial role in forecasting above-ground biomass (AGB) and below-ground biomass (BGB). Site-specific parameters may, however, influence the performance of the models. Research has demonstrated that allometric biomass relations and rootto-shoot ratios vary both regionally and environmentally and hence need localized model formulation to improve accuracy (Kenzo et al., 2020). While generalized allometric relations can be developed for Teak plantations, root-to-shoot ratio diversity highlights the regional application of biomass estimation models (Ounban et al., 2016).

Despite the economic and environmental importance of Teak plantations in Ghana, a deficit in allometric equations tailored to the country's environmental conditions continues to prevail. This is rather alarming in light of the declining condition of the Upper Guinean Forest in Ghana, with a deforestation rate of approximately 2% per annum (Kyere-Boateng & Marek, 2021). Critical watersheds such as Owabi and Barekese are experiencing unimaginable ecological stress as a result. They are key locations that contribute significantly to ecosystem services, including hydrological regulation, biodiversity conservation, water filtration, and soil erosion prevention (Akoto et al., 2017). Regionally acceptable allometric models must thus be formulated to enhance sustainable forest management and enhance Ghana's teak plantations' carbon sequestration capacity.

1.2 Problem statement

Accurately measuring tree height in large plantations is a major challenge, especially when estimating biomass and carbon stocks. Most allometric models used for biomass estimation rely heavily on tree height, but measuring height directly across extensive plantations is difficult, timeconsuming, and requires skilled personnel. Because of this, researchers often estimate height indirectly using allometric relationships.

Although this approach is practical, it can introduce significant errors. These errors may lead to biased biomass and carbon stock estimates, especially when the models used are not properly tested or corrected. When such inaccuracies go undetected, they weaken the reliability of carbon accounting. This poses serious risks for carbon offset programs, where dependable carbon stock estimates are crucial. Inaccurate estimates can undermine financial projections, reduce trust, and affect the overall credibility and integrity of carbon markets.

Accurate calculation of tree height is necessary to improve biomass and carbon stock modelling, where slight errors propagate towards biomass models. Advances like the application of machine learning technology on SAR imagery (Colverd et al., 2024) reduced error in height estimation to less than 3 meters, an affirmation of the importance of accuracy. Biomass is estmimated using allometric equations, which are informed by accurate measurement and There is limited information in Ghana on how mathematical relationships influence Teak growth and biomass accumulation (Adutwum et al., 2023; . Ma et al., 2024)

Direct approaches, where sampling is destructive, provide accurate data but are time-intensive and ethically challenging (Lin et al., 2023). Indirect techniques, such as remote sensing and LiDAR, provide cost-efficient, non-destructive alternatives, with high accuracy when it comes to estimating stand-level biomass (Song et al., 2023).

Because of the above limitations, forest scientists increasingly rely on non-destructive methods, which integrate remote sensing technology with advanced statistical modelling in order to estimate biomass. These are less invasive but are not without difficulty, particularly in modelling variability associated with environmental drivers. Production of localized allometric models with site-specific predictors, for instance, soil health, climatic conditions, and species-specific growth rhythms, is thus important (Picard et al., 2025). For instance, in Ghanaian Teak plantations, tailored models can significantly enhance the accuracy of carbon stock and biomass estimates. Further, improvement in height estimation methods and integration of systematic bias correction techniques into indirect measurements are highly valuable measures to further enhance the maximum integrity of forest carbon accounting. These improvements will not only enhance effectiveness in climate change mitigation approaches but also support the adoption of sustainable forest management.

1.3 Justification

Ghana relies heavily on Teak plantations as a source of quality timber that, in the process, promotes environmental sustainability through their activities as carbon sinks (Fuseini et al., 2025). Plantations play an important role in the mitigation of climate change by sequestering atmospheric carbon, thereby conserving ecosystem integrity and carbon storage in biomass. With the growing focus on carbon trading initiatives, estimating the amount of carbon stored in Teak plantations has become increasingly important. The stored carbon is to be quantified for the integration of these plantations into national and international carbon credit mechanisms, which are not only economically rewarding but also environmentally friendly. Improved techniques of carbon stock estimation would enable Ghana to achieve optimum economic gain from its forest resources while ensuring sustainable management of forest resources and playing a major role in climate change mitigation (Kumi et al., 2021).

Forests have been well documented to play a central role in the earth's carbon cycle due to their ability to absorb and fix enormous amounts of carbon, thereby reducing greenhouse gases in the atmosphere (Baccini et al., 2017; Mitchard, 2018). There is, however, a substantial knowledge gap in Ghana regarding mathematical relationships that account for powering growth patterns and affecting biomass in Teak plantations. This gap must be plugged to develop accurate and locally relevant biomass estimation models. Development of models involves a sound knowledge of allometric relations, particularly those among diameter at breast height (DBH), tree height, and crown volume, some of the most significant variables influencing biomass as well as carbon sequestration potential.

This study attempts to bridge this knowledge deficit by examining Ghanaian Teak plantation allometric scaling relationships. Through the examination of the DBH, height, and crown volume relationship, the study would establish their combined contribution towards biomass accumulation and carbon stock estimation. The development of context-specific allometric equations would significantly enhance the carbon estimates' accuracy and thereby enhance Ghana's credibility and competitiveness in emerging carbon markets.

The greatest limitation of this study is the evaluation of actual problems of obtaining mass measurements over large spans, which are a requirement in biomass estimation. Tree height estimation is normally conducted using allometric models due to the fact that direct measurement is logistically and technically complicated over large plantation cover. Indirect methods have the potential of yielding large errors with potentially catastrophic consequences for carbon stock estimates. The research explores the magnitude of the errors and how they affect biomass estimates to facilitate the formulation of improved height estimation methods to make carbon accounting in teak-dominated forests accurate (Song et al., 2023).

The prospective results of this research are manifold and have important implications for environmental science, economic analysis, and policy-making. The improved accuracy of carbon stock estimation will enable efficient integration of Teak plantations into carbon market mechanisms, generating financial incentives that can be used to encourage sustainable management of plantations (Singh et al., 2020). In addition, the use of such market-based instruments is expected to increase afforestation and reforestation efforts that align with the climate change mitigation strategy of Ghana (Peprah, 2017). Additionally, science-informed biomass estimation techniques will guide evidence-based decision-making and sustainable forest management. Apart from its environmental benefits, the methods proposed in this study have the potential of creating new economic value via carbon credits, hence furthering rural livelihood enhancement, climate resilience, and biodiversity conservation (Senadheera et al., 2019). The ultimate aim of the study is to contribute to improving national forestry programs and the contribution of the sector towards realizing sustainable development goals.

1.4 Research Aims and objectives

Aims

The research aimed to investigate the relationship among diameter at breast height (DBH), tree height, and crown volume of Teak plantations in Ghana, and assess how these factors can be used to improve biomass carbon stock estimation methods for more accurate carbon sequestration assessments in tropical forestry systems.

The specific objectives of this study were:

1. To determine the relationship among DBH, height, and crown volume of Teak plantations and their conformity to theoretical predictions
2. To estimate the carbon sequestration potential of Teak plantations (calculate carbon stocks and carbon income)
3. To assess the impact of allometric-based tree height estimates on carbon calculations

1.5 Scope of the study

This study aimed to evaluate the development characteristics and biomass accumulation of Ghanaian *Tectona grandis* (Teak) plantations with a focus on their carbon sequestration potential. The study involved ordered on-site measurements of some relevant tree parameters, including diameter at breast height (DBH), standing height, and crown volume, to enable intensive data collection on stand structure and growth habits. Through robust statistical techniques, the research aims to develop novel site-specific allometric equations for local conditions. The models will be validated and compared with existing theoretical allometric models to assess their ability to predict aboveground biomass and carbon storage accurately.

One of the key objectives of the project was to investigate the impact of changing methods of estimating tree height on the precision of estimates of carbon stocks. This involved a comparative evaluation of biomass estimates based on directly measured tree height and those derived using allometric height prediction equations. By investigating differences and biases embedded within each method, the study hopes to establish the most reliable method of carbon stock estimation in Teak plantations. Lastly, the study would contribute value to improved carbon accounting methods and enhance the role of Teak plantations in climate change mitigation and sustainable forest management in Ghana (Kumi et al., 2022).

1.6 Significance of the study

The study is a valuable contribution to the growing literature on carbon dynamics in forests, particularly among tropical plantations. The critical evaluation of the limitations of existing allometric models highlights the necessity of developing site-specific models for predicting biomass for Ghanaian Teak plantations. Such models are important for initiating the Teak plantations into carbon offsetting schemes, thereby increasing Ghana's international contribution towards climate change mitigation (Aabeyir et al., 2020). The research has demonstrated that the application of generic allometric equations prevalent in the region but ostensibly developed outside the region decreases the accuracy of biomass and carbon stock estimations, thereby affecting the credibility of carbon accounting and the worth of forecasted revenue streams from carbon markets.

The conclusions of the study have direct, practical implications for policymakers, forest managers, and other main forestry actors. In offering empirically based models to contribute to achieving stable carbon stock estimation, it is a solid foundation for carbon accounting and raises the transparency level of revenue projections for forestry-based carbon initiatives. To this end, this introduces the adoption of sustainable forest management that is to socio-economic development and environmental conservation. The research also shows how Teak plantations can be an instrument of strategic value in aiding the convergence of economic development goals and environmental conservation goals, especially in Ghana.

Above all, the research underscores the pivotal role that site-specific models play in advancing the credibility of biomass estimation as the precursor to successful carbon offset programs. Accuracy in making such estimates is important for the integration of plantation forests into national and international carbon accounting frameworks, thus enabling full potential contribution from them towards climate change mitigation. Furthermore, the study identifies sustainable Teak plantation management as being among the potential sources of socio-economic co-benefits, including job creation and the generation of incomes, which are strongly relevant in rural areas. The co-benefits point to the broader development opportunities of forest interventions.

Overall, the research offers a broad outline of how Teak plantations would serve as effective instruments for environmental protection alongside economic growth. It offers an exemplary model for guiding Ghana towards fulfilling climate change mitigation through sustainable development and prioritizing forestry as the central theme of low-carbon,and inclusive growth.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Teak plantations in Ghana

Teak is one of the most widely planted exotic timber species in Ghana due to its fast growth rate, high market value, and tolerance for degraded and marginal lands (wanders et al., 2021). The scaling-up of the National Forest Plantation Development Programme, combined with increasing private sector investment, has led to widespread plantation establishment, mainly in the forest–savanna transition zone. Such plantations are often promoted as providing a range of ecological, social, and economic benefits related to restoration, job creation in rural areas, and long-term timber supply.

Most available literature has continuously proved that good silviculture ensures maximum Teak productivity. Well-implemented thinning regimes in the Tain II Forest Reserve significantly improved diameter growth, height increment, and mean annual increment of retained trees (Nero & Asuenabisa, 2023). Complementary studies across Ghana have also shown that spacing, pruning, and timely thinning affect the crown development, stem form, and ultimate quality of the timber produced (Kumi et al., 2021). This evidence suggests that poor management might result in lower productivity and prolonged rotation cycles.

Research on soil aspects for teak plantations in Ghana presents both positive and negative impacts. A recent multi-site study by Asigbaase et al. (2024) indicated that Teak can alter conditions of soil nutrients through the reduction of nitrogen and available phosphorus, while marginally increasing soil pH and not affecting organic carbon levels. Earlier results by Wehr et al. (2017) further indicate that the influence of plantation age, soil type, and previous land use modulates the impact.

This points to the fact that over long rotations, Teak may deplete the nutrients on low-fertility sites, and therefore, soil monitoring and integrated nutrient management practices are advisable.

The genetic quality of the planting stock also affects the long-term productivity of Teak plantations in Ghana. According to Wanders et al. (2021), Ghana's Teak populations have a relatively narrow genetic base, which originates from the limited number of original provenances introduced during the country's history. This reduced genetic diversity diminishes the resilience against climate variability, as well as certain pest outbreaks and diseases. Therefore, expansion of provenance trials and adoption of better seed sources are crucial for enhancing performance and adaptability of the plantations.

Teak plantations have remained an important source of livelihood benefits, as income derived from thinning operations, pole production, and eventual harvests of timber remains critical. In the Dormaa area, Bannor (2014) found that smallholder farmers value teak as a long-term financial asset, although land tenure insecurity, competition with food crops, and unfair benefit-sharing remain major concerns. The environmental challenges include a reduction in understorey plant diversity and altered hydrological processes where teak replaces natural forests (Osei et al., 2023). Therefore, establishing sustainability will require a stronger process of community ownership, consideration of mixed-species systems, and continuing ecological monitoring.

2.2 Importance of biomass and carbon stock estimation in Teak plantations

Accurate quantification of forest biomass and carbon pools is relevant to assessing plantations' role in climate change mitigation. Forests are significant carbon sinks, absorbing atmospheric carbon dioxide (CO_2) and storing it in the various pools of biomass, including tree trunks, branches, roots, and soil organic matter. Understanding the distribution and dynamics of stored carbon is crucial for developing effective climate policy, enhancing carbon credit schemes, and promoting sustainable forestry (Adu-Poku et al., 2023).

The Teak population and its habitat in the natural forest have been decreasing constantly; thus, the IUCN Red List considers it an endangered species. The logging of the Teak trees from the natural forest is banned, and commercial Teak wood can be collected only from the plantation. Teak is cultivated by humans on their private property or in the community forest to meet the increasing demand. (Gua et al., 2022).

Teak, a widely planted tropical hardwood species, is highly valued for its durable timber and excellent carbon sequestration capacity (Santosa et al., 2020). Biomass prediction in Teak plantations is not only valuable because it brings added value to timber production, but also due to its significance in global carbon balance and climate change mitigation. Precise biomass and carbon stock estimation enables forest managers to make informed decisions regarding plantation management, thinning regimes, harvesting cycles, and carbon offsetting. One of the most straightforward ideas in biomass estimation is the appreciation of tree structural variables' interdependence (Diameter at Breast Height (DBH), height, and crown volume) that are the foundation of building allometric models. The models provide the prospect of non-destructive estimation of tree biomass and carbon stock, providing a cost-saving and scalable approach to large-scale forest monitoring (Akoto et al., 2016).

In addition, the precision of estimates has been even furtther improved by new techniques in remote sensing and ground inventories for more accurate carbon estimation. Biomass estimation studies to date have focused primarily on aboveground biomass, i.e., living tree carbon. However, a more comprehensive assessment will need to evaluate belowground biomass (roots), soil organic carbon, and harvested wood products (HWPs) as well. Soil-vegetation interaction has an important bearing on carbon sequestration potential because soil is a vast reservoir of carbon that impacts nutrient cycling, tree growth, and the long-term stability of ecosystems (Gameiro et al., 2025) Teak is widely cultivated in most Southeast Asian, African, and Latin American tropical regions to reforest degraded lands and enhance economic returns (Veridiano et al., 2020). Beyond its timber value, Teak is increasingly attracting interest because of its carbon sequestration ability, encouraging the search for accurate means of carbon stock estimation (Pelletier et al., 2020). Several studies have attempted to estimate carbon storage in Teak ecosystems in total.

Boonyanuphap and Kongmeesup (2016) assessed aboveground carbon, belowground carbon, and soil organic carbon in Teak plantations in northern Thailand. The majority of studies have focused solely on aboveground biomass, ignoring the extended carbon cycle, i.e., carbon sequestration in HWPs generated through periodic thinning and final harvesting. These HWPs, which are used in durable products such as furniture and construction materials, help provide long-term carbon storage through the slowing of carbon release into the atmosphere (Howard, 2021)

2.3 Allometric relationships in tree biomass estimation

Allometric models are widely used in forestry to estimate tree biomass and carbon sequestration based on measurable tree attributes. The most widely used variables in these models are DBH, height, and crown volume, which are utilized as a substitute for total biomass (Chave et al., 2014). Research has proven that DBH is the most consistent variable for biomass estimation, and height and crown dimensions improve model performance (Brown, 1997; Henry et al., 2010).

The allometric model of biomass is built on easily measurable data (diameter, height, age) and could be used in practical and scientific applications (Istrefi et al. 2018). An indirect, nondestructive method was used in the research in the form of a previously derived allometric equation with DBH (Abd Rahman et al., 2017). DBH is mainly used as an independent variable to measure the biomass because it is more precise compared to other variables, and between a tree's diameter and biomass, there is a high correlation (Wang et al., 2023). All these of allometric models are species-specific and also vary along with the physiographic gradients and also vary from location to location. It also varies species to species and age to age within one species of tree (Picard et al., 2025). Various parts of a tree contain differing amounts of carbon, with the highest concentrations found in branches, followed by tap roots, fine roots, and boles. Leaves, lateral roots, seeds, twigs, and bark have progressively lower amounts, with bark containing the least (Jha, 2015; Widagdo, 2021).

Though allometric modelling has been used since the early 20th century, when regression analysis was developed, Aabeyir et al. (2020) observe the absence of locally developed allometric models in Ghana since the country relies on pantropic models that may not capture local ecological characteristics. The research highlights the necessity of species-specific models to increase biomass estimation precision in Ghanaian tropical woodlands, but the allometric equations vary with forest ecosystem types. Therefore, it is helpful to explore the height-DBH relationship in forests at points of interest.

However, the accuracy of allometric models is highly dependent on local environmental factors and growth patterns at the species level. Various studies by Asante & Jengre (2012) and Aabeyir et al. (2020) in Ghana have demonstrated the need for region-specific allometric equations for teak plantations to optimize carbon stock estimates. It has been ascertained from these studies that the application of generic allometric models developed elsewhere tends to generate biases in biomass estimation.

2.4 Importance of DBH, height, and crown volume in biomass prediction

2.4.1 Diameter at breast height (DBH) diameter at breast height (DBH) is probably the most handy and common way of estimating how much biomass a specific tree will have. It's measured at about 1.3 meters (four feet) high and is easy to take in the field. Because of the good correlation between DBH and volume and the volume of wood within a tree, it is extensively utilized by researchers and forest managers as a quantification tool for volume as well as tree biomass (West, Brown, & Enquist, 1999).

Several studies have confirmed that DBH can explain most, or even 90%, of the variation in biomass among trees (Chave et al., 2005). This makes DBH such a versatile and effective measure, especially when one is conducting inventories on a large scale. Nevertheless, its use without other backing data is not always the best option, especially in older or more diverse forests where trees with the same DBH are extremely different from each other in shape and size (Storch et al., 2018).

To be more precise, scientists typically add other measurements, like tree height or crown size (the tree's leafy top). Tree height provides a measurement of a tree’s height, which in turn provides an approximation of the amount of wood it contains. Crown size provides us with how much space the tree takes up and how much sunlight it might receive. The incorporation of these extra details helps in building a better image of the overall structure and biomass of the tree (Vieilledent et al., 2012).

In brief, DBH is a reliable starting point to estimate tree biomass because it is easy and accurate. But for more accuracy, especially in mature forests, it is preferable to utilize DBH in conjunction with other data such as height and crown measurement. This gives more of a notion of the tree and facilitates forest management and ecology studies.

