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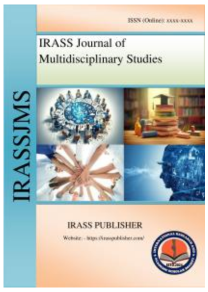

Methods For Assessment Biomass And Carbon Stock Of Tamarind Tree (Tamarindus Indica): A Comprehensive Review

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Abstract: Tamarindus indica L plays a pivotal role in enhancing Climate change resilience through its ability to sequester atmospheric carbon. Numerous studies have evaluated its carbon storage capabilities across various ecosystems, yet inconsistencies in estimation methods persist across different research papers. This study aimed to identify and compare these estimation techniques to reduce biases. Method of estimation Aboveground Biomass of tamarind trees by multiplying calculated trunk volume with the specific density of the trees was the most encountered. Some researchers have associated the shape of the tamarind trunk with cylinders and paraboloids for volume estimation. Specific equations for the species are available, especially in southwest Madagascar, while the pantropical equation by Chave et al 2009 is commonly used in forested areas. However, Soil Organic Carbon and the carbon assessment of Tamarind orchards are frequently neglected. Recommendations include utilizing Newton's volumetric formula or the Forest Survey of India's formula for stem volume estimation and creating orchard-specific equations. Future research should focus on advanced non-destructive techniques like remote sensing for Tamarind tree assessment.

Keywords: Allometric equations; Biomass ; Carbon stocks; Climate change; Tamarind tree

Abbreviations: AGB, Aboveground Biomass; Cc, Climate change; SOC, Soil Organic Carbon

Introduction

The 21st century faces the urgent challenge of climate change, driven significantly by human-induced global warming, primarily from fossil fuel (Dembele et al. 2023; Moundounga Mavouroulou et al. 2022; Ramamohan 2017; Nicolas, Matieu 2013). Forest ecosystems play a crucial role in sequestering atmospheric CO2, combating global warming (Dembele et al. 2023). Researchers worldwide evaluate woody species' carbon storage potential to meet requirements for assessing terrestrial carbon stocks, especially in implementing mechanisms like REDD+ (Moundounga Mavouroulou et al. 2022). There are two main methods for estimating tree biomass in different ecosystems: the first, known as destructive methods (Figure 1) and the second, known as non-destructive methods based on the first one (Nicolas et al. 2012). Non-destructive methods, including allometric/volumetric equations and remote sensing, offer effective ways to evaluate tree biomass while supporting sustainable forestry practices (Korra et al. 2021; Chave et al. 2014). These methods aid in environmental preservation and enable harmonization between biomass assessment and forestry operations, contributing to global efforts to mitigate climate change.

Trees outside forests play a significant role in national carbon sequestration efforts, especially pertinent in vulnerable arid and semi-arid ecosystems (Ranaivoson et al. 2015; Fayolle et al. 2013; Feldpausch et al. 2011). Tamarindus indica, a symbol of subtropical regions, has garnered attention for its substantial carbon storage potential (Ramamohan, 2017). Numerous studies worldwide have evaluated its contribution to carbon sequestration, highlighting its importance across Africa, Asia, and Latin America (Anil et al. 2021; Bhattacharya et al. 2020; Ranaivoson et al. 2015; Srinivasa Rao et al. 2012a; Srinivasa Rao et al. 2012b). Despite its decline in the wild due to overexploitation and slow regeneration, domestication programs aim to conserve and genetically improve the species (IPCC 2023; Amadou et al. 2020; Rebbas 2020- 2021; Abdillah, Bambang 2018; Bondé et al.

2017; Srinivasa Rao et al. 2012a). However, uncertainties persist in estimating Tamarind's biomass, echoing challenges in estimating biomass for various species (Korra et al. 2021; Chave et al. 2014). Despite these challenges, Tamarind's substantial carbon sequestration potential underscores its importance in climate change adaptation and resilience strategies worldwide.

This literature review aims to consolidate equations for estimating Tamarind biomass and carbon stocks across diverse ecosystems, including forest and non-forest areas. Previous studies have employed various methods for estimating Tamarind's carbon storage potential, yet these methods are scattered across different articles. By compiling equations used in previous research, this review seeks to reduce estimation biases and propose more accurate means of estimation for Tamarind biomass and carbon stocks in different ecosystems. Such a compilation would provide valuable insights for future studies and contribute to improving our understanding of Tamarind's role in carbon sequestration.

