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Allometric Biomass Equations and Form Factor Determination for Four-Year-Old *Eucalyptus* Hybrid DH3229

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ABSTRACT

Effective inventory methods are crucial for managing short-rotation plantations. This study evaluates the aboveground biomass and morphometric characteristics of four-year-old *Eucalyptus* hybrid DH3229. We used a stratified random sampling method to destructively sample 30 trees from a low-maintenance terrain plot. Each sample was fractionated and weighed across fresh, air-dried, and oven-dried states. Results demonstrated that total biomass, particularly for the fresh weight equation, exhibited greater performance across all log positions compared to air-dry weight and oven-dry weight equations. Using Newton's formula as a volumetric benchmark, error analyses (Mean Bias Error, Root Mean Square Error, and Standard Deviation) confirmed the reliability of Smalian's, Huber's, and Bruce's formulas, with Huber's method consistently exhibiting the lowest error across all evaluated metrics and log intervals. An estimated empirical form factor was determined to be 0.579, surpassing the previously reported values for older age classes (6-9 years). These findings provide reliable, site-specific allometric equations and form factors for early-age short-rotation plantations.

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INTRODUCTION

Malaysia's hardwood resources have struggled to meet the increasing demand from the domestic wood processing sector. To reduce reliance on natural forests,

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extensive forest plantations are aggressively commercialised. Efforts to optimise wood production frequently prioritise species traits such as rapid growth, high timber yield, and pest resistance (Climent et al., 2024). *Eucalyptus* species are preferentially selected for reforestation due to their adaptability to tropical and subtropical climates, resilience to moisture stress, nutrient-poor soils, fire, and pests (Cookson & McCarthy, 2013; Ginwal, 2014). With the expanding interest in these species, a thorough understanding of their resource characteristics and end-use potential has become essential.

The harvest cycle for fast-growing species for solid timber production requires a period of six to nine years to reach optimal wood density (Hii et al., 2017; Taziwa, 2023). However, the growth pattern of *Eucalyptus* species shows that the Mean Annual Increment (MAI) peaks at three years of age and declines significantly in subsequent years (Harwood & Nambiar, 2014; Hung et al., 2015). This suggests the potential to meet the demand of medium-value product industries, such as packaging materials and finger-jointed laminated plywood, as early as four years of age.

Under tropical conditions (mean annual temperature: 26 °C; rainfall: 2500 mm), *Eucalyptus* hybrid (*E. urophylla* × *E. grandis*) exhibits 23% greater DBH $p< 0.05$ and an 18% increase in height (Yahya, 2020). Meanwhile, the survival rate was high (> 90%) compared to *E. pellita* (Zuhaidi et al., 2020). Productivity data from Sabah Softwood Berhad (5° N, 118° E) corroborated these findings, in which *E.* hybrid achieved 44% higher mean annual increment (39.7 versus 27.6 $m^3\ ha^{-1}\ yr^{-1}$ over a nine-year assessment period) (Japarudin et al., 2020). Despite extensive research on *Eucalyptus* at steady harvest ages (six to nine years), destructive biomass and volumetric data for early-stage tropical plantations remain limited.

Estimating tree aboveground biomass involves the allometric relationship between the biomass of whole trees (dependent variable), as well as readily measured parameters such as the diameter at breast height (DBH) and stem height (H), which serve as independent variables. Developing allometric equations with destructive biomass of a small number of trees by considering small and large tree sizes was preferable instead of mean-tree methods that require the harvesting of all planted trees in developing the equation (Chave et al., 2014; Fayolle et al., 2013; Komiyama et al., 2008).

Good precision of tree variables at the plot level can also be used to estimate individual tree volume by applying mathematical expressions, including Newton, Smalian, Huber and Bruce (Bruce, 1982; Husch et al., 2003). To overcome the overestimation or underestimation of volume estimation, a stem taper model is required in predicting changes in the volume in stem form from the ground to the tip, and a form factor that adjusts the volume of a cylinder to match the actual tree form (Silva et al., 1994; Tenzin et al., 2017).

While traditional biomass determination incorporates multiple secondary variables such as total height and crown distribution, these measurements are often time-consuming, expensive, and less critical for uniform, even-aged monoculture plantations. To maximise operational efficiency, this study used the DBH parameter as the sole predictive variable. The specific objectives of this study were to: (1) develop species-specific, DBH-driven allometric equations for aboveground biomass components, and (2) preliminarily determine the form factor and evaluate the accuracy of the standard volume formula.