2.4.2 Tree height

Tree height is an essential forest biomass quantification parameter because it has a direct impact on the calculation of total tree volume as well as carbon sequestration. It is, however, notoriously difficult to get a good measure of tree height in the field, particularly in closed or inaccessible forests, where terrain, weather, and accessibility all have the potential to get in the way. While height-to-diameter relationships have been widely utilized to determine biomass, research indicates that height-to-diameter relationships are not universal (Baia et al., 2025). They vary significantly depending on a variety of ecological and environmental factors, including tree species, forest stand density, and site conditions (Feldpausch et al., 2011).

Species-specific growth habits, for example, can result in differences in height-to-DBH relationships, with some species growing to larger heights and more rapidly than others for the same DBH (Kafuti et al., 2022). The density of forest stands is also a significant consideration in tree growth. There may be competition between the light and nutrients for the height of the individual trees while their DBH is large. Trees in less dense stands, however, can potentially acquire more resources in order to develop and thus are able to grow taller (Beauchamp et al., 2025).

In addition, factors on the ground, such as the fertility of the soil, the availability of water in the soil, and the climate conditions regulate tree growth significantly. More specifically for Ghana, a study was conducted in Ghana Teak plantations by Mensah et al. (2016), where they determined that tree height growth was relatively quite high in variability for plantations. The increase in height was very sensitive to changes in soil fertility and moisture availability, with the trees growing more quickly and taller under more fertile soils and better moisture regimes. These environmental conditions can therefore cause extreme variations in biomass estimation models, making it difficult to precisely estimate biomass and carbon storage across various sites, even within the same species (Larson et al., 2023).

Such variation being available suggests that biomass models need to be tailored to conditions at the site, considering not just the tree species and DBH but also local climatic as well as soil conditions. Failure to account for these variations can lead to errors in biomass estimation and thus influence our understanding of carbon dynamics in forests, especially in regions where accurate biomass data are critical to carbon sequestration and climate change mitigation. A single universal method for estimating biomass is inadequate; instead, location-specific and context-sensitive models are required to enhance accuracy (Vorster et al.,2020).

2.4.3 Crown volume

Crown volume is also a most important driver of tree productivity and carbon sequestration contribution because it controls the amount of intercepted solar radiation in trees and distributes resources to. Crown shape and size are also extremely important in maximizing photosynthesis, growth rate, biomass yield, and carbon uptake. Experiments have also emphasized the importance of crown characters in enhancing biomass projection models and developing a more accurate characterization of forest dynamics in terms of variation in light capture and resource partitioning among tree species. They are especially valuable for climate change mitigation and forest management because they offer a way of predicting the performance of trees under varying conditions (Poorter et al., 2012).

Also, the research revealed that crown size made a more significant contribution to biomass accumulation in younger plantations. Since at this stage of development, trees are not yet maximally sized, and crown growth trends have a highly active contribution to make towards overall productivity. With age, however, other factors such as root growth and nutrient cycling can become dominant factors in determining growth rates. However, the function of the crown in the early development phase is significant in assisting the trees to settle and utilize resources (He et al., 2023).

Crown traits also play a significant role in understanding the interaction between environmental factors like light, soil fertility, water availability and the physiological processes of the tree. Trees with broad crowns are more adapted to survive under competitive conditions where light is scarce. This is especially relevant in closed forests or plantations where competition for light is high.

Additionally, the diameter of the crown can impact a tree's ability to absorb and transport carbon, and this has major consequences for carbon sequestration policy, particularly when applied to afforestation and reforestation efforts to counteract global warming (Goodman et al., 2014)

Aside from biomass formation, crown volume also has broader ecological significance. Welldeveloped crown not only increases tree growth but also the overall structure and forest ecosystem diversity. The canopy contains numerous species that affect forest diversity and ecosystem processes such as storage of water, stabilization of soil, and air purification. Therefore, crown characteristics can be used as an indicator of forest health and resilience, and offer clues about how forests can respond to a change in climate, pests, or disease (Lowman and Rinker, 2004). The inclusion of crown volume and its characteristics in biomass estimation models fundamentally enhances the accuracy and validity of forest productivity calculations. As we refine our understanding of how crown size influences tree growth, biomass development, and carbon sequestration, we are in a position to manage forest resources more effectively and improve sustainability strategies (Zhu et al., 2021).

2.5 Challenges in tree height measurement and carbon stock estimation

Accurate tree height measurement remains a central component in biomass estimation, yet is also the largest source of error due to the issue of field data collection. Conventional measuring methods, such as clinometer and hypsometer utilization, are highly prone to observer bias, canopy occlusion, and terrain challenges that cause variations in measured values (Hunter et al., 2013). These limitations not only influence tree height predictions but also result in enormous uncertainties in biomass and carbon stock inventory estimates. Recent improvements in remote sensing technologies, such as Light Detection and Ranging (LiDAR) and satellite data has greatly improved the precision in measuring heights (Asner et al., 2012). With recent improvements, monitoring forest carbon stock at large scales is made possible with fewer human errors. However, contrary to their promise, their adoption in Ghanaian Teak plantations is still hindered by the aspect that they are costly to implement, not easily accessible, and technically challenging (Johnson et al.,2021).

The economic and infrastructural constraints of applying these advanced approaches highlight the need to formulate cost-effective, scalable solutions that are specific to plantation forestry in the region. Aside from measurement problems, estimation of biomass in large-scale plantations is also beset by the intricate relationship between vegetation dynamics and soil processes.

Land use, soil type, organic matter turnover, and microbial processes are significant factors in soil organic carbon content. (Asigbaase et al., 2024) These have to be considered when assessing the potential of carbon sequestration for Teak plantations in general.

An integrated monitoring system that would include above-ground biomass inventories and longterm soil carbon processes must be created to enhance the precision of carbon stock estimates. Post-harvest wood product sequestration of carbon must also be incorporated into carbon accounting systems in order to obtain a better understanding of the long-term climatic advantages of teak production Chayaporn et al., 2021. Environmental heterogeneity, such as elevation and topography, also controls soil properties and tree growth, hence carbon storage and biomass accumulation (Nero et al., 2025; Zhang et al., 2025).

Future research should focus on creating even more sophisticated allometric models for improved biomass estimation, more reliance on remote sensing technologies with adequate validation for Teak forests, and the incorporation of carbon sequestered in wood products upon harvest into total carbon accounting methods. By targeting these topics, scientists can improve the accuracy of carbon sequestration estimations, which will benefit policymakers, carbon market actors, and forest managers (Haya et al., 2023).

All these advances will play a critical in planning the management of Teak plantations, combining economic sustainability with environmental sustainability. Finally, the evolution of reliable biomass and carbon stock estimation methods will support global climate change mitigation and ensure that Teak plantations are a beneficial partner in long-term carbon sequestration, ecosystem stability, and land-use planning for sustainability.

2.6 Carbon sequestration potential of Teak plantations

Teak planting is a valuable carbon sequestration activity that renders it a significant component of each nation's approach to reducing the impacts of climate change. Impacts have been that Teak has the potential of sequestering 100 to 200 megagrams of carbon per hectare (Mg C ha^{-1}) in its 20 to 30-year rotation period (Kaul et al., 2010). This carbon-sequestering potential qualifies Teak as a likely collaborator in reducing the carbon content of the atmosphere.

A steep rise in the level of greenhouse gases, particularly carbon emissions in the atmosphere, is a cause of worry across the world. All-time high forest degradation and deforestation are a few of the major sources of increased carbon emissions (Persson, 2020). Carbon is accumulating in the atmosphere at a record level of approximately 3.5 billion tons annually worldwide, primarily because of fossil fuel combustion and clearance of tropical rainforests for the creation of grazing land and cropland (Coady et al., 2017). Reduction of this mounting carbon load requires sustainable land use, i.e., afforestation and reforestation with high carbon sequestration capacity, i.e., teak plantations. Forest ecosystems can play a pivotal role in controlling the probable rise in atmospheric CO_2 levels through their biomass and carbon storage pools. Forests are natural sinks of carbon, absorbing and storing atmospheric carbon and thereby reducing the amount of greenhouse gases in the atmosphere. The extent of carbon sequestration by forests is species-, forest age-, management-, and climate-dependent (Ameray et al., 2021)

studies by Zeng et al. (2018), and Pandey et al. (2019) offer evidence of an appeal for the preservation and accumulation of forest carbon storage as a measure towards mitigating climate change. Practically sustainable forestry, reforestation, and afforestation can also contribute to encouraging additional carbon sequestration, supplementing the global effort of mitigating rising levels of CO_2 and fighting climate change (Ofosu et al., 2025).

Tiryana (2016) has examined multipurpose Teak plantation management in Perhutani, paying particular attention to Teak production and carbon sequestration. Furthermore, Tiryana (2016) emphasizes that simulation between carbon sequestration and timber harvesting schedule can help forest managers to realize optimal volumes and keep the age composition of Teak stands at cycle closure, and hence such simulation must be applied to other plantations.

Comparative analysis between the comparison of the carbon sequestration potential of 20-year- old Teak plantation and 20-year-old cocoa agroecosystem revealed an extremely high degree of variation in carbon stock. Carbon stock value was found to be 739.33 ± 2.24 Mg C ha^{-1} for Teak plantation, whereas for the full-sun cocoa system, it was only 9.36 ± 2.24 Mg C ha^{-1} (Nimo et al., 2021). This is in relation to the fact that Teak's carbon sequestration potential is greater than that of certain agricultural land-use systems, which suggests its climate change mitigation potential. Follow-up studies by Chaturvedi and Raghubanshi (2015) showed that the sequestration of carbon in Teak plantations varies in mono-specific and multi-species stands and had an average rate of sequestration of 532 Mg C ha^{-1} yr^{-1}. Carbon storage is also greater in older plantation stands, with younger stands having less carbon storage. For example, 19-year-old Teak plantation contained approximately 51.32 Mg C ha^{-1}, while a mature 33-year-old stand contained up to 101.40 Mg C ha^{-1}. This reveals that the age of the Teak plantation is significant in the sense that it optimizes carbon sequestration utility (Chayaporn et al., 2021).

The contribution that well-managed Teak plantations can make to carbon offsetting operations is being perceived more and more. They can be an integral part of climate finance tools such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) by making the production of carbon credits possible (Salimath et al., 2023). From evidence in studies, the fact has been proven that carbon sequestration potential is acquired in Teak plantations in enormous amounts, with different values ranging from 1.3 to 79.31 t ha^{-1} of carbon in different locations (Yoneda et al., 2017; Patel & Naik, 2024). Even now, it is not possible to get accurate carbon stock values for Teak plantations from variation in site condition, management, and measurement technique variability for biomass. For instance, India and Thailand variations of carbon stock with plantation age and site condition illustrate the intricacy of having homogenous evaluation methods (Yoneda et al., 2017; Patel & Naik, 2024).

Furthermore, topography and local soils also have a great influence on carbon sequestration, as indicated by Ghanaian Teak plantations (Kumi et al., 2021). Improving the measurement methods and harmonizing evaluation processes may also contribute to carbon stock data credibility improvement and confirming Teak's role in carbon sequestration worldwide (Kumi et al., 2021; Ghimire et al., 2024)

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study area

The study was conducted at Teak plantations owned by FORM Ghana Limited (FGL) at Akumadan and Berekum sites (see Figure 3.1). FGL was selected as the study location because of its leading position in their plantations towards economic and environmental sustainability. Diversity in plantation size, age, and management practices gives an extensive base for observation. FGL is a forest plantation business that owns and operates plantations in Ghana's central region. FGL aims to reforest depleted forest reserves, as well as preserve and restore indigenous and riparian forest lands. Form Ghana Ltd. was established in 2007 as a subsidiary of Netherlands-headquartered Sustainable Forestry Investments BV. Form Ghana Ltd. has become a leader in sustainable forest management in Ghana.

Among the highlights of achievement for FGL was the agreement on the very first public-private partnership (PPP) forest management lease agreement with the Ghana Forestry Commission. The agreement set the stage for subsequent reforestation efforts and highlighted the company's leadership role in bringing about sustainable forestry to the region. The research locations, Berekum and Akumadan, are in the Bono and Ashanti regions of Ghana, respectively. The two locations are major agricultural centres with unique ecological and climatic conditions, presenting a diverse setting for the research. The variation in these conditions is important for identifying how different environmental conditions affect Teak growth and carbon sequestration. The variability in plantation age, size, and management practices between these sites allows for broad analysis. By examining these factors, the study aims to provide an indication of optimal conditions for Teak growth and carbon sequestration, both while ensuring economic and environmental sustainability.

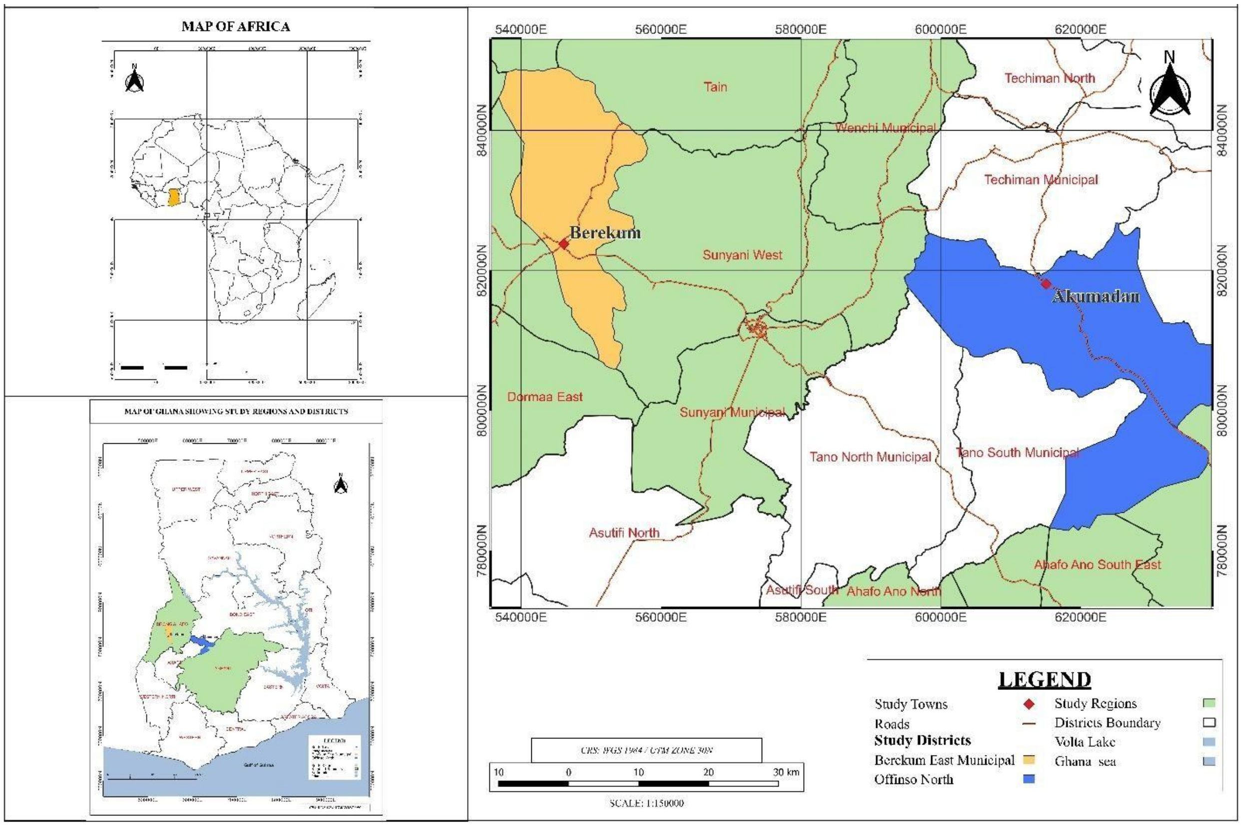

Figure 3. 1 : Map of Ghana, showing the two study sites showing (Akumadan and Berekum, in red diamond-shaped colour), in Ashanti Region and Bono Region

3.1.1 Socio-economic and biophysical description of the Berekum study area

Berekum is a municipal district capital of the Berekum East Municipal District of Ghana in the Bono Region. It covers an area of approximately 1,100 square kilometers. The town is situated about 35 kilometers west of Sunyani, a regional capital, and has a population of about 110,762, with the dominant ethnic group being Akan, and minorities including Moshie, Dagarti, Kusasi, Bimoba, and Ewe. According to the Ghana Statistical Service, 2021, its GPS coordinates are 7.4577° N, 2.5842° W. The main religious composition within the communities is made up of Christians, Muslims, and traditionalists.

Berekum lies within the Deciduous Forest Zone and is made up of semi-deciduous vegetation. The area experiences a bimodal rainfall pattern, and the mean annual rainfall varies between 1,250 mm and 1,750 mm. The main rainy season falls from April to July, while the minor rainy season normally ranges from September to October. This gives rise to a vegetative period of 150 to 160 days in the primary season and about 90 days in the secondary. The kind of climatic pattern experienced in the study area, coupled with its fertile soil, thus creates suitable conditions for cassava, plantain, and cocoyam production, among others, and livestock (Owusu & Frimpong, 2020; Baffour-Ata et al., 2023).

Agriculture is the backbone of Berekum's economy, though trading activities are also high in the town. The geographical location of the town, coupled with its cultural diversity and favorable climatic conditions, places it as an agricultural hub within the Bono Region. In any case, infrastructural challenges, especially roads and water supply, have to be met if the economic growth and development of the town are to be sustained and improved.

3.1.2 Socio-economic and biophysical description of the Akumadan study area

Akumadan is the district capital of Offinso North District in the Ashanti Region of Ghana. It is estimated to have a population of about 20,000 people and is located at 7.3960° N and 1.9539° W. Akumadan has won national acclaim as the home of large-scale tomato cultivation, since almost 90% of the adult population are into tomato farming. As described by Adjei et al. (2018), alongside other major crops, tomatoes have become synonymous with the agricultural environment of Akumadan: other crops grown include cassava, pepper, onion, garden eggs, plantain, and maize. Ecologically, Akumadan falls within the dry semi-deciduous forest zone of Ghana's transitional belt between the forest and savannah zones.

Favorable climatic and hydrological conditions in the region make for high agricultural productivity. Akumadan, falling within the Transition Zone, has an annual average rainfall of about 1,300 mm. The primary growing season is 200 to 220 days, while the secondary growing season is around 60 days. With the availability of a dam and irrigation facilities, the farming activities in Akumadan can be carried on for all twelve months of the year, firmly establishing Akumadan as one of the key agricultural centers. High temperatures are experienced throughout the year, and quite uniformly so, with a mean annual temperature of 26°C; February and March tend to be the hottest months.

Apart from agriculture, Akumadan is also known for its forestry activities, especially through the Akumadan FORM Ghana Teak Plantation. The teak plantation covers an area of about 3,500 hectares and covers portions of the Asubima and Afrensu Brohuma Forest Reserves. FORM Ghana Limited has been granted this area for commercial teak plantation development, and over the past ten years, the company has been involved in the actual reforestation and sustainable development of the plantation. These forest reserves are located at the northern fringe of Ghana's semi-deciduous forest belt and have a tropical monsoon climate with wet and dry seasons alternating. The rainy season lasts from March to July, followed by a short dry spell in July and August. A short rainy season occurs in September and October, followed by a long dry season that lasts from November to March, with an average annual rainfall of about 1,227 mm (Oduro, 2018).