Materials and methods

Search strategy development and implementation and inclusion and exclusion criteria

First of all, relevant academic databases such as Google Scholar, PubMed, Web of Science, Elsevier, Scopus, Semantic Scholar and AGRICOLA were Identified and selected. Then, Keywords like "Tamarindus indica biomass measurement," "carbon sequestration in Tamarindus indica," "biomass estimation methods," "carbon stock evaluation," and "tamarind tree carbon reserves" were used. The documents consulted included peer-reviewed articles, conference papers, dissertations, and technical reports published between 5 and 10 years and downwards in exceptional cases. Studies not focused on Tamarindus indica, articles not in English, and those lacking empirical data were excluded (Gargaran et al. 2024).

Relevance assessment, data extraction and bias assessment

The selection and screening of articles involved a multi-step process. Initially, titles and abstracts were reviewed to identify studies relevant to the research objectives. This was followed by a full-text review of the selected articles to ensure they meet the inclusion criteria. Finally, a quality assessment was conducted for each study, evaluating factors such as the presence of Tamarind in the settlement table resulting from the inventories carried out by the researchers in the various articles, the existance of a method of estimation of biomass and the relevance to the research objectives, ensuring that only high-quality and pertinent studies were included in the review (Gargaran et al. 2024).

Data analysis

Data extraction and synthesis involved creating a data extraction sheet to gather key information from each study. The methods were then categorized into groups such as volumetric methods, allometric equations, and remote sensing techniques. Finally, these methods were analyzed based on factors like accuracy, ease of use, and adaptability to different environments, providing a comprehensive evaluation of each approach.

Results

Review of litterature

For several years now, a number of literature reviews have focused on the importance of the Tamarind tree worldwide. The most frequent are as follows:

• Origin and distribution of the species;

• Cultivation of the species (multiplication and germination, pest control);

• Use and socio-economic development of the species;

• Chemistry and photochemistry of the species;

• Pharmacological uses of the species.

The Tamarind tree, crucial in combatting climate change due to its carbon sequestration capacity, lacks a comprehensive literature review on methods for assessing its biomass and carbon stocks, despite its significant potential in this regard as highlighted in scientific research. The present literature review focuses on biomass and carbon stock assessment methods for different habitats, namely

• In Natural tropical Forest

• In Trees Outside Forest

A. Tamarind in natural tropical forests

A.1. Single-species allometric/volumetric equations

In a study by Babu et al. (2018) in the Southern Western Ghats, methods including species-specific and generalized volume equations, along with wood specific gravity data, were employed to evaluate Tamarindus indica biomass and carbon stocks. Regression equations were developed for trees with DBH < 10 cm, using basal area and stem biomass relationships (table 1). A shoot/root ratio of 0.26 and a conversion factor of 0.47 were applied to estimate below-ground biomass and carbon content, respectively.

A.2. Multi-species allometric/volumetric equations

Korra et al. (2021) assessed Tamarind tree biomass and carbon stock in Chintapalle Forest Range, utilizing DBH, tree height, and allometric equations (Table 2), with biomass calculated by a 120% multiplier and carbon stock using a 0.5 concentration factor. Soil carbon assessment indicated minimal organic levels, suggesting insignificant contribution to CO_2 sequestration.

Chave et al. (2014) aimed to improve Pantropical Aboveground Biomass Equations for tropical forests, developing new allometric models and evaluating associated uncertainty.

Fayolle et al. (2013) validated pantropical allometric equations for estimating biomass in Central Africa's forests, suggesting their applicability for precise carbon stock estimates.

B. Tamarind trees outside forest

B.1. Monospecific allometric/volumetric equations

Ranaivoson et al. (2015) investigated tamarind trees' distribution, biomass, and local importance in south-western Madagascar across diverse habitats in non-forest ecosystems. Their study utilized allometric and volumetric equations (Table 3) along with remote sensing to estimate wood biomass and assess carbon stocks in the region, providing valuable insights into the ecosystem's dynamics and carbon sequestration potential.

Bhattacharya et al. (2020) conducted a study along National Highway-27 in Guwahati, Assam, India, evaluating the biomass and carbon stocks of Tamarind trees using field measurements and established equations. They determined both aboveground and belowground biomass through Tamarind-specific allometric equations and assessed soil organic carbon (Table 3). Additionally, QGIS software was utilized to map tree carbon stock distribution along the highway.