MATERIALS AND METHODS

Study Site

Four-year-old *E. hybrid* DH3229 trees were selected randomly from a plantation at Mustafa Bubjee College (2.9783° N, 101.7156° E, 54 m a.s.l), planted at a spacing of 1.0 m × 1.5 m. The plot was established on sloped terrain (22.4°) within a university campus and maintained under low-intensity silvicultural conditions. The site received annual rainfall (2,000 - 2,500 mm) without artificial irrigation. Weed interference was managed with regular manual slashing, and no intensive routine of commercial fertilisation was applied post-establishment, closely reflecting the actual smallholder agroforestry and degraded land rehabilitation practices.

Field Sampling and Laboratory Preparation

Destructive sampling procedures were adopted from Doruska et al. (2006), Abdul-Hamid et al. (2022), and Hossain et al. (2023). Tree diameter was measured at DBH approximately 1.3 m above the ground using the Forestry Suppliers Metric Fabric Diameter Tape (Model 283D/10M, Jackson, MS, USA). To guarantee that the samples accurately reflected the stand's distribution, a stratified random sampling approach was used to select 30 standing trees (DBH: 8.10 cm to 12.50 cm). In uniform, even-aged plantation settings, a destructive sample size of 30 trees is statistically robust for establishing preliminary species-specific allometric baselines and form factors. To evaluate potential biological shifts in biomass allocation as trees surpass the stand's mean diameter (~10 cm), the harvested samples were deliberately stratified into two equal classes: DBH ≤10 cm (n=15) and DBH >10 cm (n=15).

The fresh weight of each component (stems, leaves, and branches) from the 30 destructive trees was measured in situ using a digital scale (Model 150 kg/ 200 kg Proace Electronic Scale) (Figure 1). For all trunk sample trees, the trunk diameter was measured at the lower, middle, and upper part of the log that was cut from ground level in the following lengths: 0-0.3 m, 0.3-1.3 m, 3.3-5.3 m and then every 2 m length. Thereafter, 500 g of the fresh weight of each part was taken to the laboratory. To determine air-dry weight (ADW), the samples were stored in a well-ventilated, shaded room at ambient tropical temperatures and weighed periodically until equilibrium moisture content was reached (constant weight). Subsequently, to determine the absolute oven-dry weight (ODW), the samples were dried in a laboratory oven at 70 °C for 15 days until a strict constant weight was attained, ensuring complete moisture removal.

Figure 1. The diameter and fresh weight at the specified trunk length were collected, and samples were cut into a disc shape, approximately 2 to 3 cm thick and weighed *in situ*

Biomass Estimation

The biomass of each component was calculated by (Eq. 1):

$$B = M_{Fre} \times \left(\frac{M_{sam,Dry}}{M_{sam,Fre}}\right) \quad [1]$$

where M_{Fre} is the fresh mass of each component, and $M_{sam,\ Dry}$ and $M_{sam,\ Fre}$ are the dry mass and fresh mass of the samples of each component, respectively. The total aboveground biomass was obtained by summing the biomasses of each component.

Volume and Form Factor Estimation

The observed tree volume was calculated using Newton's formula (Eq. 2) (Husch et al., 2003);

$$V_i = \left(\frac{1}{6}\right) \times f \times L \times ({d^2}_A + 4{d^2}_M + {d^2}_B) \quad [2]$$

where;
V_i = Log volume at $_i$th (m^3)
L = Length of log (m)
f = 0.00007854 (metric units)
d_A = Diameter at the small log end (cm)
d_B = Diameter at the large log end (cm)
d_M = Diameter at the mid-length log end (cm)

Meanwhile, for predicted volume, various methods have been explored in estimating log volume, with log formulas being among the most used due to their straightforward application with available datasets that include one or two measurements of log diameter (Mushar et al., 2020). We selected three commonly used volume formulas to obtain the necessary coefficients for volume calculations, ensuring accuracy and relevance to our study. The statistical analyses were performed using SPSS. We employed nonlinear regression models at the 5% significance level to compute each equation. For our study, we specifically considered Smalian's (Husch et al., 2003), Huber's (Husch et al., 2003), and Bruce's formula (Bruce, 1982) (Table 1).