Overall, Akumadan represents a special juncture of agriculture and forestry in Ghana's Transition Zone. The favorable climate, guaranteed water availability, and rich soils combine to make it the hub of tomato production, and projects like the FORM Ghana teak plantation show that sustainable forest management is possible. Ecological and economic perspectives position Akumadan as an important contributor to regional agricultural productivity and national forestry development.

3.2 Research design and data collection

This study consisted of field observations and statistical modelling to form allometric connections among DBH, height, and crown volume, and biomass and carbon calculations.

3.2.1 Sampling method

Simple random sampling was used to select sample plots for data collection. This sampling method gives every tree in the plantation an equal chance of selection, minimizing bias and maximizing representativeness. Also, Systematic errors happen when sampling lines up with natural patterns, like differences in soil, slope, or moisture (Minarsch et al., 2025). By choosing plots randomly, simple random sampling avoids these patterns and reduces the chance of consistent errors in the data.

Three sampled plots covering 20m x 20m (400m^2) from each year group were measured using simple random sampling. Factors like height, breast height diameter, crown length, crown width and crown height were measured in all the plots sampled. With the use of a laser range finder and a tape measure. In every plot, there were at least 30 trees sampled to ensure statistical reliability.

Table 3. 1 : Variations in the ages of Teak trees and number of sampled plots between the two sites.

Location	Age of Teak	Sampled plots
Akumadan	25 years	3
Akumadan	15 years	3
Berekum	10 years	3
Berekum	5 years	3

3.2.2 Tree measurements

DBH measurements were recorded at 1.3 m above ground level with a diameter tape.

Total Tree Height measurements were recorded with a laser range finder (Recon, GS2 LR0500P, Australia). For crown dimensions, crown width was measured along two perpendicular axes, and crown height was calculated with the same mentioned laser range finder and measuring tape.

3.3 Data Analysis

3.3.1 Data processing and Statistical analysis

Data analysis in the study used SPSS (version 26) and Excel (2019), employing a variety of statistical techniques to present tree attributes, to test associations between tree parameters and biomass.

3.3.2 Estimation of biomass, carbon stock and crown volume parameters

Table 3.2 below describes how the various parameters used in this study were calculated using different standardize model equations suitable for tropical scenarios.

Table 3.2 Standardized model equations adopted for the computation of biomass, carbon and monetary value

Parameter	Equation	Reference
Above Ground Biomass **(AGB)**	$AGB = a^*(Ht^*\rho^*D^2)^b$	Adu-Bredu and Birigazzi (2014)
Below Ground biomass **(BGB)**	$BGB = 1.582(AGB)^{0.636}$	Ayesu et al. (2022)
Total Biomass **(TB)**	AGB + BGB	
Above ground biomass carbon **(AGB carbon)**	AGB carbon = AGB × 0.47	Eggleston et al. (2006)
Below ground biomass carbon **(BGB carbon)**	AGB carbon = BGB × 0.47	Eggleston et al. (2006)
Gross Monetary Value **(MV)**	MV = P x CE	Bai and Ding. (2024)
Crown volume **(CV)**	$CV = \pi CD3CL$	Zhu et al. (2021)

Where, Ht = height of tree, ρ = wood density of Teak, D = diameter of tree, a = constant (0.0588), b = constant (0.9409), CE carbon equivalent of carbon stocks, which is obtained by multiplying the carbon stock by 3.64, P denotes the unit price (in US dollars) of the carbon equivalent, CD = crown diameter, CL = crown length

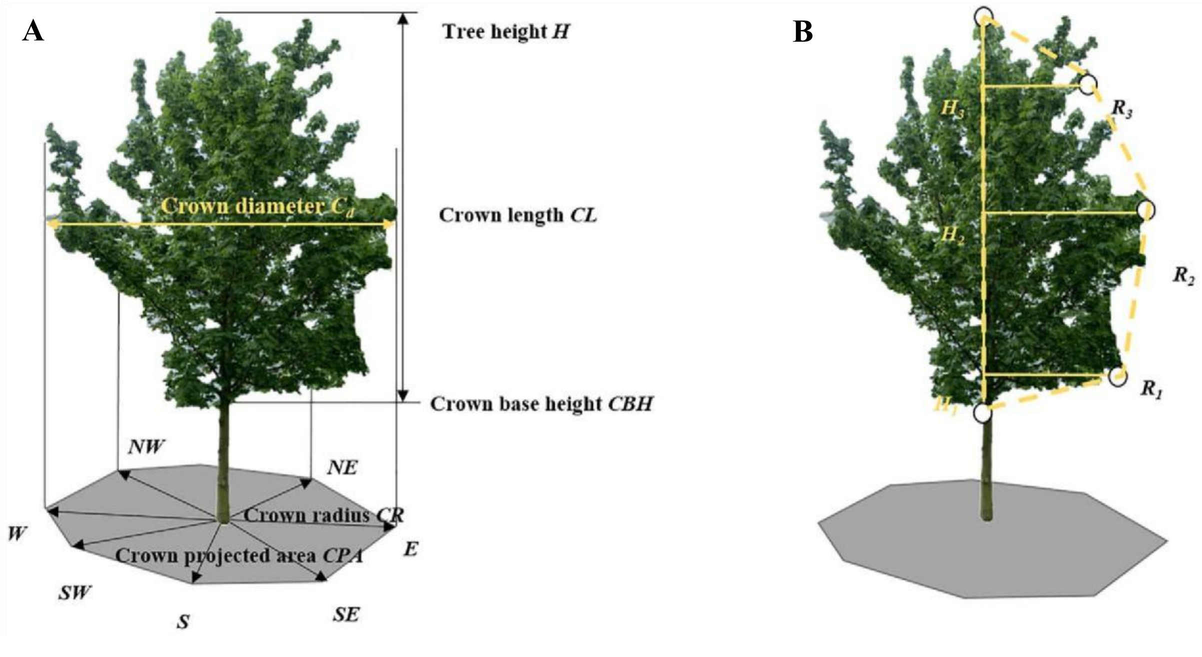

Figure 3. 2 : A Diagram Showing the Calculation Method for Crown Volume Estimation By (Zhu et al., 2021).

3.3.3 Statistical analysis

Regression analysis was performed to determine relationships between DBH and height, again between DBH and crown volume. The earlier relationship focused on the creation of a predictive model for tree height estimation using DBH measurements, while the latter relationship aimed to construct a model of predicting crown volume from DBH measurements. These regression models were formulated for different age classes in the population sampled to ensure that the models would comprehensively describe the growth modes of trees for different stages of growth.

Prior to conducting an Analysis of Variance (ANOVA) to assess differences among treatments, the normality of the independent variable, diameter at breast height (DBH)**,** was examined. The DBH data were log-transformed (LOGdbhcm) to reduce skewness and improve approximation to normality. A One-Sample Kolmogorov-Smirnov (K-S) test was performed to assess whether LOGdbhcm followed a normal distribution. The test indicated no significant deviation from normality (K-S statistic = 0.034, p = 0.200), suggesting that the data were approximately normally distributed. This confirmed that the assumptions for parametric analysis were met, allowing the use of ANOVA

To test the statistical significance of variation in biomass, carbon stock, and tree allometric parameters (i.e., DBH, height, crown volume) across the four age classes (5, 10, 15, and 25 years), a one-way analysis of variance (ANOVA) was performed at p-value of 0.05. The method was appropriate for identifying the existence of any significant effect of age on measured variables, and thereby, identifying trends in growth dynamics and carbon sequestration potential over time. Separate regression analysis for each plot was conducted to examine the relationship between the variable of interest. The standard deviation (SD) and regression slope coefficient were recorded for all regressions. The one-sample t-test of the slopes was then conducted to determine if the observed relations agreed with theoretical expectations. The test was utilized to determine if the mean slope differed significantly from the expected theoretical value from the model and thus determine the degree of concordance between empirical results and theoretical expectations.

3.3.4 Development of allometric equation and biomass carbon comparison

There were two approaches for the estimation of biomass: one was the use of field-measured height and field-measured diameter. The second technique employed the utilization of the allometric height, which was calculated using derived regression equations from this study. This allometric height and the field diameter were used to calculate Teak biomass carbon.

Comparison between the two approaches to calculating biomass was intended to verify the precision of the allometric height estimation using regression. By making the comparison of the results, the study was meant to determine whether regression equations may be applied in estimating carbon or biomass or not. The results that were obtained played a central role in quantifying tree growth and Teak's capability in sequestering carbon for different age classes. Comparison of allometric height-based with field-measured height biomass estimates serves to validate the model and aid in accurate carbon estimation.

3.4 Limitations of the study

While conducting research in forestry, several types of limitations may arise that influence the reliability and validity of trials and outcomes of the research. This section lists and explains the significant limitations encountered in the research.

3.4.1 Site variability

One of the primary limitations is the variability of site conditions between different plots in the study. Site condition variability can add to model prediction uncertainties. The factors that encompass soil, microclimate, and topography may be significantly different from one place to another and can affect tree growth as well as biomass development. This variability might make it challenging to develop models that can be applied in all plots and may require site-specific adjustments for more accurate prediction.

3.4.2 Measurement errors of tree height

Accurate measurement of tree height is crucial for the development of valid allometric models. However, the measurement of tree height is prone to error due to various reasons such as the limitations of equipment, observer, and environmental screens (e.g., leaf cover). Tree height measurement errors would further affect the validity of the models and the resulting differences in biomass and carbon estimates. Standardized measurement protocols and the use of high technology equipment would help reduce such errors.

3.4.3 Assumptions in allometric equations

Allometric models used for the estimation of biomass and carbon stock are founded on an assumption of fixed relationships between tree parameters (e.g., DBH, height, crown volume) and biomass. The relationships can, nonetheless, vary under different stand conditions, species genetics, and management practices. Generalized models can be fault-prone if the assumptions do not hold across all site conditions.

3.4.4 Human errors

Field measurements also have the inherent tendency to be prone to error and human bias and can therefore impact the accuracy and reliability of data collected. Measurements such as crown size (e.g., crown width, crown depth) tend to be visually estimated or hand-measured using rough instruments and are thus likely to yield inconsistent observations between observers. Similarly, DBH measurement on sloping terrain or irregular trunks might be problematic since the reference height of 1.3 meters from the ground surface could vary depending on the land contour. Misestimating in determining the correct point of measurement, especially in irregular ground or where buttresses are present, could result in overestimation or underestimation of DBH.

CHAPTER FOUR

4.0 RESULTS

4.1 Relationship between DBH and height in Teak at different age classes.

Generally, the results establish that although DBH and height showed a strong relationship during

Teak stand growth, the intensity and nature of this correlation vary with age. As shown in Figure 4.1. The Results indicated a distinct positive relation between DBH and height of trees at all growth phases, though the intensity of this relationship differed significantly with age. In the 5-year-old Teak stand, the analysis revealed a relatively strong and statistically dependable relationship, with an R^2 value of 0.630, indicating that approximately 63.0% of the variance was explained by the model. The association was highly significant ($p < 0.001$).

However, the DBH and height of 10-year-old stand appeared to show a weak relationship ($R^2 = 0.2249$, $p = 0.00$) to the point that DBH explained only 22.49% of the variation in height. At 15year-stand, the regression relationship showed a moderate enhancement ($R^2 = 0.4360$, $p = 0.00$), which reflects a recovery of DBH's predictive ability to a certain degree.

In the 25-year-old stand, the strength of the allometric relationship declined ($R^2 = 0.3677$, $p < 0.001$), suggesting that long-term abiotic and biotic interactions—such as crown architecture development, accumulated environmental stress, and legacy effects of past management practices on growth patterns. Although diameter at breast height still accounted for a moderate proportion of height variation, the results indicate a progressive reduction in predictive reliability of the model as stands age.

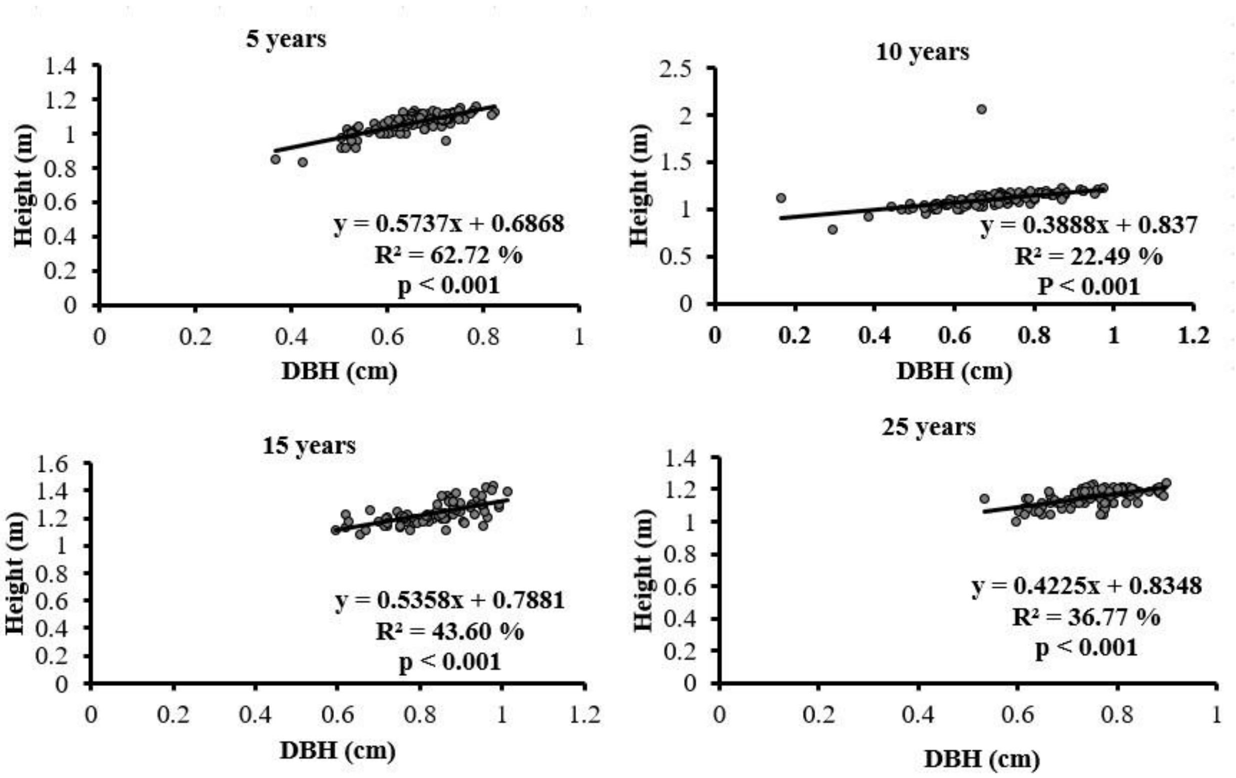

Figure 4. 1: Relationship between DBH and height for different age classes

4.2 Relationship between DBH and crown volume at different age class of Teak

The regression in the 5-year-old-stand showed a statistically significant but weak positive relationship between DBH and crown volume ($R^2 = 0.0858$, $p = 0.002$). This means that stem diameter explained only 8.88% of the differences in crown volume at this young stage. Tree crowns were likely shaped more by other influences such as small-scale soil and site differences, competition for space, and natural variation between individual trees than by DBH alone (see Figure 4.2).

In the 10-year-old-stand, the relationship became much stronger and highly significant ($R^2 = 0.3375$, $p < 0.001$). At this stage, DBH explained about 33.75% (over one-third) of the variation in crown volume, showing that differences in stem size were a major driver of crown growth.

The relationship almost disappeared in the 15-year-old-stand. The regression results showed an extremely low $R^2 = 0.001$ and a non-significant p-value ($p = 0.781$), indicating that DBH had no meaningful influence on crown volume during this mid-maturity stage.

In 25-year-old-stand, the relationship became statistically significant again, though still weak ($R^2 = 0.0418$, $p = 0.048$). This shows that DBH explained 4.18% of the crown volume differences in older trees. While this influence was small, the result suggests that stem diameter still had a minor remaining effect on crown size, even at later maturity. However, long-term factors—such as past competition, natural aging of trees, and reduced site resources—likely played a larger role in crown development than DBH at this age.

Overall, the study shows that DBH's ability to predict crown volume changes with age. The strongest relationship occurred at 10 years, while the link was very weak at 5 and 25 years, and almost non-existent at 15 years.

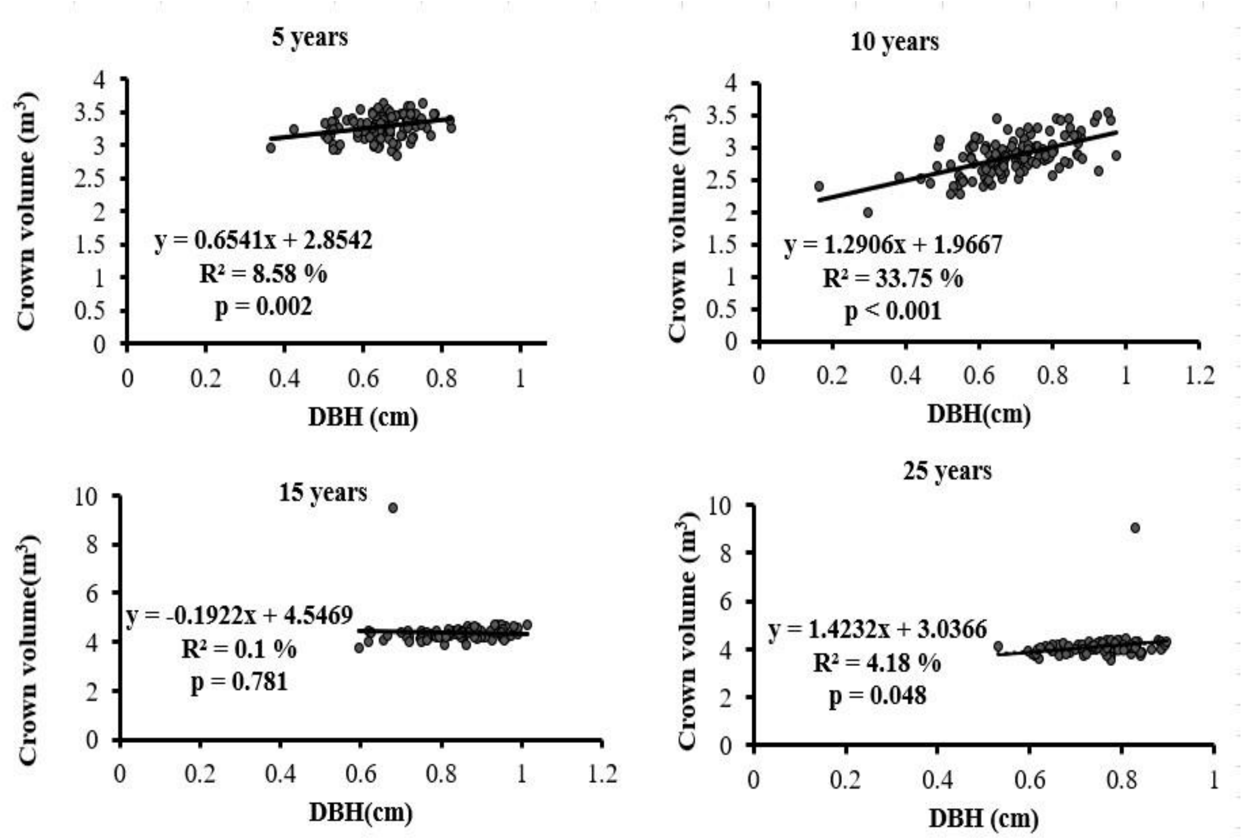

Figure 4. 2 : Relationship between diameter at breast height (DBH) and crown volume for the different age classes

4.3 Conformity of allometric relationship to theoretical predictions

The allometric scaling relationships among the key structural traits of trees, namely stem height (H), stem diameter (D), and crown volume (Cvol), are predicted by theoretical models such as geometric similarity (GS), elastic similarity (ES), and metabolic scaling theory (MST). These models provide the standard exponent values used as reference points in allometric calibration for structural trait relationships**.**

For the H-D relationship, the model by GS predicts a scaling exponent of 1.0; that is, a proportional linear growth of height and diameter. The ES model assumes an exponent of 2/3, a quantity derived from mechanical stability constraints under bending loads. Under assumptions about vascular transport efficiency, the MST model also predicts an exponent of 2/3 for this scaling relation.