Srinivasa Rao et al. (2012) examined above-ground standing biomass and carbon stocks of trees outside forests in Prakasam district, Andhra Pradesh, India, including Tamarind trees. They considered Tamarindus indica's presence in both linear and scattered structures and employed a non-destructive method for biomass and carbon stock evaluation using volumetric equations and specific wood densities (Table 3). Data were primarily sourced from the Forest Survey of India (FSI) reports and Reyes et al. (1992). Similarly, the authors conducted a similar assessment in Kadapa District, Andhra Pradesh, with variations in coefficients in the allometric relationships (Srinivasa Rao et al. 2012b).

In their study, Anil et al. (2021) assessed the carbon sequestration potential of roadside trees in Kamareddy municipality, Telangana, India. They aimed to determine the volume, biomass, carbon stocks, and sequestration potential of various tree species to inform climate change mitigation and urban planning efforts. Using systematic sampling, they estimated biomass and carbon stocks of tree species, including Tamarind, utilizing volumetric equations and specific gravity (Table 3).

Ramamohan et al. (2017) conducted a study to estimate the biomass and carbon stock of breeding trees, notably Tamarindus indica, in the Telineelapuram Bird Protected Area, India. Using non-destructive allometric equations and species-specific methods (Table 3), they determined total biomass and carbon stock, shedding light on these trees' contribution to carbon sequestration and biodiversity support in the region.

B.2. Multi-species allometric/volumetric equations

Abdilah, Bambang (2018) examined the economic value of the green line model for Tamarindus Indica in Rembang district, Indonesia, estimating biomass and carbon stocks using an allometric equation (Table 4), revealing a substantial carbon sequestration capacity of approximately 380,931 tons per hectare.

Srinivasa Rao et al. (2012a; 2012b) studied above-ground biomass and carbon stocks of trees outside forests in Prakasam district, Andhra Pradesh, using multispecific allometric relationships (Table 4) to assess Tamarind tree biomass and carbon stocks in sampled plots. The study also extended to Kadapa District, Andhra Pradesh, in the same year, establishing similar multispecific allometric relationships with different coefficients for biomass estimation.

Discussion

This literature review examines Tamarind biomass assessment via allometric equations, with both monospecific and multispecific equations applied in various ecosystems. Researchers predominantly use a common evaluation formula to estimate biomass, particularly in Trees Outside Forest, emphasizing the significance of standardized methodologies across environments (Dembele et al. 2023; Anil et al. 2021; Ranaivoson et al. 2015; Srinivasa Rao et al. 2012a; Srinivasa Rao et al. 2012b; Feldpausch et al. 2011; El-Siddig et al. 2006).

Above Ground Biomass = volume (m3) × Specific Gravity (kg m-2) (1)

Researchers commonly employ the volumetric equation from the Forest Survey of India (FSI) to estimate Tamarind volume, as detailed in the Indian Forest State of Report (IFSR). Additionally, specific gravity data for Tamarind trees are predominantly sourced from the Global allometric database (Dembele et al. 2023; Anil et al. 2021; Ranaivoson et al. 2015; Srinivasa Rao et al. 2012a; Srinivasa Rao et al. 2012b; Feldpausch et al. 2011).

GV = 0.16948-1.85075·D+10.63682·D2 (2)

Where, GV= generalized volume equation (m3); D: diameter at breast height (m).

However, other researchers assimilate the trunk of the Tamarind tree through the volume equations used to different geometric shapes , namely:

• The Cylinder (HUBER formula): V= Lbdxt; Lbd = [(diameter/100) x0.5]2 x Π (3)

Where Lbd: Broad base area; Π: Pi (3.14); t: height (m) (Abdillah, Bambang 2018).

• The paraboloid trunk (Smallian Formula)

V= π.L. (do2+ds2) / 8 (4)

Where V: tree volume (in cm3) L, d0 and ds represent respectively the length of the log, the diameter at the base section, and the diameter at the terminal section (top) (Ranaivoson et al. 2015).

It has been noted that no study has been focused until now on the general morphology of the trunk of the Tamarind tree. However, the review of the literature shows that independently of the general shape of the trunk, Newton's formula can evaluate the volume of trees without bias.