Table 1
Predicted volume estimation by using Smalian's, Huber's and Bruce's formulas by using a statistical method for different log sectional lengths

Volume Formula	Equations	
Smalian	$V_i = \left(\frac{1}{2}\right) \times L \times (d^2{}_A + d^2{}_B)$	[3]
Huber	$V_i = f \times L \times (d^2{}_M)$	[4]
Bruce	$V_i = f \times L \times [0.25\ (d^2{}_B) + 0.75\ (d^2{}_A)]$	[5]

Note. Vi = log volume at i^{th} (m^3), L = length of log (m), f = 0.00007854 (metric units), d_A = diameter at the small log end (cm), d_B = diameter at the large log end (cm), and d_M = diameter at the mid-length log end (cm)

The observed tree volumes calculated using Newton's formula were then applied to the real form factor. We calculated the real form factor value for each tree sample using the given formula in Eqs. 6 and 7:

$$\mathrm{FF} = \frac{V_{sum\ of\ logs}}{BA * Total\ Height} \quad [6]$$

$$\mathrm{B}A = \frac{\pi\ \times \mathrm{DBH}^2}{40{,}000} \quad [7]$$

The volume (V) of the tree is measured in m^3, calculated using Equation (1), where BA is the basal area of the tree (DBH) measured in cm, H is the total tree height measured in meters (m), and FF represents the form factors of a tree. 40,000 for denominators was used to convert the DBH from cm to square meters for the basal area, which can be summarised as $0.00007854 \times \mathrm{DBH}^2$.

Accuracy Assessment

The volume estimates derived from Smalian's, Huber's, and Bruce's formulas were evaluated in comparison to the reference tree volumes calculated using Newton's formula. To avoid a logical fallacy, Newton's formula was strictly employed as the benchmark "observed" volume and was not evaluated for predictive error. Meanwhile, the three predictive formulas' performance was assessed using three standard statistical metrics: Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Standard Deviation (SD).

The Mean Bias Error (MBE) estimates the average systematic error between the predicted and observed values. A positive MBE indicates an overestimation, while a negative MBE indicates an underestimation. It is calculated using Eq. 8:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(V_{pred,i} - V_{obs,i}\right) \quad [8]$$

The Root Mean Square Error (RMSE) evaluates the overall predictive accuracy by measuring the magnitude of the errors. Lower RMSE values indicate improved model performance. It is calculated using Eq. 9;

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(V_{pred,i} - V_{obs,i}\right)^2} \quad [9]$$

At the end of the accuracy assessment, the Standard Deviation (SD) of the errors was calculated to assess the precision of the models, indicating how widely the prediction errors are dispersed around the mean error. It is calculated using Eq. 10;

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(E_i - MBE)^2}{n-1}} \quad [10]$$

where $V_{pred,i}$ is the predicted log volume utilising Smalian's, Huber's or Bruce's formulas (m^3), $V_{obs,i}$ is the observed log volume utilising Newton's formula (m^3), E_i is the individual estimation error ($V_{pred,i} - V_{obs,i}$) and n is the total number of log samples.

Statistical Analysis

For the differences in biomass accumulation between the two size classes (DBH ≤10 cm and DBH >10 cm), an Independent Samples T-Test was conducted using IBM SPSS Statistics software (version 25.0; IBM Corp., Armonk, NY, USA). The relationships of three independent and dependent variables (DBH, total height, and biomass components) were examined using Pearson's correlation analysis. Further, non-linear regression models were projected at a 5% significance level to obtain the species-specific allometric equations ($Y = aD^b$) and volume estimation coefficients. Significance levels were set at $p < 0.05$ for statistically significant differences and $p < 0.001$ for highly significant differences.

RESULTS

Overview of the Destructive Samples

The *E.* hybrid DH3229 trees sampled in this study presented a wide range of characteristics. The average DBH was 10.07 cm, with values ranging from a minimum of 8.10 cm to a maximum of 12.50 cm. Similarly, the average tree height was 12.13 m, with the smallest tree measuring 8.80 m and the tallest 15.10 m (Table 2). Figure 2 illustrates the relationship between DBH and total tree height for the 30 sampled *E.* hybrid DH3229 trees, which were assessed for aboveground biomass, real tree volume, predicted volume and form factor determination. The coefficient of determination ($R^2 = 0.097$) indicates a weak correlation between DBH and tree height, suggesting high variability in height growth within this DBH range.

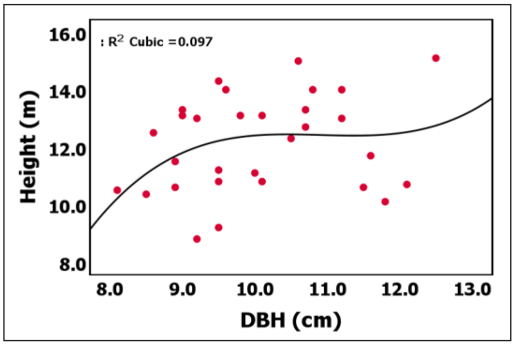

Figure 2. The relationship of tree height and tree diameter at breast height (DBH) for the 30 sampled trees