For the relationship of the crown volume and diameter, Cvol-D, the GS model predicts an exponent value of 3.0, with cubic volumetric scaling under isometric growth assumptions. Both ES and MST models predict a lower exponent value of 2.0 for the Cvol-D relationship (Sileshi et al., 2023).

Table 4. 1 : Theoretical prediction values

Theoretical Prediction	Geometric similarity	Elastic similarity and MST
Stem height (H) with stem 1	2/3 diameter (D)	
Crown volume (Cvol) with 3	2 stem diameter (D)	

4.3.1 Conformity of Stem Height (H) vs. Stem Diameter (D), with Geometric Similarity

The geometric similarity model predicts a theoretical height–diameter scaling slope of 1, representing isometric growth. Observed slopes in the Teak plantations were considerably lower, ranging from 0.3687 to 0.495 (Table 4.2), indicating non-isometric scaling, where height growth exceeds diameter growth across age classes. The slope for the 5-year-old class did not significantly differ from the geometric similarity prediction (p = 0.47), showing a near-isometric height–diameter relationship at the juvenile stage. The 10, 15, and 25-year-old stands showed significant deviations from isometric scaling ($p < 0.05$), confirming a reduced height–diameter scaling slope relative to the geometric model.

Table 4. 2 : One sample T-test (Geometric Similarity, n=1, Showing conformity to theoretical predictions)

Years	Allometry	slope	SD	P-value
5 years Teak	Stem height(H) with stem diameter	0.495	0.196	0.47
10 years Teak	Stem height(H) with stem diameter	0.388	0.061	0.003
15 years Teak	Stem height(H) with stem diameter	0.3687	0.101	0.008
25 years Teak	Stem height(H) with stem diameter	0.472	0.191	0.041

SD = standard deviation

4.3.2 Conformity of Stem height (H) vs. Stem diameter (D), with elastic similarity/MST

In all ages, the empirical allometric exponents were significantly lower than the theoretical value of 0.67(Table 4.3). The 5-year-old Teak stand had a height-diameter slope of 0.495 (SD = 0.196) with a p-value of 0.263, showing no significant difference from the expected slope. The 10-year stand had a lower slope of 0.388 (SD = 0.061, p = 0.150), which was also not statistically significant. Likewise, the 15-year stand recorded the lowest slope of 0.3687 (SD = 0.101, p =

0.350), remaining non-significant. The 25-year-old stand had a nominally steeper slope of 0.472 (SD = 0.191), even though departure from theoretical predictions remained statistically nonsignificant (p = 0.215

Table 4. 3 : One sample T-test (Elastic Similarity and MST, n =2/3, Showing conformity to theoretical predictions)

Years	**Allometry**	**slope**	**SD**	**P-value**
5 years Teak	Stem height (H) with stem diameter	0.495	0.196	0.263
10 years Teak	Stem height (H) with stem diameter	0.388	0.061	0.150
15 years Teak	Stem height (H) with stem diameter	0.3687	0.101	0.350
25 years Teak	Stem height (H) with stem diameter	0.472	0.191	0.215

(MST) metabolic scaling theory

4.3.3 Conformity of Crown volume (Cvol) vs. stem Diameter (D), with geometric similarity

The real slopes of the various age classes ranged from 0.451 to 1.40, all much lower than the theoretical one by Sileshi et al. (2023). Statistical testing showed the stands of 5-year-old ($p<0.004$) and 10-year-old s ($p< 0.02$) Teak departed significantly from the prediction of geometric similarity In contrast, the 15 and 25-years old stands had no statistically significant departures from the anticipated slope, with p-values of 0.25 and 0.29 (Table 4.4).

TABLE 4. 44 : One sample T-test (Geometric Similarity, n=3, Showing conformity to theoretical predictions)

Years	Allometry	slope	SD	P-value
5 years Teak	Crown volume (Cvol) with stem diameter (D)	0.451	0.266	0.004
10 years Teak	Crown volume (Cvol) with stem diameter (D)	1.075	0.562	0.027
15 years Teak	Crown volume (Cvol) with stem diameter (D)	0.759	0.621	0.250
25 years Teak	Crown volume (Cvol) with stem diameter (D)	1.400	0.478	0.290

4.3.4 Conformity of crown volume (Cvol) vs. stem diameter (D), with elastic similarity/MST

The allometric exponents were found to have agreement with Elastic Similarity and MST (n=2) in most age classes, except at 5 years where there was strong deviation (Table. 4.5). At 5 years, the slope was 0.451 (SD = 0.266) indicating a very large deviation from geometric similarity.

In the 10-year-old forests, the slope increased to 1.075 (SD = 0.562), but this association did not achieve statistical significance (p = 0.104). For the 15-year-old trees, there was a slope of 0.759 with more variability (SD = 0.621) and a statistically non-significant p-value of 0.740, showing an inconsistent and weak scaling pattern. At 25 years, the slope was 1.40 (SD = 0.478), but departure from the geometric similarity model remained statistically non-significant (p = 0.162

Table 4. 5 :, One sample T-test (Elastic Similarity and MST, n=2, Showing conformity to theoretical predictions)

Years	Allometry	slope	SD	P-value
5 years Teak	Crown volume (Cvol) with stem diameter (D)	0.451	0.266	0.010
10 years Teak	Crown volume (Cvol) with stem diameter (D)	1.075	0.562	0.104
15 years Teak	Crown volume (Cvol) with stem diameter (D)	0.759	0.621	0.740
25 years Teak	Crown volume (Cvol) with stem diameter (D)	1.400	0.478	0.162

(MST) metabolic scaling theory

4.4 Carbon sequestration potential of Teak plantations

4.4.1 Biomass and biomass Carbon (Aboveground, Belowground, and Total) in Teak Plantations.

Carbon accumulation and biomass estimation in different age classes of teak stands (5, 10, 15, and 25 years) are highly indicative for understanding stand growth, productivity, and carbon sequestration dynamics. Figure~~.~~ 4.3 and 4.4 indicate the temporal trend of aboveground biomass (AGB), belowground biomass (BGB), and total biomass (TB), along with their respective fractions of carbon. The responses mirror the increases in patterned biomass and carbon stock from the 5year to the 15-year age class, which is a period of active growth with more carbon deposition and biomass accumulation. It is the pole to juvenile stages of the stand development by intensive above- and belowground growth of the trees. Above all, both aboveground and belowground biomass showed their highest values at 15 years. AGB increased most sharply over time, reaching a mean of 18.11 Mg/ha (range: 4.30–47.29 Mg/ha), while BGB also peaked at 9.66 Mg/ha (range: 1.46–18.38 Mg/ha). These trends are indicative of characteristic root-to-shoot ratios of forest communities where belowground biomass is always smaller than aboveground traits but important in facilitating nutrient cycling, sequestration of carbon into the ground, and ecosystem stability.

Cumulative biomass (TB) followed the component trends, increasing in step-wise fashion to a maximum of 27.77 Mg/ha at 15 years and declining at 25 years. Reduced growth in all the components after the 15th year signifies retardation of net productivity owing to intra-specific competition for light, water, and nutrients, canopy closure, and physiological senescence. Senescence caused by natural factors such as death and root rot may also be involved. Particularly, the maximum cumulative biomass during the study period was 65.66 Mg/ha, representing the maximum spatial heterogeneity, and it was caused by differential soil fertility, rainfall, stand density, and treatments such as thinning and fertilization.

Estimation of carbon stock was comparable. Aboveground carbon accumulated linearly with age to a total of 8.51 Mg C/ha after 15 years, while belowground carbon accumulated to a total of 4.54 Mg C/ha. Cumulatively, the 15-year stands had the highest cumulative carbon of 13.05 Mg C/ha while the lowest carbon content of 4.55 Mg C/ha was obtained in the 5 years stands. Such stark contrast is indicative of the mid-rotation stands' efficiency in carbon sequestration, mainly due to their relatively high growth rate and balancing photosynthetic equilibrium. The smaller increment achieved by the 25-years-old stands owes to a balance realignment of the carbon budget, where respiration, reduced growth increments, and organic matter decomposition balance new carbon addition.

The concurrent trends of AGB, BGB, and their corresponding carbon pools are significantly correlated with shoot-root growth. Site and silvicultural regimes that promote larger developmentgrowth promote belowground biomass accumulation and soil carbon pool. The 15-year midrotation age class were identified as being most optimal in biomass accumulation and carbon sequestration and as an optimum point for optimization of climate change mitigation return through teak plantation management.

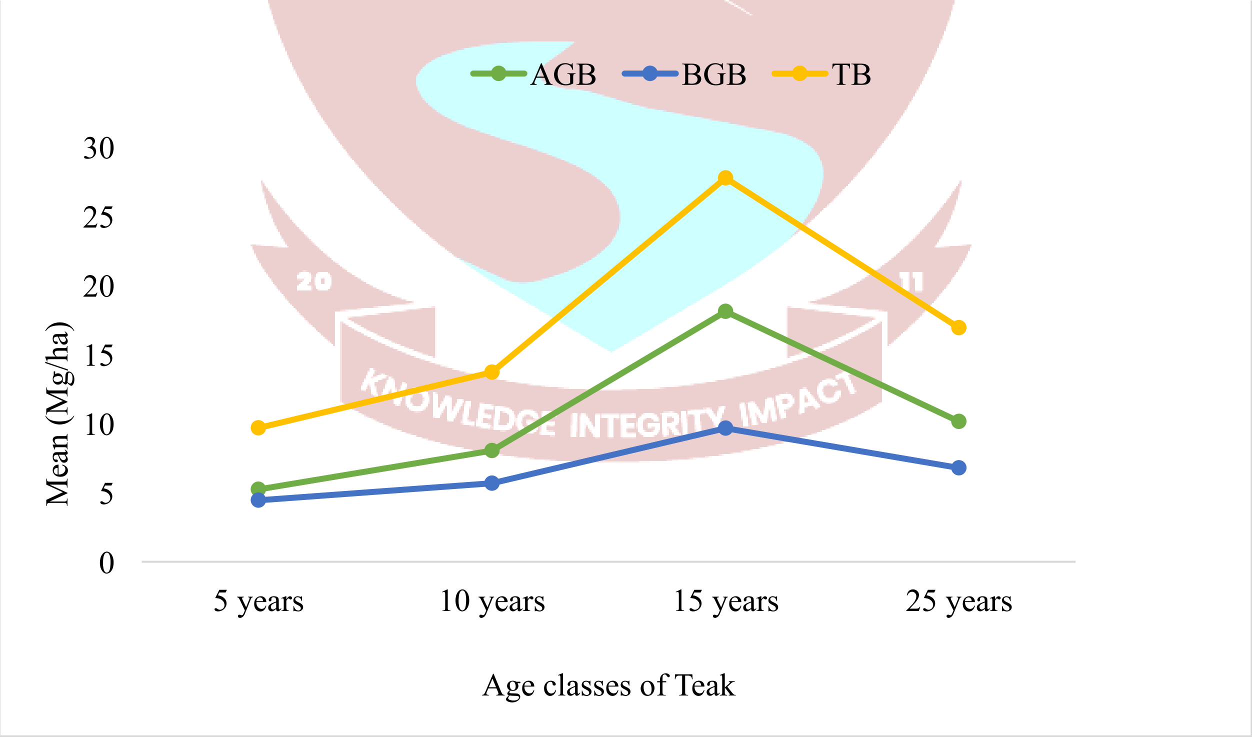

Figure 4. 3 : Comparison of the three biomass parameters (aboveground, belowground, total biomass) among the different age classes of Teak stands

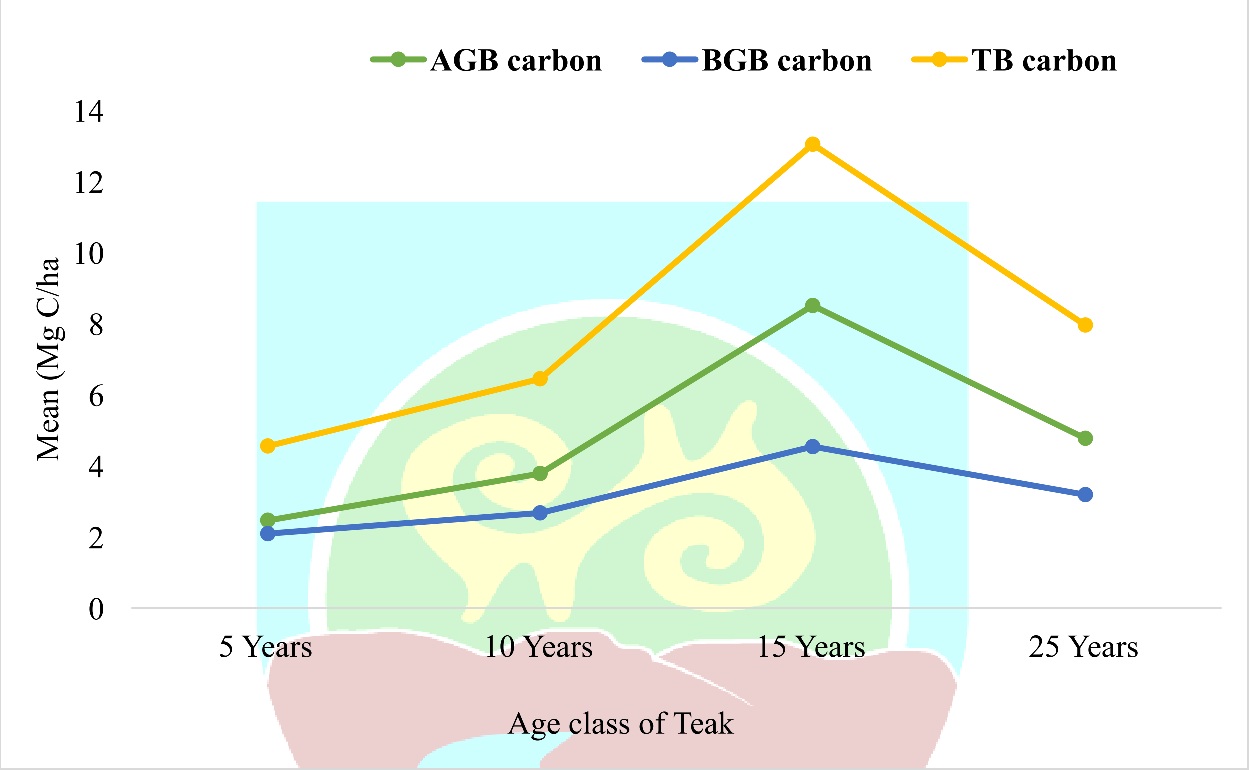

Figure 4. 4 : Comparison of the three biomass parameters (aboveground, belowground, total carbon) among the different age classes of Teak stands

4.4.2 Monetary value of total carbon and carbon accumulation rate of Teak plantations.

The economic value of cumulative carbon sequestration in Teak stands has an apparent and consistent increasing trend from the 5 years old to 15 years old stands, with the highest economic value recorded at 15 years (Figure 4.5). The carbon accumulation rate is relatively stable in all the different age classes, with a small peak among Teak stands of 15-year-old. There was a positive correlation between value of sequestered carbon and cumulative biomass and cumulative carbon content. The 15-years-old Teak stand, with the maximum cumulative biomass carbon, also possesses the maximum average market value of $950.16 per hectare. The 5-years-old stand, despite its highest growth rate, possesses the minimum market value of $331.37 per hectare. This stark contrast indicates the economic value that is invested in maintaining and conserving highbiomass forest products for carbon sequestration purposes. The outcome confirms the hypothesis that as trees age and biomass accumulates, value in monetary terms as well as carbon storage becomes increasingly important, supporting the incorporation of carbon finance into sustainable forest management.

Unexpectedly, the current rate of carbon accumulation, expressed in megagrams of carbon per hectare per year (Mg C/ha/year), does not consistently increase with stand age. The 5-year-old Teak stand exhibited the highest rate of carbon sequestration at 66.27 Mg C/ha/year, slightly exceeding that of the 15-year-old stand, which recorded 63.34 Mg C/ha/year. In contrast, the 25year-old stand had the lowest rate, only 23.17 Mg C/ha/year. This pattern indicates that younger stands, with higher physiological activity and greater leaf productivity, sequester more carbon per unit area annually. However, their total cumulative carbon remains relatively low due to limited overall biomass development at this early stage.