V=π.L. (do2+4dm2+ds2) / 24 (5)

Where L, d0, dm and ds represent respectively the length of the log, the diameter at the base section, the middle diameter and the diameter at the end section (top) (Rebbas 2020- 2021).

A specific equation for evaluating the biomass of the Tamarind tree was set up by (Ranaivoson et al. 2015) in the South West region of Madagascar and could be used for a better reduction of biases in biomass estimates in tropical ecosystems. Researchers using the conversion factor proposed by the Intergovernmental Panel on Climate Change (IPCC), which is applicable for many other forest species, evaluate the underground biomass of the Tamarind tree. This factor is 0.24 according to the following formula:

BGB= AGBx0.24 (6)

Where BGB is the belowground biomass, AGB is the aboveground biomass and 0.24 is the conversion factor (IPCC 2023).

Bhattacharya et al. (2020) used an equation to evaluate the underground biomass of Tamarind stems:

BGB= ¼ exp {- 1.059 + 0.884 ln (AGB) + 0.284} (7)

This review highlights the lack of soil biomass assessments in Tamarind ecosystems, emphasizing the need for future research in soil carbon stocks, particularly in Tamarind plantations. Remote sensing techniques, like QGIS software, were utilized for carbon stock mapping along National Highway-27. In forest environments, the pantropical allometric equation by Chave et al. (2014) is widely used for biomass assessment, while linear and scattered structures dominate discussions in non-forest environments. However, assessments of Tamarind trees in block structures, integral to trees outside forests, are lacking. Future research should consider exploring this aspect further.

Tables

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Table 1: Monospecific allometric/volumetric equations used for the estimation of Tamarind biomass in natural tropical forests by different authors. **AGB:** Aboveground biomass (AGB in kg or ton); W=green weight (kg or tone); **D:** diameter at breast height (in cm); GV= generalized volume equation (m3); ϱ= specific wood gravity

Phytogeography zone and types of vegetation	Spatial layout	Formulas and sources
Tropical dry forest of Southern Western Ghats, India	Scattered structure	**Allometric equation** • AGB = volume (m 3) × Specific Gravity (kg m 3) with **ϱ=** 0.960(Babu et al. 2018) **Volumetric equation** GV = 0.16948-1.85075·D+10.63682·D^2 (Babu et al. 2018; FSI 2019)

Table 2: Allometric/volumetric equations used for the estimation of Tamarind biomass in natural tropical forests by different authors. **AGB:** Aboveground biomass (AGB in kg or ton); W=green weight (kg or tone); **D**: diameter at breast height (in cm); **H:** total height (in m); GV= generalized volume equation (m^3); **ϱ=** specific wood gravity.

Phytogeography zone and types of vegetation	Spatial layout	Formulas and sources
Chintapalle Forest Range, Narsipatnam Division, Visakhapatnam, Andhra Pradesh, India	Scattered structure	**Allometric equation** • W = 0.25 × D^2 × H for trees with D ≤ 10 cm • W = 0.15 × D^2 × H for trees with D > 11 cm (Korra et al. 2021)
Tropical dry forest of Southern Western Ghats, India	Scattered structure	**Allometric equation** • **AGB** = volume (m 3) × Specific Gravity (kg m 3) with **ϱ=** 0.960(Babu et al. 2018) **Volumetric equation** GV = 0.16948-1.85075·D+10.63682·D^2 (Babu et al. 2018; FSI 2019)
Pantropical Forests	Scattered structure	**Allometric equation** • **AGB**= 0,0673x (ϱ $D^2H)^{0,976}$ ϱ =0,357; **AGB**= exp (-1,803 - 0,976x E + 0,976 x lnD + 2,673 x lnD - 0,0299 x $(lnD)^2$)(Chave et al. 2014) • **AGB**= exp (-1,822+ 2,337x lnD + 0,163x$(lnD)^2$ - 0,024 x $(lnD)^3$ + 0,979 x lnϷ (Fayolle et al. 2013) • **AGB**= exp (-2,2920 + 0,989 x ln(ϷD^2H))^2 (Feldpausch et al. 2011)

Table 3: Monospecific allometric/volumetric equations used for estimating Tamarind biomass in non-forest environments by different authors. **Ln:** natural Logarithm ; **B:** Dry biomass (y in Mg ha^{-1} and **B** in kg);; **DBH**: diameter at breast height (in cm); **H:** total height (in m); **R²:** coefficient of determination; **AdjR²**: adjusted coefficient of determination; **RMSE**: root mean square error; **FI:** Furnival Index; **CF**: correction factor; **CA**: crown area (in m^2); **V:** tree volume (in cm3) **L**: length of the log, the **d0**: diameter at the base section, ds: diameter at the end section (top).