Table 2
Characteristics of 30 destructive sample trees of four years of Eucalyptus hybrid DH3229

Variable	Sum	Mean	Min	Median	Max	Std.
No. of tree	30	-	-	-	-	-
Height (m)	-	12.13	8.80	12.40	15.10	1.683
DBH (cm)	-	10.07	8.10	9.90	12.50	1.150
Total Volume (m^3)	1.751	0.058	0.030	0.056	0.101	0.018

Biomass Estimation

The independent-sample *t*-test revealed substantial mean differences in biomass accumulation between the two diameter classes (≤10 cm versus >10 cm) (Table 3). For instance, for oven-dry weight of full height (ODWFH), the larger tree class yielded a mean biomass of 35.32 ± 2.51 kg compared to the smaller class averaging only 19.97 ± 1.34 kg. This represents an absolute mean difference of 15.35 kg of solid dry wood per tree. This allocation pattern stays consistent for the fresh weight of full height (FWFH), where the larger diameter class achieved a mean weight of 67.48 ± 3.00 kg, compared to 44.10 ± 2.32 kg in the smaller class, resulting in a mean difference of 23.38 kg.

Table 3
Independence t-test of tree at DBH ≤ 10 cm and DBH >10 cm for fresh weight, air-dry weight and oven-dry weight states

Components	**Mean ± SD (≤ 10 cm, *n* =15)**	**Mean ± SD (> 10 cm, *n* = 15)**	**Mean Diff.**	***t***	***df***	***p***
FH (m)	11.75 ± 1.71	12.50 ± 1.62	0.75	-1.23	28	0.230
DBH (cm)	9.12 ± 0.47	11.03 ± 0.76	1.91	-8.28	23.42	< 0.001
FWFH (kg)	44.10 ± 9.02	67.48 ± 11.64	23.38	-5.08	28	< 0.001
ADWFH (kg)	23.30 ± 5.79	40.56 ± 11.81	17.26	-5.38	20.36	< 0.001
ODWFH (kg)	19.97 ± 5.21	35.32 ± 9.73	15.35	-6.12	21.40	< 0.001
FWMH (kg)	42.23 ± 8.94	64.69 ± 11.06	22.46	-5.00	28	< 0.001
ADWMH (kg)	21.41 ± 6.07	38.46 ± 11.73	17.05	-5.07	21	< 0.001
ODWMH (kg)	18.74 ± 5.38	33.47 ± 9.9	14.73	-2.13	21.60	< 0.001
FWL (kg)	3.86 ± 0.86	4.62 ± 1.09	0.76	-3.9	28	0.040
ADWL (kg)	1.98 ± 0.53	2.96 ± 0.81	0.98	-3.48	28	< 0.001
ODWL (kg)	1.73 ± 0.55	2.67 ± 0.89	0.94	-3.27	28	< 0.001
FWB (kg)	6.04 ± 1.94	9.72 ± 3.9	3.68	-2.27	28	0.030
ADWB (kg)	4.43 ± 1.59	6.88 ± 3.88	2.45	-2.18	28	0.040
ODWB (kg)	3.85 ± 1.53	6.00 ± 3.49	2.15	-6.15	28	< 0.001
TCFW	54.00 ± 9.25	81.82 ± 13.88	27.82	-6.46	28	< 0.001
TCADW	33.20 ± 6.25	54.90 ± 14.06	21.70	-5.46	19.32	< 0.001
TCODW	25.56 ± 5.43	43.99 ± 11.69	18.43	-5.54	19.77	< 0.001

Note. DBH = diameter at breast height, FH = full height, MH = merchantable height, FW = fresh weight, ADW = air-dry weight, ODW = oven-dry weight, L = leaves, B = branches, TC = total components

In contrast, relatively small variability was found in the canopy components. Fresh weight of leaves (FWL) showed a much smaller mean difference of only 0.76 kg between two diameter classes, showing that diameter changes heavily influence main stem expansion rather than canopy development.

Regardless of diameter class, the correlation between DBH and FW for total aboveground biomass ($R^2 = 0.86$) and its individual components were consistently stronger than that for their corresponding ADW and ODW. Among all tree components, the pooled aboveground biomass exhibited the highest coefficient of determination, indicating a highly robust relationship with overall biomass accumulation. In contrast, the leaf component yielded the lowest R^2 value (0.39 - 0.47), reflecting a higher natural variability in canopy foliage compared to the more predictable accumulation of woody stem biomass (Figure 3).