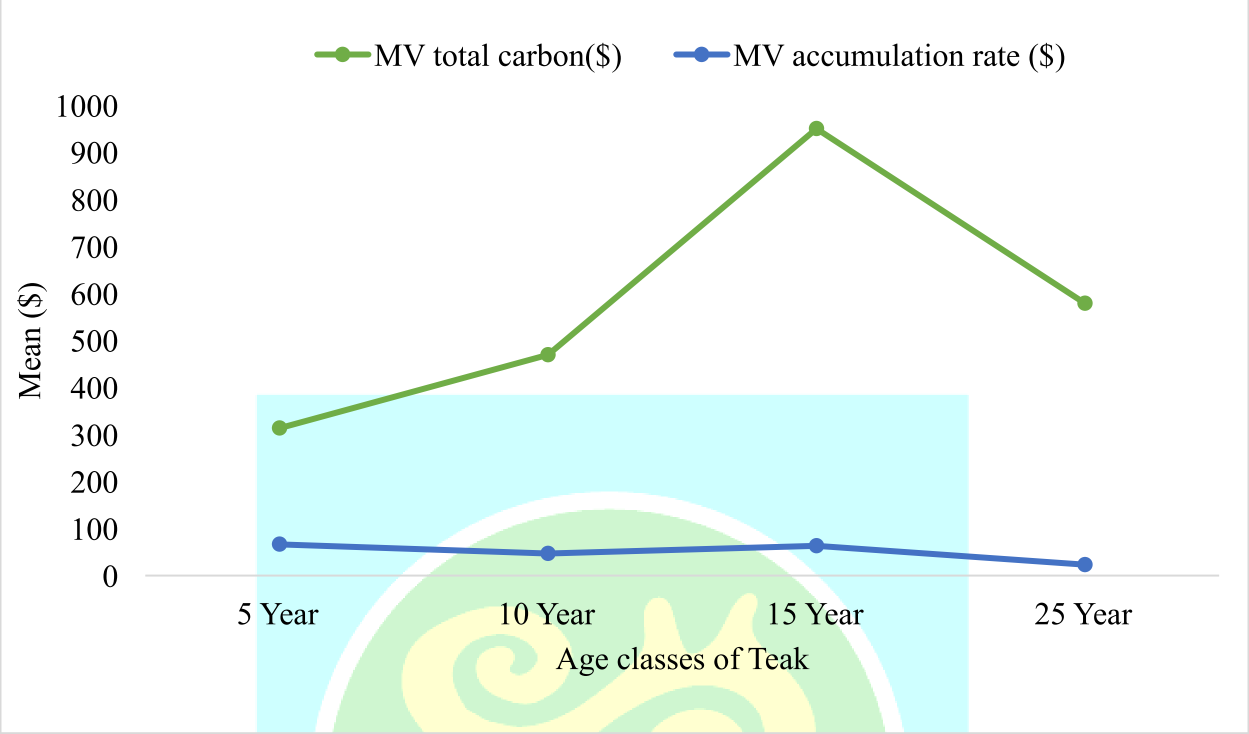

Figure 4. 5 : Monetary value (mv) of total carbon ($) and Monetary value (mv) accumulation rate across four Teak age classes.

4.5 Impact of allometric-based tree height estimates on carbon calculations

4.5.1 Comparison of estimated height and field height.

The comparative analysis of observed mean height (HGT) and estimated height (Estimated H) across different age classes, as shown in Figure 4.6, reveals a close correspondence between measured and predicted values, with field measurements consistently slightly higher than estimates. The differences between observed and estimated heights were minimal across all age classes. For instance, in the 5-year age class, the field-measured height was 11.6 m, compared to an estimated 11.5 m. In the 10-year class, the observed height was 13.5 m, slightly higher than the estimated 12.9 m. The 15-year class recorded the tallest trees, with a field height of 17.5 m versus an estimated 17.3 m. Even in the 25-years-age class, where height reduced slightly compared to 15 years, observed and estimated heights (14.4 m and 14.3 m, respectively) remained near each other. These frequent but slightly lower estimates suggest that while the model correctly records growth patterns, it is more apt to slightly under estimate actual field performance. Statistical comparisons through one-way ANOVA confirmed that differences between estimated and observed heights were very significant by age classes ($p < 0.001$ for observed; $p < 0.001$ for estimated). The data confirm the hypothesis that age is a significant factor in height increase and that observed and estimated measurements reflect significant growth patterns in teak stands. These findings validate the applicability of the model and highlight the worth of field data application to improve height estimates, especially for silvicultural decision-making.

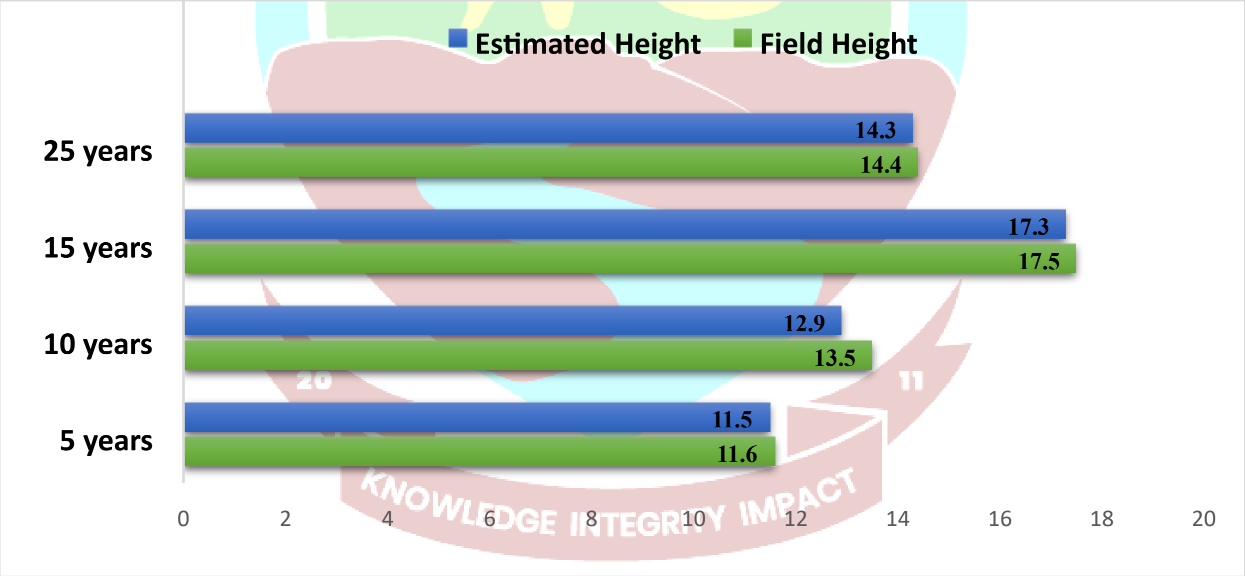

Figure 4. 6 : Comparison of field measured height with estimated using developed allometric model equations

4.5.2 Above ground estimated biomass, below ground estimated biomass and Total estimated biomass of Teak

Biomass accumulation by age classes of Teak plantations demonstrated a distinct trend with age in both aboveground and belowground fractions of biomass as shown in figure 4.7. Estimated mean aboveground biomass (AG Estimated biomass) increased steadily from 5.2445 Mg/ha at age 5 to its peak of 17.87 45 Mg/ha at age 15, indicative of a phase of accelerated growth in the early and middle stages of stand development. However, a large decline in the aboveground biomass was experienced at age 25, which dropped to 10.1145 Mg/ha. The belowground estimated biomass (BG Estimated biomass) also developed on the same trend, where it rose from 4.45 Mg/ha in the first youngest age class to 9.6245 Mg/ha at 15 years, before declining to 6.77 45 Mg/ha at 25 years. The total estimated biomass (below and aboveground parts together) showed characteristic pattern with maximum mean value of 27.48 45 Mg/ha in year 15 and decreasing to 16.89 Mg/ha in year 25.

Statistical analysis confirmed that such biomass accumulations were highly significant over the age classes. Analysis of variance (ANOVA) also provided high statistical significance for age effect on all biomass components: aboveground biomass ($p < 0.001$), belowground biomass ($p < 0.001$), and total biomass ($p < 0.001$). It was clearly indicated by the results that tree age is a key factor in biomass productivity in Teak plantations. The highest accumulation of biomass at 15 years assumes this age to be a likely optimum for yield of a maximum quantity of biomass, beyond which the decline could be due to senescence, reduced efficiency of growth, or competition within the stand.

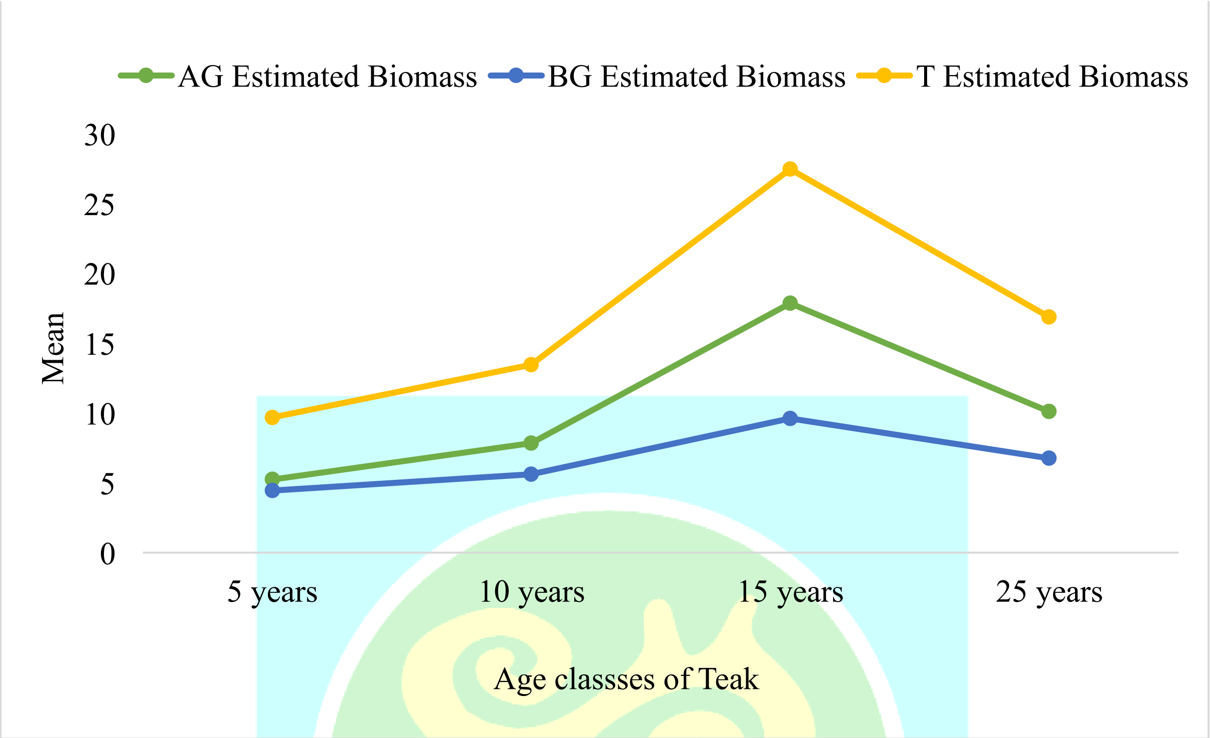

Figure 4. 7 : Estimated biomass calculated using allometric height and field measured diameter

4.5.3 Above ground estimated biomass carbon, below ground estimated biomass carbon and Total estimated biomass carbon of Teak

The carbon sequestration trend of Teak plantations was in parallel accordance with the trends exhibited by biomass accumulation across different age classes as shown in figure 4.8. Aboveground estimated biomass carbon (AG estimated biomass carbon) increased steadily from the developmental stages to mid-rotation age, the lowest value being recorded in the 5-years-old stands (2.46 Mg C/ha). This value increased progressively to 15 years with 8.40 Mg C/ha, indicating that mid-rotation stands have the maximum possibility of carbon sequestration above ground. A similar trend was shown by belowground carbon (BG estimated biomass carbon), which increased from 2.09 Mg C/ha at 5 years to a level of 4.52 Mg C/ha at 15 years. But the subsequent decline was noted in 25 years old plantations, where BG estimated biomass carbon reduced to 3.18 Mg C/ha.

Total biomass carbon, that is, the sum of above and belowground components was maximum at 15 years at 12.92 Mg C/ha. This declined significantly to 7.94 Mg C/ha in 25 years old plantations, reflecting reduced efficacy of carbon sequestration by older plantations, it may be a consequence of the natural decline in physiological function with age, or because of intense competition for resources in dense stands. Analysis of variance (ANOVA) indicated that the differences in carbon storage among the age classes were significant. The p-values were significant for aboveground carbon ($p < 0.001$), belowground carbon ($p < 0.001$), and total biomass carbon ($p < 0.001$), indicating extreme variation across stand age. Therefore, for climate mitigation policy and carbon offset schemes, this age category might offer maximum return on investment in terms of provisioning ecosystem services.

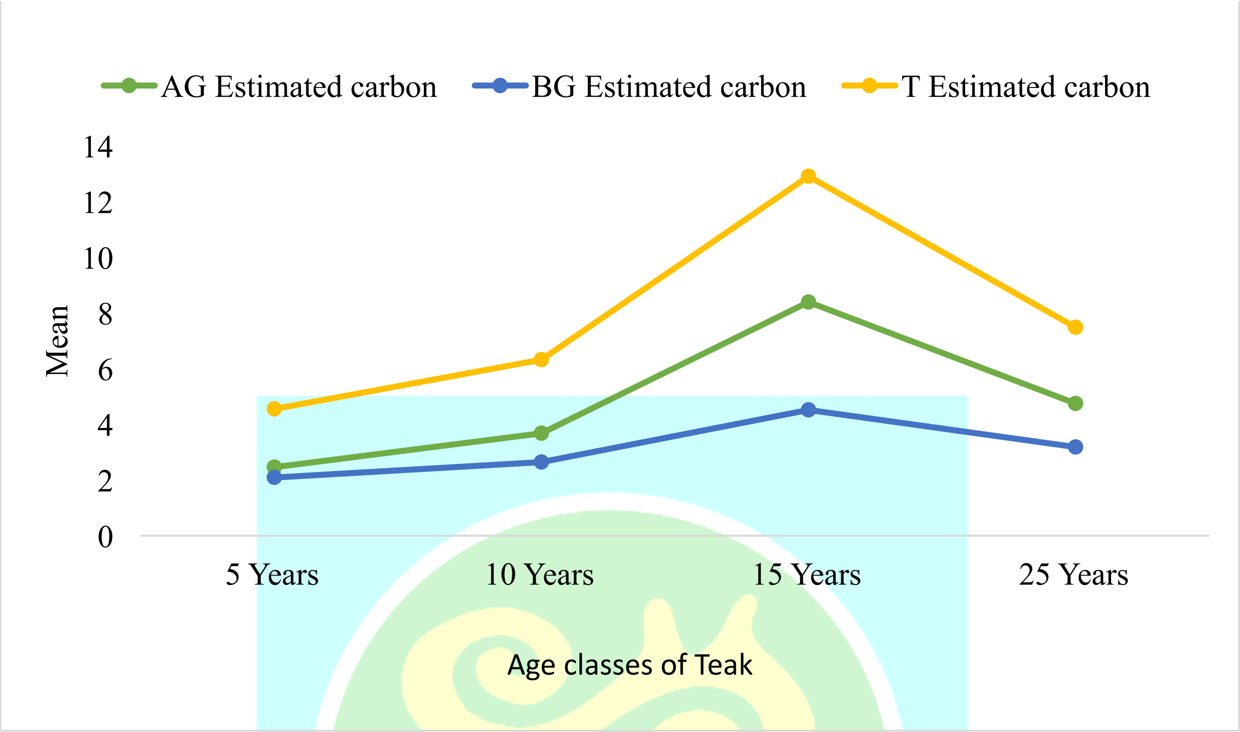

Figure 4. 8 : Comparison of Above ground estimated carbon, below ground estimated carbon and total estimated carbon

4.5.4 Comparison between biomass derived from field-measured height and biomass derived from estimated height

The comparative evaluation of biomass values derived from field measured height and estimated height for the four different age classes 5, 10, 15, and 25 years in (Figure 4.9) reveals similar trends and provides insights on the accuracy of predictive modeling in forest biomass estimation. The biomass parameters were separated into Aboveground Biomass (AGB), Belowground Biomass (BGB), and Total Biomass (TB), and were subjected to both empirical and estimated data sets. Interestingly, both the methods of measurements have the same pattern of biomass accumulation, with increments of 5 to 15 years and a decline at 25 years. The pattern reflects the biological growth cycle of the trees, where biomass accumulation happens in the middle in the rotation periods.

For AGB, the field-measured values increased from 5.24 Mg/ha at age 5 to a peak of 18.10 Mg/ha at age 15 before declining to 10.14 Mg/ha at age 25. The estimate height-based estimates for AGB moved in exactly the same way, from 5.24 Mg/ha to 17.87 Mg/ha and declining to 10.11 Mg/ha. High correspondence between the estimated and the observed AGB suggests that the regression model provides an accurate estimate of biomass growth in the aboveground parts. Similar correspondence is visible for the estimation of BGB values. The field-based values of BGB varied from 4.44 Mg/ha at 5 years to 9.66 Mg/ha at 15 years, with a decreasing trend towards 6.78 Mg/ha at 25 years. The estimates height-based for BGB closely followed, at 4.44 Mg/ha and rising to 9.61 Mg/ha before dropping to 6.77 Mg/ha. The minimal values of deviation between observed and estimated BGB attest to the robustness of the model's predictability for BG biomass.

The total biomass (TB), calculated by summing AGB and BGB, also increases the regression model's confidence. Field measured height-based TB showed an upward trend from 9.68 Mg/ha after 5 years to 27.77 Mg/ha after 15 years and then declined to 16.92 Mg/ha after 25 years. The estimated height-based TB also increased in a similarly similar pattern, to 27.48 Mg/ha at age 15 and to 16.88 Mg/ha at 25 years. The high reliability of the two data sources for all classes of ages validates regression-based or allometric models as very good alternatives to time-consuming field measurements.

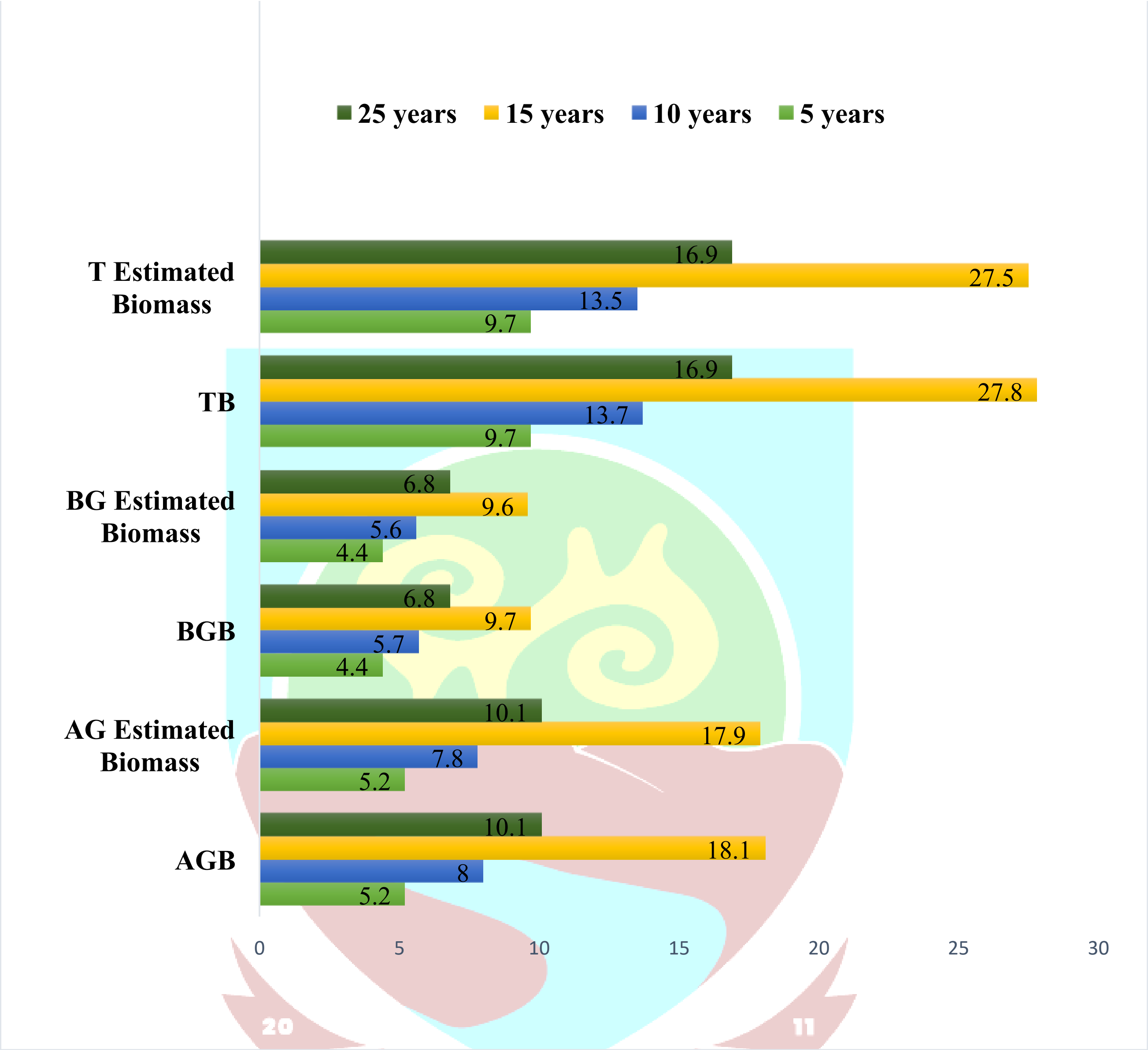

Figure 4.9: comparison of biomass calculated from field measure height and biomass from estimated height

4.5.5 Comparison of biomass carbon derived from field-measured tree height and biomass carbon derived from estimated height

(AG) above ground, belowground (BG), and total (T) biomass carbon of Teak plantations at four different age classes, 5, 10, 15, and 25 years as shown in figure (4.10) revealed a consistent trend of increasing carbon stock with plantation age. The highest carbon accumulation was shown by the 15 years old plantations in all three biomass fractions.