Phytogeography zone and types of vegetation	Spatial layout	Formulas and sources
Mahafaly Plateau region, south-western Madagascar	Scattered structure	**Allometric equation** • **Ln B =**0.097+0.861(Ln DBH)^2- 0,094 (Ln DBH)^3 **R²** = 0.982; **AdjR²**= 0.981; **RMSE**= 0.188; **FI**=1.092; **CF**=1.019 • **Ln B =**4.378+0.336 (Ln CA)^2-0,031 (Ln CA)^3 **R²** = 0.723; **AdjR²**= 0.720; **RMSE**= 0.707; **FI**= 5.670; **CF**= 1.287 • **Ln B =** −7.193+ 1.002 LnV **R²** = 0.999; **AdjR²**= 0.999; **RMSE**= 0.052; **FI**= 0.261; **CF**= 1.002 **Smallian Formula of volume** **V** = π.L.(do2+ds2) / 8 (Ranaivoson et al. 2015)
Kadapa district of Andhra ,pradesh, india	Linear structure	**Allometric equation** AGB = volume (m 3) × Specific Gravity (kg m 3) **Volumetric equation of Tamarind tree** GV = 0.16948-1.85075·D+10.63682·D^2 (FSI, 2019; Srinivasa Rao et al. 2012b)
Prakasam district of Andhra pradesh, india	Linear structure	**Allometric equation** AGB = volume (m 3) × Specific Gravity (kg m 3) **Volumetric equation of Tamarind tree** GV = 0.16948-1.85075·D+10.63682·D^2 (FSI 2019; Srinivasa Rao et al. 2012a)
Road side standing trees in kamareddy municipality, telangana, india	Linear structure	**Allometric equation** AGB = volume (m 3) × Specific Gravity (kg m 3) **Volumetric equation of Tamarind tree** GV = 0.16948-1.85075·D+10.63682·D^2(Anil, Shyam, & Suryakiran, 2021) (FSI, 2019)
bio-edaphic ecosystem of National Highway-27 in Guwahati, Assam, India	Linear structure	**Allometric equation** • AGB = volume (m 3) × Specific Gravity (kg m 3) • BGB= ¼ exp {- 1.059 + 0.884 ln (AGB) + 0.284} (Bhattacharya et al. 2020) **Volumetric equation** GV = 0.16948-1.85075·D+10.63682·D^2 (FSI, 1996) (Bhattacharya et al. 2020)
Telineelapuram Bird Protected Area, an IBA Site; IN 229 India	Scattred structure	**Allometric equation** AGB = volume (m^3) × Specific Gravity (kg m^{-3}) **Volumetric equation of Tamarind tree** GV = 0.16948-1.85075·D+10.63682·D^2 (FSI 2019; Ramamohan 2017)

Table 4: Multi-species allometric/volumetric equations used for the estimation of Tamarind biomass in non-forest environments by different authors. **Y and B:** Dry biomass (y in Mg ha^{-1} and **B** in ton); **a** and **b** = Constanta; **X** basal area (m^2 ha^{-1}); **DBH**: diameter at breast height (in cm); **R²:** coefficient of determination; **Lbd**: Broad base area; Π: Pi (3.14); **t:** height (m); **AGB:** Aboveground biomass (AGB in kg or ton); BGB= Below Ground Biomass (AGB in kg or ton)**.**

Phytogeography zone and types of vegetation	Spatial layout	Formulas and sources
Kadapa district of Andhra ,pradesh, india	Linear structure	**Allometric equation** • **Y**=8.5457x-56.13; **R²** = 0.986 (Srinivasa Rao et al. 2012b)
Prakasam district of Andhra pradesh, india	Linear structure	**Allometric equation** • **Y**=3.1117x-1.9325; **R²**= 0.9518(Srinivasa Rao et al. 2012a)
Green Line Street Rembang District in indonesia	Linear structure	**Allometric equation** B = a (DBH) ^b ; a = 0,133 and b = 1,164 **Huber formula of trees volume** V= Lbdxt; Lbd = [(diameter/100) x0.5]^2 x Π(Abdillah, Bambang, 2018).