Total carbon, the highest stock occurred in the 15 years class at 13.05 Mg C/ha, derived using field-based height followed very closely by the estimated height-based at 12.92 Mg C/ha. The same age-related pattern of carbon accumulation was also seen in aboveground carbon stock was 8.51 Mg C/ha in the 15 years plantations, and the estimated value 8.40 Mg C/ha. The lowest AG carbon content was in the youngest stands, which was 2.46 Mg C/ha derived from field-measured height and 2.46 Mg C/ha derive from estimated-based hieght. Belowground carbon also showed the same trend with a maximum at 15 years and the minimum values observed at 5 years.

Interestingly, carbon the 25-year-old plantations were not higher than the carbon stock at 15-yearold. Instead, a reduction was seen in all the carbon components with total, aboveground, and belowground carbon stock values.

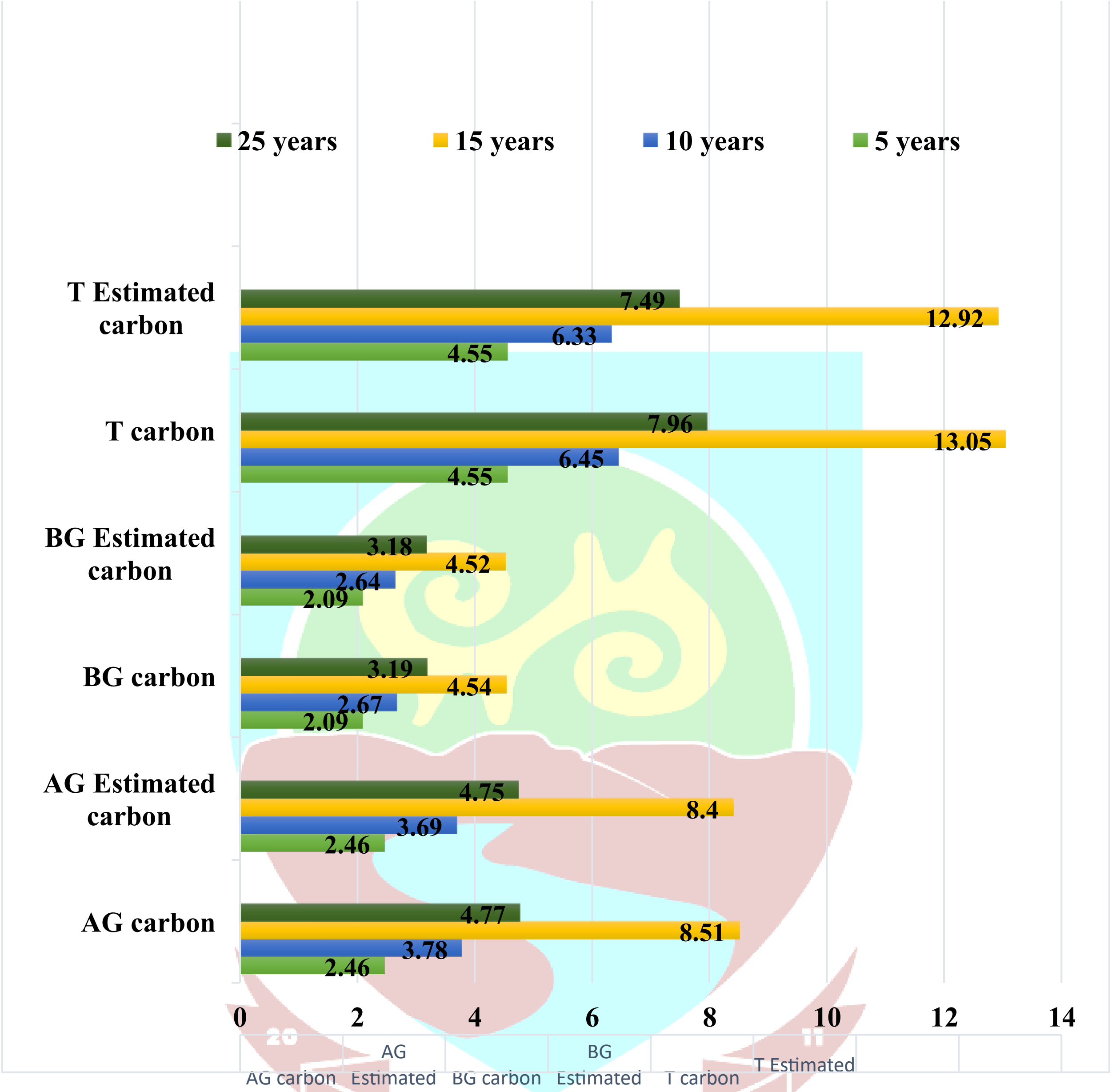

Figure 4.10: comparison of carbon calculated from field measure height from height calculated using regression equations

CHAPTER FIVE

5.0 DISCUSSION

5.1 Allometric relationship between DBH and height of Teak

The understanding of the relationship between diameter at breast height (DBH) and tree height is central to forest science of forest science because it is the basis of many applications such as growth modelling, yield prediction, biomass estimation, and the design of plans for sustainable forest management. Teak, a highly commercially valuable tropical hardwood species widely planted in Ghana, India, and Southeast Asia, the DBH–height relationship has been described to differ with different phases of stand development (Deb et al., 2016; Aabeyir et al., 2020). This difference is a function of an interaction between physiological, environmental, as well as silvicultural factors (Detto & Pacala, 2022). This analysis considers the DBH–height relationship at four ages of major development 5, 10, 15, and 25 years and thus provides information on dynamic development of teak plantation structure both in Ghana and comparable ones elsewhere.

At the age class of 5 years, DBH versus height relationship was highly positive. Regression analysis provided a p-value ($p < 0.001$) and R^2 of 0.627, that is 62.7% of the variability in tree height could be explained by variability in DBH. These findings suggest that during the juvenile stage of stand development, height and diameter growth are tightly coupled, reflecting a nearsynchronous allocation of resources to both vertical and radial stem expansion (Asigbaase et al., 2023). In Ghana, equally strong correlations between DBH and height are common in young plantations established under the National Forest Plantation Development Programme (NFPDP), with regular spacing and low intra-specific competition favouring rapid height growth (Asigbaase et al., 2023). Similarly, studies conducted in India and Nigeria revealed that significant DBH–

height correlations among young Teak stands where site quality is ideal and silviculture management is maximally practiced (Dantani et al., 2019; Karmakar et al., 2023).

Such similarities underscore that intense vertical growth in young stands is a global phenomenon, despite locally varying site conditions to influence the strength of the correlation.

In age class of 10, DBH–height correlation was reduced by a decrease in R^2 to 0.225 though statistically significant ($p < 0.001$). The decline reflects increased competition and heterogeneity in the face of mid-rotation conditions. In Ghana's Ashanti and Bono regions, there is generally a high degree of competition and variability in most Teak plantations around age 10, this is due to no or less management practices (Amissah et al., 2021). In Indonesia and Myanmar Teak, has a decreased DBH–height predictability at mid-aged stands due to site productivity heterogeneity and lack of systematic silvicultural treatment (Krisnawati et al., 2019). The study results indicate that regionally, DBH as a predictor of height becomes less precise at mid-rotation ages unless supplemented with site and management variables.

The increase strength between DBH–height relationship at 15-year-old class, was attributed to thinning and pruning operations that were carried out in well-managed plantations, such as those by private estate companies and the Forestry Commission. Thinning reduces competition, improves the availability of resources, and increases the consistency of DBH – height relationships (Kumi et al., 2021). The same findings are observed in Indian and Indonesian Teak stands, where the DBH–height correlation recovers after removing suppressed trees and the dominant trees gaining access to more resources (Gupta & Sharma. 2022).

In contrast, the DBH – height relationship was weaker and even reversed in 25-years-old Teak, this is due to senescence, reduced vertical development, and structural heterogeneity typical in aged plantations in Volta and Brong Ahafo (Polinder et al., 2022). This weaker DBH – height relationship are also found in old aged Teak in Thailand and India, with height growth stagnant, radial growth being dominant, and structural variation increasing due to microsite variation and disturbance history (Krisnawati et al., 2019). Studies in tropical forests also indicate that hydraulic limitation constrains height growth in mature trees, reducing DBH–height relationships (Rajput., 2025).

These findings generally demonstrate that the DBH–height relationship in teak stands follows a non-linear trajectory across the full stand life span in Ghana and other tropical regions. The relationship is strongly positive and highly correlated in young stands, weakens considerably during mid-rotation growth, and then shows moderate recovery after thinning or silvicultural intervention. However, this improvement is typically temporary, as the relationship gradually declines again in mature and old stands, largely due to aging processes (senescence) and increasing influence of environmental and site limitations. Research in Ghana confirms that biomass and volume estimates are more accurate when DBH, height, crown dimensions, and soil type are included (Matsuo et al., 2025).

Integrating data-driven modeling, ecological knowledge, and direct field measurements offers major opportunities to improve growth prediction, carbon accounting, and the sustainable management of Teak plantations worldwide.

5.2 Allometric relationship between DBH and crown volume of Teak.

This finding indicates that at the mid-rotation phase, structural stand uniformity and reduced early growth variation render DBH a more reliable predictor of crown volume and thus a useful measurement for silvicultural modelling and decision-making at this phase.

In 5-year-old teak stands, the relationship between DBH and crown volume was statistically significant but weak This suggests that structural heterogeneity strongly influences crown development at juvenile stages. Such weak allometric coupling aligns with observations in Ghanaian teak plantations, where DBH is a poor predictor of crown size due to high microsite variability, lateral competition, and soil fertility gradients (Donkor et al., 2023). Similar patterns have been reported in other tropical agroforestry systems, where stand heterogeneity during the early years reduces the predictive strength of DBH-based allometric models (Salamanca et al., 2022). These insights highlight the importance of incorporating crown length, tree height, and stand density into growth models to improve predictions of crown characteristics and initial biomass in juvenile teak stands. The 10-years-stand, however, improved significantly the DBH–crown volume relationship ($R^2 = 0.34$). This process means that mid-rotation plantations undergo structural regularization involving dominance hierarchies, self-thinning, and canopy closure. These events reduce tree-to-tree variability and the explanatory power of DBH. Other Teak plantations in mid-rotation in other tropical nations also exhibit more allometric stability and show evidence for the validity of DBH-based models for thinning, prediction of yield, and biomass estimation (Santos et al., 2023).

This age group is thus the most suitable management window when applying DBH as a predictor of crown volume in plantation forestry in Ghana.

Unexpectedly, the correlation between DBH and crown volume collapsed at age 15 years age stand, without record of any correlation. This decoupling means that when maturity begins, crown development becomes less dependent on the stem diameter and more on competition asymmetry, crowns retrenchment, and microhabitat heterogeneity. Stand density and site quality have been shown to significantly mediate Teak crown growth in Ghana's Volta and Ashanti regions, with a tendency to produce alternative growth patterns between dominant and suppressed trees (Aabeyir et al., 2020). Such findings justify the argument that DBH cannot be employed to project crown volume in structurally varied stands. Parallel inconsistencies have been reported in tropical forest studies, in situations of heterogeneous stand conditions in which DBH validity as a general predictor decreases (Matsuo et al., 2024).

The DBH–crown volume relationship was statistically significant once more but weak in the 25years-old stand. This reflect structural stabilization following mid-rotation reorganization. However, low explanatory power indicates that maturity-associated physiological and biomechanical constraints e.g., hydraulic limitations, biomechanical stability, senescence, and reproduction–vegetative growth trade-offs constrain crown growth relative to stem diameter. Field observations in mature Teak plantations in Ghana indicate that branch shedding, loss of apical dominance, and senescence associated architectural changes further reduce DBH–crown relationships (Asante et al., 2021). These findings agrees with general tree biomechanics and architecture theories, which point out that simple allometric scaling laws break down as trees age (Tondjo., 2018).

5.3 Conformity of allometric relationships to theoretical predictions

Allometric relationships represent useful sources of information on the structural and functional organization of trees since they measure how various tree dimensions scale relative to one another. Empirical relationships are most usefully compared with a theoretical model that derives exact scaling exponents from geometry, biomechanics, and metabolic processes. The most widely used frameworks are geometric similarity (GS), elastic similarity (ES), and metabolic scaling theory

(MST), which generate alternative predictions for scaling exponents in relations like stem height (H) vs. stem diameter (D) and crown volume (Cvol) vs. stem diameter.

GS theory, on the basis of proportionality scaling of tree dimensions with tree size growth, predicts the scaling exponent value as 1.0 for H-D relation in the form of tree height increasing in direct proportion to stem diameter. By contrast, mechanistically based ES theory incorporating buckling resistance and stability of trees under gravity-induced self-weight loads constrains the H–D correlation scaling exponent as 2/3. Likewise, MST of vascular network optimization for metabolic efficiency and resource supply also computes a 2/3 exponent of H–D scaling under physiological growth constraints (Berry et al., 2024)

Recently, empirical studies like that of Sileshi et al. (2023), have these theoretical predictions been tested by comparative analysis of observed allometric relations among different tree species and environments with the suggested exponents. For instance, conformity with the GS model may suggest proportional growth without biomechanical or physiological constraint, while conformity with ES or MST exponents may indicate that tree structure is most controlled by mechanical support requirement or resource allocation efficiency, respectively.

The alignment between observed data and theoretical model predictions provides useful insight into the key biological and environmental processes shaping tree growth and architecture, while also highlighting the dominant forces controlling tree form and structural development. Such analyses are important for interpreting species-specific regimes of growth, for simulating forest dynamics, and for quantifying ecosystem services such as carbon sequestration. In addition, deviations from predicted exponents may be influenced by external factors such as environmental stress, silvicultural treatment, or ontogenetic modification, furthering our understanding on tree allometry in natural and managed ecosystems (Van Valkengoed et al., 2025).

5.3.1 Stem height (H) vs. stem diameter (D), conformity with geometric similarity (GS)

The empirical findings of the present study present that for all the assumed age classes of Teak (5, 10, 15, and 25 years), the realized height-diameter scaling exponents are always smaller than the theoretical value of 1 provided by the geometric similarity (GS) model. In fact, the exponents ranged from 0.3687 to 0.495, and statistically significant differences ($p < 0.05$) are observed in the mature stands i.e., the 10, 15, and 25 years old stands. This departure reflects that height does not increase in an isometrically clean manner with stem diameter as GS theory has indicated, particularly with the age of trees.

These findings contribute to a growing body of evidence against the global applicability of geometric similarity in tree growth. Several previous research studies have already reported the same departures from GS predictions among temperate and tropical tree species (Ledo et al., 2018; Lu et al., 2021). The departure is most likely to be caused by a mixture of several explanatory variables like species-specific growth strategy, biomechanical constraint, available resources, and stand structural heterogeneity factors that cannot be fully accounted for by idealized allometric models.

The sub-projected scaling exponents repeatedly obtained in this study indicate tree height growth becoming progressively more conservative with respect to diameter growth as Teak trees age. This may be an adaptive shift in resource allocation away from vertical growth that is redirected toward horizontal growth, structural reinforcement, and reproduction. Additionally, the deviation from the

GS hypotheses highlights that tree growth patterns cannot be fully explained by universal rules alone. This supports the need to embed stronger ecological and silvicultural context, such as site conditions, competition, and management history into allometric modelling frameworks. It also important to apply more advanced scaling techniques, such as elastic similarity (ES) or metabolic scaling theory (MST), that encompass mechanical stability and physiological mechanisms in tree structure predictions.

5.3.2 Stem height (H) vs. stem diameter (D), conformity with elastic similarity and MST

The height–DBH scaling slope observed for Teak showed no statistically significant deviation from the theoretical 2/3 (0.67) slope predicted by the ES and MST models across all age classes ($p > 0.05$). Such statistical consistency demonstrates that Teak height growth adheres to the biomechanical and vascular constraints assumed under such models. Specifically, the ES model accounts for mechanical stability of trees by the assumption that the height is equal to the diameter in a way that minimizes buckling probability, while the MST model assumes metabolic efficiency, or water and nutrient conductance in the vascular tissue, regulates tree architecture. The findings of this research align Jucker et al. (2022) hypothesis that the scaling of tree structure is governed by intrinsic physical and physiological limitations. For Teak, such compliance is in that height development, with advancing age in trees, is increasingly governed by needs to maintain structural integrity and efficient systems of internal transport. These are likely to grow strongest in the older stands, where biomass accumulation and mechanical loading effects grow greater.

In addition, the findings are consistent with recent work on tropical forest species that hold that the H-D relationship stabilizes at the ES and MST predictions, particularly as stands approach canopy closure and competitive pressures for light and resources become equalized (Zea-Camaño et al., 2025). These trends emphasize the value of ES and MST as robust model theories for the characterization of patterns of growth in tropical hardwoods, in which both physiological and mechanical forces exert robust control over ontogenetic height development.

5.3.3 Crown volume (Cvol) vs. stem diameter (D), conformity with geometric similarity (GS)

Geometric similarity (GS) theory would assume a cubic scaling function between stem diameter and crown volume with a predicted exponent of 3. However, in this study, the observed scaling exponents for diameter versus crown volume ranged from 0.451 to 1.40 for all the stand age classes, which were significantly lower than the GS theoretical prediction. This deviation was strongest in the 5 and 10-years-old plantations, where deviation from predicted value was statistically significant ($p < 0.05$), indicating a significant deviation from geometric similarity in early growth stages.

These contradictions are consistent with the existing literature, with crown structure in young trees being more malleable and strongly influenced by competitive and environmental factors (Digby et al., 2018; Plaga et al., 2024). Trees continue to be establishing dominance and optimizing light capture at this stage, thus leading to asymmetrical patterns of crown expansion. The high crown development variability in younger stands has been hypothesized to be induced by local competition for light, nutrient gradients, and microsite heterogeneity that can constrain or enable crown development regardless of stem growth in diameter. These factors individually challenge the geometric similarity assumptions, which postulate proportional and uniform growth in all sizes of the plant.

As trees age and structural and physiological constraints become more established, the scaling relations stabilize, converging on values corresponding to biomechanical or metabolic constraints rather than purely geometric ones. Deviations in the younger stands thus not only illustrate the limitation of applying GS across all age classes but also highlight the ecological significance of developmental stage and stand dynamics in controlling allometric trends in tropical hardwoods such as Teak.

5.3.4 Crown volume (Cvol) vs. stem diameter (D), conformity with elastic similarity and MST

The findings from this research provides useful information on the age-related conformity of crown volume (Cvol) and diameter (D) allometry of Teak, compared to the prediction of Elastic Similarity (ES) and Metabolic Scaling Theory (MST). According to both models, a scaling exponent of 2 for crown volume vs. stem diameter (Cvol - D) is predicted. Empirical analysis showed no significant deviation from this expected slope in older age groups (10, 15, and 25 years old stands; $p > 0.05$), such that crown volume increases linearly with diameter in mature plantations. The 5-year-old stand, however, lay outside of this theoretical requirement to a highly significant degree ($p = 0.010$), Implying that young trees have not yet manifested the structural and physiological constraints these models are based on. These results are consistent with those of Sullivan et al., (2020), who detected increasing congruence with MST predictions for large forests and credited such patterns to long-term optimisation of structure.

This observed alignment between empirical data and theoretical predictions suggests that Teak allometric patterns are dynamic, changing with tree maturation and forest development. Specifically, while height-diameter (H-D) relationship consistently follows ES and MST predictions across all age classes thanks to biomechanical limitation in vertical growth and optimization of vascular transport the relationship between crown volume and diameter shows large departures during initial developmental stages. These departures are likely due to a high intraspecific crown shape variation brought about by intense competition, light heterogeneity, and juvenile tree plasticity to neighborhood conditions.

Age-dependent allometric patterns in Teak are crucial for improving forest biomass assessments, carbon pool evaluations, and the development of dynamic models of the forest. For old stands, where growth trends in age are stabilized and structure forms are more reliable, application of ES and MST provides a robust platform for forest structure and productivity modeling. But one has to be careful while applying these models in the event of young stands. At these stages of development, ontogenetic mechanisms and heterogeneity in the microenvironment significantly regulate tree growth, leading to significant deviations from idealized scaling (Sileshi et al., 2023). Models for scaling in young plantations must therefore account for this heterogeneity, potentially through site-specific and stage-specific developmental parameters in the allometric equations. This was a subtle tactic aimed at improving the precision of biomass estimates and ensuring forest simulation models' credibility across a broad spectrum of stand ages.

5.4 Carbon sequestration potential of Teak plantations

5.4.1 Aboveground biomass, belowground biomass, and total biomass of Teak plantations

The results of the study indicate a clear pattern of age-related biomass accumulation in Teak, with the most pronounced growth increments occurring between 5 and 15 years of age. During the growth period, aboveground biomass (AGB) (stem, branch, leaf) and belowground biomass (BGB) primarily root systems exhibits steady and statistically significant accumulation. The total biomass (TB), That is, AGB and BGB together, thus, demonstrates a very steep increasing trend during this time. This conforms to the physiological characteristic of rapidly growing tropical trees. In Ghana, current studies validate that plantations of the dry semi-deciduous forest zone of Teak store huge biomass and carbon stock during their early and mid-rotation stages, particularly under intensive management and silvicultural practices (Kumi et al., 2021).

The vigorous growth in biomass between 5 and 15 years reflects the biologically vigorous growth stage of Teak, where its photosynthetic potential and efficiency of resource utilization are at their best. During the Ghana plantation age, the phase is characterized by vigorous crown growth and leaf area development that optimize canopy development for maximum light capture and carbon assimilation. These alterations promote greater carbon allocation to above and below ground parts, particularly stimulating stem wood, leaves, and root biomass. The outcome aligns with existing tropical investigations demonstrating the effectiveness of silvicultural management inputs such as thinning, spacing, and fire management in influencing the rate of biomass accumulation (Ameray et al., 2021).

Growth underground at this stage is also pronounced. In Teak plantations in Ghana, a highly developed root system raises the rate of water and nutrient absorption, stimulating growth above ground at a high rate (Kumi et al., 2021). This same positive feedback between root and canopy growth has similarly been observed in other tropical conditions, illustrating the integrative nature of biomass growth in live growing stands.

The 25-year-old Teak stands exhibited a substantial decrease in biomass increment, indicative of the transition from vigorous growth to a senescent or stabilized phase. This is consistent with trends observed in Ghanaian plantations where mature Teak stands experience heightened intra and inter tree competition for light, water, and nutrients (Asigbaase et al., 2024). Canopy closure diminishes light penetration, and the overlap of root systems increases belowground competition, thereby restraining further biomass increments. The identical biomass stabilization patterns were reported in large-scale tropical forest experiments (Rozendaal et al., 2020).

Older Teak trees, however, still uphold significant carbon reservoirs relative to their size, with edge increments being lowered. Rather surprisingly, heterogeneity within class was found to be high, especially for 15-year stands, where site variability and management practices led to clear differences in biomass growth. In Ghana, this type of diversity is largely attributable to differences in soil fertility, rainfall variation, and management regimes (Kumi et al., 2021). Plantations developed on fertile forest soils under intensive silvicultural inputs, i.e., timely thinning and weeding, are more likely to grow than plantations developed on degraded or marginal land.

Genetic factors also play a role in biomass variation. The over reliance on available provenance resources in Ghana has limited productivity, yet the ongoing provenance trials initiated in 2015 and reported recently need to have genetic diversity and growing potential increased (Wanders et al, 2021). The trials indicate the necessity of incorporating genetic improvement into plantation establishment efforts to optimize biomass outcomes.

As has been shown by Ghimire et al. (2024) and follow up research in Ghana (Asare et al., 2020; Kumi et al., 2021), tree age is one of the main drivers of biomass, but tree age must be interpreted alongside site-specific and anthropogenic controls. It is a composite perspective that is important for streamlining productivity evaluations and guiding adaptive, locally relevant silviculture practices that maximize Teak's biomass and carbon sequestration in Ghana and other comparable tropical regimes.

5.4.2 Aboveground biomass carbon, belowground biomass carbon, and total biomass carbon

Teak biomass carbon content closely tracks the cumulative biomass trends with peak carbon storage at 15-year-old stands. This is precisely the trend tracked by conventional techniques of carbon estimation, e.g., those outlined by the IPCC (2019), which heavily assume carbon constituting about 47–50% of the dry biomass of a tree. Because this is a proportionate relationship, any increase in overall biomass necessarily results in greater storage of carbon as well. This would justify the argument that increased biomass growth would be a factor for determining forest stands' potential for carbon sequestration.

The 15 years old apical carbon storage has ecological and silvicultural significance. This is the growth phase that is characterized by growth and fast accumulation of carbon, especially for fastgrowing tropical species like Teak. In Ghana, Acquah (2020) reported that Teak plantations aged 10-20 years have accelerated increases in aboveground biomass and carbon stock, as has been found before in India (Karthik et al., 2022) and Thailand (Raihan et al., 2023), where maximum carbon accumulation occurs during the mid-rotation of Teak. Sanquetta et al. (2020) also reaffirm that tropical timber species will store most of their total lifetime carbon in their mid-rotation stage. In this research, 15 years old Teak plantations maintained the highest above and belowground carbon pools with approximately 13.05 megagrams of carbon per hectare (Mg C/ha). This finding not only reflects the importance of plantation age in carbon estimation but also suggests favourable site conditions and possibly superior silvicultural treatments at this age in Ghana.

The high carbon build-up at this age may be a function of an interaction of biophysical and management factors. In Ghanaian Teak plantations, positive soil fertility of old fallows, favorable nutrient cycling of leaf litter, positive microclimatic conditions, and optimal photosynthetic efficiency are likely to be the factors (Asigbaase et al., 2021). Besides, intensified silviculture treatments such as thinning, selective regeneration, and in some cases fire control practice initiated by the Forestry Commission likely heightened resource availability and stand structure to enhance conditions conducive to high biomass development and carbon sequestration (Guuroh et al., 2021). The treatments likely enhanced tree growth rates and stand productivity, thereby contributing to the observed spikes in carbon.

In contrast, that is not the case for the youngest age class being analysed, 5 years old Teak plantations, which had a significantly lower total carbon stock of 4.55 Mg C/ha. This is mostly an ontogenetic growth trend, where young trees are just beginning to accumulate biomass and are not yet at the high growth rate stage that occurs in mid-aged stands. A study by Amoako et al (2022) in Ghana's semi-deciduous zones similarly found that Teak and other off-reserve secondary stands aged 0–5 years had markedly lower carbon stocks compared to older age classes. This again underscores the vulnerability of young stands to factors like competition from weeds, water stress, and low soil fertility, which hinder early biomass and carbon accumulation. Therefore, age-classbased adaptive management remains essential. Poor soil quality in degraded land, low water holding capacity of certain savannah soils, or insufficient silvicultural input during the first stage can also limit growth and carbon storage capacity. The difference is used to highlight the significance of age-class-based adaptive management practices contextualized with consideration for the age class of the forest stand.

A study by Brown et al (2024) examining soil carbon and bio-physicochemical dynamics in restored tropical hardwood plantations in southern Ghana found that after 40 years of restoration, both soil carbon stocks and key soil properties in plantations and secondary forests had recovered to levels comparable to those in primary forests highlighting how interventions like site preparation and reclamation considerably improve long-term carbon sequestration performance under wellestablished stand conditions

Carbon sequestration in forests, as Khan et al. (2025) argued, depends significantly on the interaction of local climatic, edaphic, and ecological forces and hence forest management must be sensitive to these forces for optimal carbon fixation. Practices including control of irrigation, mulching, and application of nutrients have been found particularly useful in the establishment phase of plantation growth in Ghana and other tropical regions. Above-ground biomass (branches, stems, and leaves) is most often the focus of most biomass estimates, but root systems, or belowground biomass, are a significant source of carbon sequestration. Although below-ground carbon makes up a small portion of total biomass, it plays a major role in long-term carbon sequestration (Berhongaray., 2025).

In West African Teak plantations, carbon originating from roots constitutes a more recalcitrant and stable pool in soils compared to aerial biomass (Salami et al., 2021; Kumi et al., 2021). Rootorigin carbon is more stable and persistent because it gets anchored into soil aggregates and microbial frameworks to create a relatively recalcitrant pool that decomposes very slowly over an extended period of time. Recent findings further emphasize that fine-root inputs, in association with microbial processes, disproportionately contribute to the buildup of long-lasting soil carbon sinks, as they are less subject to rapid turnover than aboveground biomass (Liu et al., 2022).

Additionally, belowground carbon sustains the buffering capacity of ecosystems against abiotic stresses such as fire and drought, which are common in Ghana's transitional and savannah ecosystems and have the potential to mobilize massive pools of carbon otherwise from aboveground biomass (Adu-Poku et al.,2023). Soil carbon resilience sustains long-term carbon sink stability, and sustained sequestration capacity ensures sustained carbon sequestration even under variation in aboveground vegetation. Silviculture practices that favour the establishment of robust root systems e.g., correct tree spacing (as under Ghana's Forest Plantation Development Programme), prevention of soil compaction at harvest of timber, enhancement of microbial development in soil, and provision of sufficient water supply can significantly enhance carbon sequestration within belowground biomass. These are not only useful for enhancing stand productivity but also for enhancing long-term carbon storage. For instance, recent research of West African savannas indicates that belowground carbon particularly at deeper soil levels can be restored in around 4 to 13 years following disturbance, specifically where early-season prescribed burning is practiced, highlighting the resilience and regenerative potential of soil carbon stores (Dodoo et al., 2023)

Investment in stabilizing above and belowground carbon storage practices benefits overall greenhouse gas reduction endeavours while enhancing the ecological resilience of forest ecosystems. Soil stabilization or improvement management practices such as organic mulch, reduced disturbance, and cover crop incorporation are already being promoted in Ghana's ClimateSmart Agriculture programs and can result in a resilient carbon sink with the potential for perpetual sequestration (Boliko, 2019). Integrated systems improve ecosystem function and resilience and link silvicultural objectives with world environmental objectives.

In summary, Teak plantation patterns of carbon accumulation highlight the dynamic nature of biomass and carbon accumulation by stand age. The high 15 years old stand carbon sequestration potential highlights the importance of age for forest carbon dynamics and the ability of intermediate-aged plantations in Ghana and other tropical regions to serve as carbon sinks. At the same time, the role of root system inputs in sustaining long-term carbon storage and growth highlights the often-overlooked contributions of belowground processes and root functions. Agedifferentiated management that includes above and belowground measures can theoretically increase by orders of magnitude the tropical timber plantation Teak's carbon sequestration capacity. By co-ordinating silvicultural operation with the trees' biological growth cycles and prevailing local environment conditions, the Teak plantations of Ghana can be efficient and durable climate change mitigation measures

5.4.3 Monetary value of total carbon and carbon accumulation Rate of Teak Plantations

Monetized economic worth of sequestered carbon based on carbon market price provides valuable information about the economic worth of Ghana Teak plantations by age class. One finding of this study is that the most economically valuable age class in Ghana is the 15-year-old age class, with an approximate value of around US $950.16 per hectare. This peak is paralleled by the highest levels of aboveground biomass (AGB), total biomass (TB), and carbon stock for Ghanaian Teak stands, which translates to mid-rotation stands being the point of turnaround for both ecological profitability and economic productivity in the case of Ghana. It is a season of maximum biomass production and efficient carbon sequestration. In Ghana Teak around this age can serve as the optimal season for commercial timber production or in leveraging participation in carbon offset markets and REDD+ programs through Ghana's climate-smart forestry initiatives (Acquah. 2020)

The trend observed in carbon value increasing to mid-rotation ages in Ghana concurs with findings made in other global studies. For example, studies in Latin America and Southeast Asia indicated that intermediate-aged plantations would be expected to yield more balanced economic returns and delivery of ecosystem services (Ledo et al., 2020), an indication of what happens globally within Ghana.

Further study into the pattern of carbon accumulation corroborates this information. While Ghana's 5-years-old plantations contain the smallest total carbon stock, they contain the most carbon accumulation of 66.27 Mg C/ha/year. This is the phase of exponential growth typical of young forests caused by high photosynthetic capacity, low competition, and high availability of resources. This highest early stage sequestration is in accord with proxy forest growth models and physiological studies (Asare et al., 2020), underlining resource use efficiency and rate of increased metabolic activity in developing stands a trend certainly evident in young Ghanaian Teak plantations.

In contrast, old Ghanaian plantations 25 years old stands have the lowest rate of carbon accumulation at 23.17 Mg C/ha/year although they carry unimaginable standing biomass. This trend is caused by physiological maturity, closure of the canopy, and high biomass turnover, all of which cause reduced net primary production. Additionally, at this moment the Ghanaian forest system is beginning to approach carbon sink saturation with low biomass growth rates and decreased marginal sequestration. The observed reduction in accumulation rates exemplifies the principle of diminishing returns, as mature stands exhibit progressively lower gains in annual carbon sequestration and, consequently, reduced carbon market value.

Nonetheless, the lower economic value of old stands must be considered within the broader ecological context in Ghana. Old plantation stands provide significant ecosystem services beyond carbon sequestration. They offer valuable co-benefits in biodiversity protection (e.g. more diverse understory and wildlife habitats), microclimate regulation, soil stabilization, and long-term ecological resilience. These advantages are becoming increasingly important in high-quality carbon markets and Ghana's new voluntary initiatives, where permanence and co-benefits receive attention in carbon offset project assessment. Thus, mature stands are valuable carbon pools that maximize long-term sequestration a parameter of particular importance in the validity of certified emission reductions under REDD+ programs.

These findings have significant implications for carbon-driven land-use initiatives in Ghana such as REDD+, afforestation, and reforestation efforts under the national forestry and climate change policies of the country. The 10 to 15-years-old Ghanaian Teak plantations seem particularly strategic, constituting a unique point of confluence where biological growth, sequestered carbon, and market worth are collectively maximized. Their worth for generating carbon credits renders them valuable capital in compliance markets (e.g., multinationals' buying of verified emission reductions) as well as voluntary carbon markets. There has been evidence in the literature of endorsement of such a perspective, with mid-rotation stands typically acknowledged as economically feasible points of return on carbon investment (Sackey et al., 2024) and such general outcomes are highly consistent with the Ghanaian case.

Although the prospects for economic returns from young and mid-aged stands in Ghana are promising, still relevant is that plantation management avoids compromising long-term ecological integrity in the interest of short-term economic profitability. Both values are need to be reconciled in management programs, an effort that brings together carbon market incentives with aims for ecosystem conservation under Ghana's forestry policy framework. These planning approaches must thus realize both time horizons of value: harvesting the income from carbon benefit from stands in mid-age while allowing on stand older plantations to provide guaranteed biodiversity and ecosystem resilience.

Consequently, environmental and economic analysis of Ghanaian Teak stands verifies that they can both be a valuable source for carbon sequestration and sustainable development for Ghana. Of these, 10 –15 years old stands are well suited for integration into carbon market systems. But to utilize such systems optimally, however, Ghana's policy systems and plantation management need to give a high value to a deliberative strategy, one balancing economic gain over short timeframes with long-term provision of forest integrity and ecosystem services.

5.5 Impact of allometric-based tree height estimates on carbon calculations

Precise biomass and carbon stock estimation of the forest is needed to understand the productivity of the forest, as well as to develop climate-related activities like REDD+ (Reducing Emissions from Deforestation and Forest Degradation). In this study, we compared the estimates of biomass and carbon stock derived with two different methods of tree height measurement: field measured height and allometrically estimated height. The results indicate that while allometric height models are a useful tool, especially in large-scale forest inventories, they do not always reflect the real growth dynamics of Teak trees, particularly in old stands.

5.5.1 Consistency and variation in height estimates across age classes

Throughout the four Teak age classes analyzed (5, 10, 15, and 25 years), the estimated tree height was generally in close agreement with actual field observations. The field measured height had a slightly higher values that estimated heights. This decline may be an indication of a shift in the pattern of tree growth according to self-thinning, resource competition, or site factors not generally incorporated into generalized height-diameter models. The models are underpinned by continuous growth, but field-based empirical observation reveals that from a certain age, Teak trees may actually stop growing in height according to ecological saturation or senescence (Mensah et al., 2018).