Figures

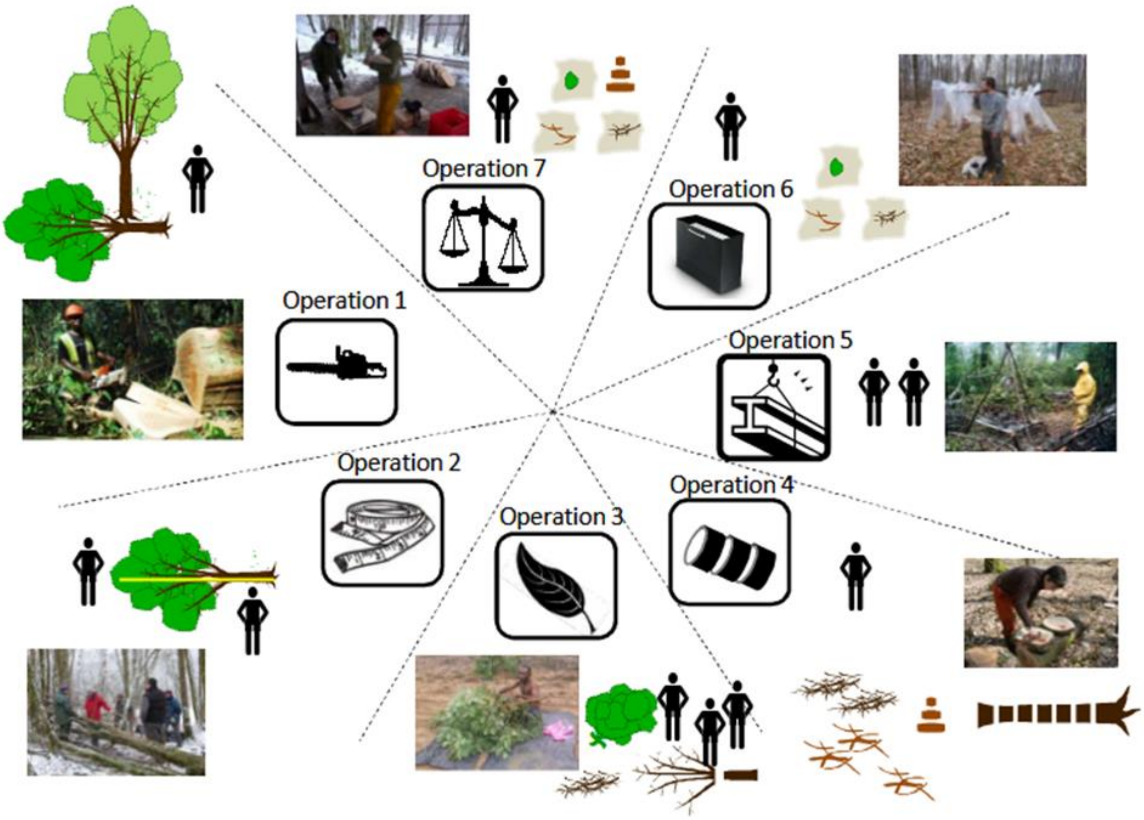

Figure 1: Organization of a biomass measurement site with 7 different operations.(Nicolas et al. 2012)

Figures legends

Figure 1: Operation 1, site preparation and felling of the trees ; operation 2, measurement of felled trees: stem profile, marking for cross-cutting; operation 3, stripping of leaves and limbing ; operation 4, cross-cutting into logs and disks ; operation 5, weighing of logs and brushwood ; operation 6, sampling of branches; operation 7, sample weighing area.

Conclusion and perspectives

In summary, accurately estimating Tamarind Tree biomass and carbon stocks is crucial for understanding its role in carbon sequestration and environmental conservation. This review addresses methodological challenges and consolidates existing research, providing Tables 1, 2, 3 and 4 summarizing allometric/volumetric equations used for evaluation. For non-forest environments, it is recommended to use the volumetric formula developed by the Forest Survey of India (FSI) or Newton's cubing formula for log volume assessment. The allometric equation specific to Tamarind in southwest Madagascar shows promise in reducing estimation biases, though local, regional, or national equations are preferred. As domestication programs expand, attention to dendrometric variations in Tamarind stands is essential, especially in orchards. Further exploration of remote sensing techniques can enhance biomass estimation, particularly in urban forestry extensions.

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