5.5.2 Impact on biomass and carbon stock estimates

The findings showed that biomass and carbon stocks calculated using estimated height values also varied significantly between age classes (ANOVA, $p < 0.001$). There were discrepancies in magnitude, however, when these were compared with those using field-measured heights.

Differences were negligible for younger age classes but became conspicuous for the 25-year class. This means that the exclusive utilization of estimated height has the potential to overestimate or underestimate the actual carbon stocks, subject to the growth dynamics of the stand. Height overestimation, particularly for older or structurally degraded plantations, can result in hyperbolic biomass and carbon stock predictions. On the contrary, underestimation can underestimate forest carbon with immediate implications for carbon trading and REDD+ programs (Yambayamba et al., 2025). Economically, it could imply erroneous carbon credit projections and poorly informed policy or project-level decision-making.

5.5.3 Growth dynamics and peak productivity

Interestingly, both height assessment techniques reflected that the maximum biomass and value of carbon were in the 15-year-old age class. This reveals that during the ages of around 15 years, Teak trees have a period of highest productivity in terms of biomass accumulation. After this age, there was some reduction or leveling off, especially in the 25-year-old class. This has been accounted for on the grounds of senescence associated with age when trees allocate their energy to maintenance rather than growth, or intensified competition for nutrients and light supplies (Wirabuana et al., 2022).

That allometric models were not able to fully explain this trend implies height-diameter equations, typically extrapolated from juvenile or optimum-condition plantations, might be less than optimally applied to predict the older and more complex stand unless recalibration occurs.

5.5.4 Implications for carbon accounting and forest monitoring

Generally, the choice of height measuring method use has implications for estimating forest carbon, particularly in those projects with a carbon offsetting scheme. Field measurements are more likely to be precise but labor intensive and time consuming, particularly where distant from field stations. Allometric models, on the other hand, offer a cost-effective option, particularly where in conjunction with remote sensing devices like LiDAR or drone photogrammetry (Puliti et al., 2018).

Parallel evidence from Ghana also validates the imperative of incorporating site-specific predictors into biomass estimation models. Aabeyir et al. (2020) demonstrated that the inclusion of wood density and DBH significantly increases the accuracy of aboveground biomass (AGB) estimation in tropical forests. Their Ghanaian model ($AGB = 0.0580\,\rho\,((DBH)^2 H)^{0.999}$) was not only locally calibrated but also produced similar results to pantropical models. This suggests that locally calibrated equations can minimize systematic biases that undermine the integrity of carbon accounting under REDD+ programs. By tailoring equations to ecological realities, such models introduce scientific accuracy and policy credibility into climate mitigation efforts.

The same findings are reported outside the Ghanaian experience. Sullivan et al. (2025), working with a large South American dataset, emphasized that site-specific predictors like tree density, rainfall, and soil nutrient status are equally crucial for improving carbon stock estimation. They established that not controlling for these effects can result in systematic over or under estimation of forest carbon, with serious implications for REDD+ projects and carbon credit markets. Among the main outcomes emerging from the study is wood density as a determinant of tree biomass. Since wood density is spatially and environmentally variable, its misrepresentation generates large-scale errors in biomass and carbon maps.

The contrast between Aabeyir et al. (2020) Ghanaian model and Sullivan et al. (2025) Amazonian research highlights a broad consensus: generalized allometric models, while useful, cannot adequately capture fine-scale ecological heterogeneity in diverse tropical landscapes. Localization of modeling in Ghana has been shown to minimize bias, and in South America, the incorporation of spatially explicit environmental gradients has reduced prediction errors compared to aspatial approaches. Both cases reinforce the argument that valid carbon accounting particularly in tropical environments with high biodiversity requires pairing ground-based ecological surveys and remote sensing imagery. Pairing not only increases predictive capacity but also increases the integrity of REDD+ projects by scaling carbon accounting to the ecological complexity of tropical forests.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The study aimed to achieve three overall objectives. The study tried to explore the interrelationships between diameter at breast height (DBH), tree height, and crown volume in Teak plantations and assess to what extent these interrelationships conform to established theoretical allometric models. The study aimed to estimate the carbon sequestration potential in different age classes of Teak plantations. Third, it determined the impact of the use of allometric-based height estimates compared to the field-measured tree heights on carbon stock assessment accuracy.

Consequently, the results confirmed DBH–height relationships in young stands (5 years) to be in moderate agreement with geometric and elastic similarity theories ($R^2 = 0.627$), reflecting to be anticipated development during the early stage. This relationship declined with age, however, in older stands (10–25 years), deviating from geometric similarity and reflecting competition, biomechanical limitation, and site factors. Conversely, DBH showed consistently weak correlations with crown volume ($R^2 = 0.001 – 0.338$), suggesting that crown development is influenced more by factors such as stand density, light competition, and silvicultural practices like thinning and pruning, rather than by stem diameter itself.

Secondly, Carbon stock measurements indicated that the 15-year-old Teak stands contained the largest biomass and carbon, followed by the 25, 10, and 5year-old stands. This pattern indicates that Teak's highest sequestration of carbon is at the middle rotation stage when the highest growth rates and resource use efficiency combined yield the highest biomass production. The results still highlight the importance of stand density as an influence on both biomass productivity and carbon storage. Well-managed stand densities reduce excessive competition for water, light, and nutrients and therefore enhance tree growth while stimulating greater carbon accumulation at the stand level.

Third, comparison with field-measured and estimated heights proved systematic underestimation of carbon stock using only universal allometric models. This affirms the limitation of using universal models that have not been calibrated to local ecology and implies a need for testing against field data to avoid systematic bias in carbon accounting.

Overall, the findings emphasize that accurate assessment of biomass and carbon in Teak plantations requires the derivation and application of locally verified, age-stratified allometric equations. In addition, the weak DBH–crown volume fit ensures that the application of direct crown measurements or remote sensing technologies such as LiDAR will improve accuracy. These approaches will not only enhance the carbon accounting system of Ghana but also the science base of sustainable Teak plantation management and accessing climate change mitigation action.

6.2 Recommendation

Based on the study's findings, several recommendations were proposed to strengthen the management, modelling, and monitoring of Teak plantations. Key priorities include improving the precision of growth estimations, advancing sustainable forest management practices, and integrating observed variations in soil fertility dynamics across different plantation age classes into management decisions. First, age-class growth models should be used by forest managers and scientists instead of a general, universal equation for every age. The study shows that correlations between DBH, height, and crown volume decline with rising age of teak trees. Therefore, young tree-based models would be inappropriate for old stands. In order to enhance predictive precision, models of growth ought to be specific to individual age classes and include supplementary variables like crown measurements and local environmental conditions.

Second, the use of crown measurements in models of growth and biomass is highly recommended. The weak and variable relationship in the observed data between DBH and crown volume particularly for larger trees between DBH and crown size shows that DBH in itself is a poor predictor of crown size. Since crown structure is crucial for light interception, competition, and overall tree productivity, direct measurement is recommended. Utilization of new remote sensing technologies, i.e., UAVs (drones) with LiDAR or photogrammetry, may enable non-destructive and cost-effective acquisition of crown data on large forest areas.

Locally Validate Allometric Height Models, generalized regression model height estimation has the potential to create systematic biases and contribute to carbon stock underestimation. Field measurements directly, or establishment of localized height-diameter models, should be accorded priority where feasible for increased precision. In addition, it is required to use site-specific management and not have uniform policies in all plantations. Plantations vary with age, soil fertility, nutrient status, and local climatic conditions. For example, older stands on poor soils would require more intensive application and soil renewal, and young plantations on favorable soils would do with regular maintenance. It will bring about efficiency and productive continuity if management practices are tailored for site conditions. Also, further research work must be promoted to study Teak growth patterns, crown form, and remote sensing integration in forest management. Long-term trials must be conducted to determine how the development relationships differ and how climate and soil nutrient level affect the growth of the tree. There should be research aimed at discovering the increased application of UAVs, satellite imagery, and other digital technology to conduct forest health, biomass, and canopy structure monitoring more efficiently.

In conclusion, the study recommends the use of age-stage growth models, direct measurement of crown volume, targeted soil fertility improvement, site management, persistent research, and technical capacity development. These measures are crucial in furthering the sustainable development and long-term ecological and economic return of Teak plantations.

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APPENDICES

APPENDIX I

Regression and anova table for diameter and height.

Relationship between DBH and Height for 5-Year-Old Teak

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.792[a]	.627	.624	.0353591

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.229	1	.229	183.376	.000[b]
	Residual	.136	109	.001		
	Total	.366	110			

a. Dependent Variable: LOGHm

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	.687	.028		24.798	.000	.632	.742
	LOGdbhcm	.574	.042	.792	13.542	.000	.490	.658

a. Dependent Variable: LOGHm

Relationship between DBH and Height for 10-Year-Old Teak

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.474[a]	.225	.219	.0910019

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.332	1	.332	40.033	.000[b]
	Residual	1.143	138	.008		
	Total	1.474	139			

a. Dependent Variable: LOGHm

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	.837	.043		19.291	.000	.751	.923
	LOGdbhcm	.389	.061	.474	6.327	.000	.267	.510

a. Dependent Variable: LOGHm

-Year-Old Teak

Relationship between DBH and Height for 15

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.660[a]	.436	.429	.0601177

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.224	1	.224	61.851	.000[b]
	Residual	.289	80	.004		
	Total	.513	81			

a. Dependent Variable: LOGHm

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	(Constant)	.788	.057		13.774	.000	.674	.902
	LOGdbhcm	.536	.068	.660	7.865	.000	.400	.671

a. Dependent Variable: LOGHm

-Year-Old Teak

Relationship between DBH and Height for 25

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.606[a]	.368	.361	.0436609

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.102	1	.102	53.497	.000[b]
	Residual	.175	92	.002		
	Total	.277	93			

a. Dependent Variable: LOGHm

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	.835	.044		19.020	.000	.748	.922
	LOGdbhcm	.423	.058	.606	7.314	.000	.308	.537

a. Dependent Variable: LOGHm

-Year-Old Teak

APPENDIX II

Regression and anova table for diameter and crown volume.

Relationship between DBH and crown volume for 5-Year-Old Teak

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.293[a]	.086	.077	.1706563

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.298	1	.298	10.234	.002[b]
	Residual	3.174	109	.029		
	Total	3.473	110			

a. Dependent Variable: LOGcrownvolume

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	2.854	.134		21.351	.000	2.589	3.119
	LOGdbhcm	.654	.204	.293	3.199	.002	.249	1.059

a. Dependent Variable: LOGcrownvolume

Relationship between DBH and crown volume for 10-Year-Old Teak

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.581[a]	.338	.333	.2279290

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.653	1	3.653	70.312	.000[b]
	Residual	7.169	138	.052		
	Total	10.822	139			

a. Dependent Variable: LOGcrownvolume

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	(Constant)	1.967	.109		18.097	.000	1.752	2.182
	LOGdbhcm	1.291	.154	.581	8.385	.000	.986	1.595

a. Dependent Variable: LOGcrownvolume

-Year-Old Teak

Relationship between DBH and crown volume for 15

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.031[a]	.001	-.012	.6074749

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.029	1	.029	.078	.781[b]
	Residual	29.522	80	.369		
	Total	29.551	81			

a. Dependent Variable: LOGcrownvolume

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	4.547	.578		7.864	.000	3.396	5.698
	LOGdbhcm	-.192	.688	-.031	-.279	.781	-1.562	1.178

a. Dependent Variable: LOGcrownvolume

Relationship between DBH and crown volume for 25-Year-Old Teak

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.205[a]	.042	.031	.5366755

a. Predictors: (Constant), LOGdbhcm

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.157	1	1.157	4.017	.048[b]
	Residual	26.498	92	.288		
	Total	27.655	93			

a. Dependent Variable: LOGcrownvolume

b. Predictors: (Constant), LOGdbhcm

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	3.037	.539		5.629	.000	1.965	4.108
	LOGdbhcm	1.423	.710	.205	2.004	.048	.013	2.833

a. Dependent Variable: LOGcrownvolume

-Year-Old Teak

APPENDIX III

One-Sample T-Test of DBH–Height Relationship

One-Sample t-Test of DBH–Height Relationship in 5-Year-Old Teak: Geometric Similarity, Elastic Similarity, and MST

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.49533	.196136	.113239

One-Sample Test

	Test Value = 1					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-4.457	2	.047	-.504667	-.99190	-.01744

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.49533	.196136	.113239

One-Sample Test

	Test Value = 0.67

	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
slope	-1.542	2	.263	-.174667	-.66190	.31256

One-Sample t-Test of DBH–Height Relationship in 10-Year-Old Teak: Geometric Similarity, Elastic Similarity, and MST

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.38833	.061273	.035376

One-Sample Test

	Test Value = 1					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
slope	-17.291	2	.003	-.611667	-.76388	-.45946

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.38833	.061273	.035376

One-Sample Test

	Test Value = 0.67					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-7.962	2	.015	-.281667	-.43388	-.12946

One-Sample t-Test of DBH–Height Relationship in 15-Year-Old Teak: Geometric Similarity, Elastic Similarity, and MST

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.36867	.100977	.058299

One-Sample Test

	Test Value = 1					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-10.829	2	.008	-.631333	-.88217	-.38049

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.36867	.100977	.058299

One-Sample Test

	Test Value = 0.67					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-5.169	2	.035	-.301333	-.55217	-.05049

One-Sample t-Test of DBH–
Similarity, Elastic Similarity, and MST

Height Relationship in 25-Year-Old Teak: Geometric

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.47167	.191891	.110789

One-Sample Test

	Test Value = 1					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-4.769	2	.041	-.528333	-1.00502	-.05165

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
slope	3	.47167	.191891	.110789

One-Sample Test

	Test Value = 0.67

					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
slope	-1.790	2	.215	-.198333	-.67502	.27835

APPENDIX IV

One-Sample t-Test of DBH–Crown volume Relationship

One-Sample t-Test of DBH–Crown volume Relationship in 5-Year-Old Teak: Geometric Similarity, Elastic Similarity, and MST

One-Sample Statistics				
	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	.451000	.2655353	.1533069

One-Sample Test						
	Test Value = 3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Slope	-16.627	2	.004	-2.5490000	-3.208626	-1.889374

One-Sample Statistics

One-Sample t-Test of DBH–-YearSimilarity, Elastic Similarity, and MST

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	.451000	.2655353	.1533069

One-Sample Test

	Test Value = 2					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Slope	-10.104	2	.010	-1.5490000	-2.208626	-.889374

Crown volume Relationship in 10 Old Teak: Geometric

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	1.075000	.5626802	.3248636

One-Sample Test

	Test Value = 3					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Slope	-5.926	2	.027	-1.9250000	-3.322775	-.527225

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	1.075000	.5626802	.3248636

One-Sample Test

	Test Value = 2					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Slope	-2.847	2	.104	-.9250000	-2.322775	.472775

One-Sample t-Test of DBH–-YearSimilarity, Elastic Similarity, and MST

Crown volume Relationship in 15 Old Teak: Geometric

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	.759000	.6209404	.3585001

One-Sample Test

	Test Value = 3					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Slope	-6.251	2	.025	-2.2410000	-3.783502	-.698498

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	.759000	.6209404	.3585001

One-Sample Test

	Test Value = 2				
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference

					Lower	Upper
Slope	-3.462	2	.074	-1.2410000	-2.783502	.301502

Crown volume Relationship in 25 Old Teak: Geometric

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	1.401333	.4780777	.2760183

One-Sample Test

	Test Value = 3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Slope	-5.792	2	.029	-1.5986667	-2.786278	-.411056

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Slope	3	1.401333	.4780777	.2760183

One-Sample Test

	Test Value = 2

One-Sample t-Test of DBH–-YearSimilarity, Elastic Similarity, and MST

	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Slope	-2.169	2	.162	-.5986667	-1.786278	.588944

APPENDIX V

Anova table and Kolmogorov-Smirnov test

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
HGT	Between Groups	1854.097	3	618.032	140.894	.000
	Within Groups	1855.489	423	4.386		
	Total	3709.586	426			
EstimatedH	Between Groups	1721.612	3	573.871	278.041	.000
	Within Groups	873.062	423	2.064		
	Total	2594.674	426			
AGB	Between Groups	8409.825	3	2803.275	81.936	.000

	Within Groups	14472.133	423	34.213		
	Total	22881.958	426			
BGB	Between Groups	1381.266	3	460.422	90.218	.000
	Within Groups	2158.759	423	5.103		
	Total	3540.025	426			
Totalbiomass	Between Groups	16588.786	3	5529.595	84.742	.000
	Within Groups	27601.749	423	65.252		
	Total	44190.535	426			
AGBcarbon	Between Groups	1857.730	3	619.243	81.936	.000

	Within Groups	3196.894	423	7.558		
	Total	5054.624	426			
BGBcarbon	Between Groups	305.122	3	101.707	90.218	.000
	Within Groups	476.870	423	1.127		
	Total	781.992	426			
Totalbiomasscarbon	Between Groups	3664.463	3	1221.488	84.742	.000
	Within Groups	6097.226	423	14.414		
	Total	9761.689	426			
AGEstimatedbiomass	Between Groups	8171.318	3	2723.773	98.892	.000
	Within Groups	11650.605	423	27.543		
	Total	19821.923	426			
BGEstimatedbiomass	Between Groups	1366.551	3	455.517	102.480	.000
	Within Groups	1880.206	423	4.445		
	Total	3246.757	426			
TotalEstimatedbiomass	Between Groups	16204.267	3	5401.422	100.474	.000
	Within Groups	22740.122	423	53.759		
	Total	38944.389	426			
AGestimatedbiomass carbon	Between Groups	1805.044	3	601.681	98.892	.000

	Within Groups	2573.619	423	6.084		
	Total	4378.663	426			
BGestimatedbiomasscarbon	Between Groups	301.871	3	100.624	102.480	.000
	Within Groups	415.337	423	.982		
	Total	717.209	426			
Totalestimatedbiomasscarbon	Between Groups	3579.523	3	1193.174	100.474	.000
	Within Groups	5023.293	423	11.875		
	Total	8602.816	426			
MVtotalestimatedcarbon	Between Groups	18970896.941	3	6323632.314	100.474	.000
	Within Groups	26622649.286	423	62937.705		
	Total	45593546.227	426			
MVofTotalcarbon$	Between Groups	19421066.638	3	6473688.879	84.742	.000
	Within Groups	32314324.138	423	76393.201		
	Total	51735390.775	426			
Carbonaccumulation rate	Between Groups	112970.014	3	37656.671	65.596	.000
	Within Groups	242829.812	423	574.066		
	Total	355799.826	426			

One-Sample Kolmogorov-Smirnov Test

		LOGdbhcm
N		427
Normal Parameters[a,b]	Mean	.723112
	Std. Deviation	.1194043
Most Extreme Differences	Absolute	.034
	Positive	.023
	Negative	-.034
Test Statistic		.034
Asymp. Sig. (2-tailed)		.200[c,d]

a. Test distribution is Normal.

b. Calculated from data.

c. Lilliefors Significance Correction.

d. This is a lower bound of the true significance.