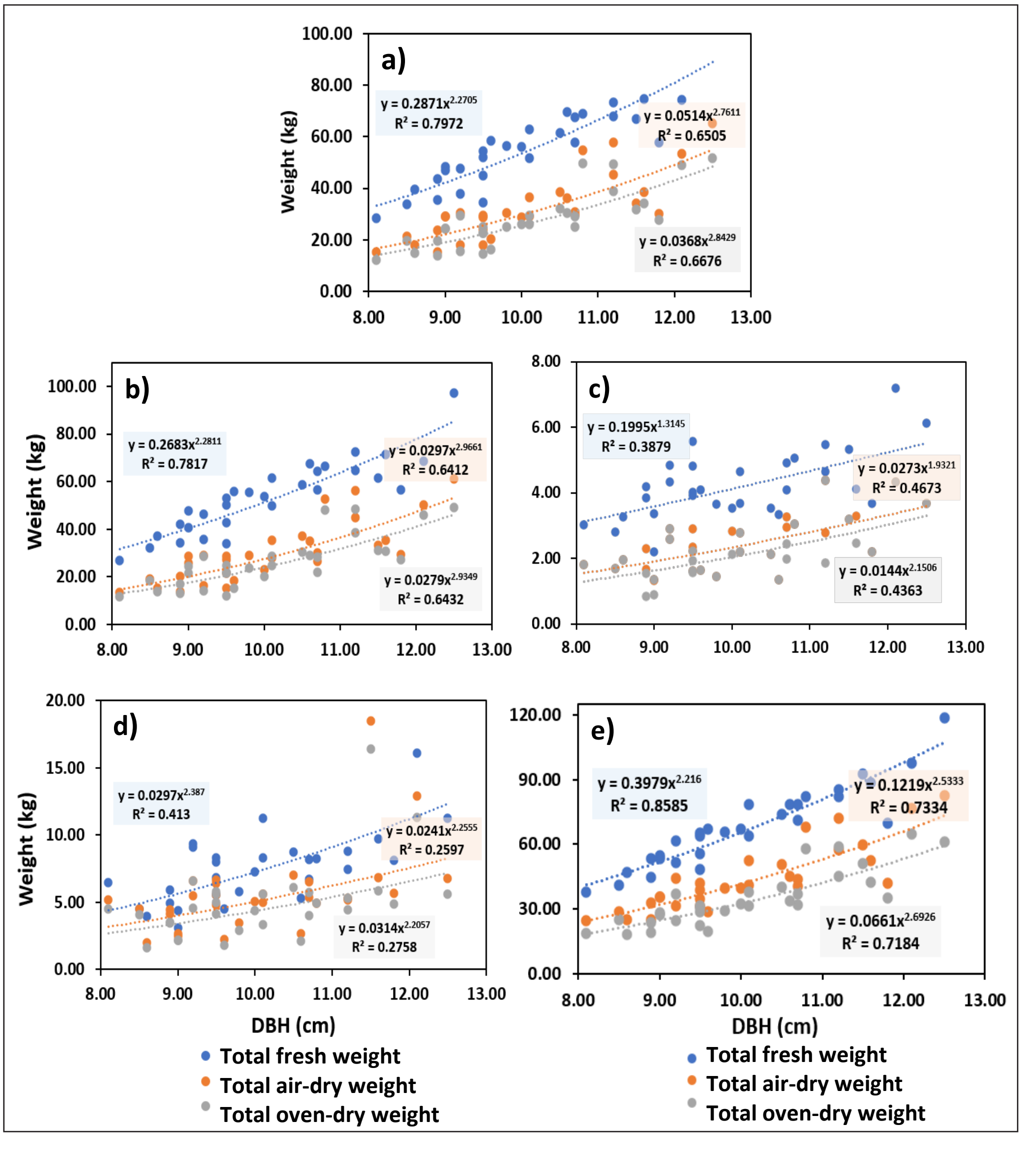

Figure 3. Relationship between diameter at breast height (DBH) and fresh, air-dry, and oven-dry weights for: a) full height logs, b) merchantable height logs, c) leaves, d) branches, and e) total aboveground biomass

Allometric Equation by Log Position

Figure 4 illustrates the relationship between the exponent (b) and the coefficient of determination (R^2) across different hydration states (FW, ADW and ODW) as well as log positions (top, middle and bottom) for FH and MH. The scatter plot reveals three distinct groups based on their b value and R^2 values. The top log in the FW state expresses a high b value and R^2 value, suggesting a well-defined relationship between DBH and biomass.

Nonetheless, the top log expresses the lowest *b* values (1.42-2.09) and weak correlations (R^2 = 0.18-0.33) at the ADW and ODW states.

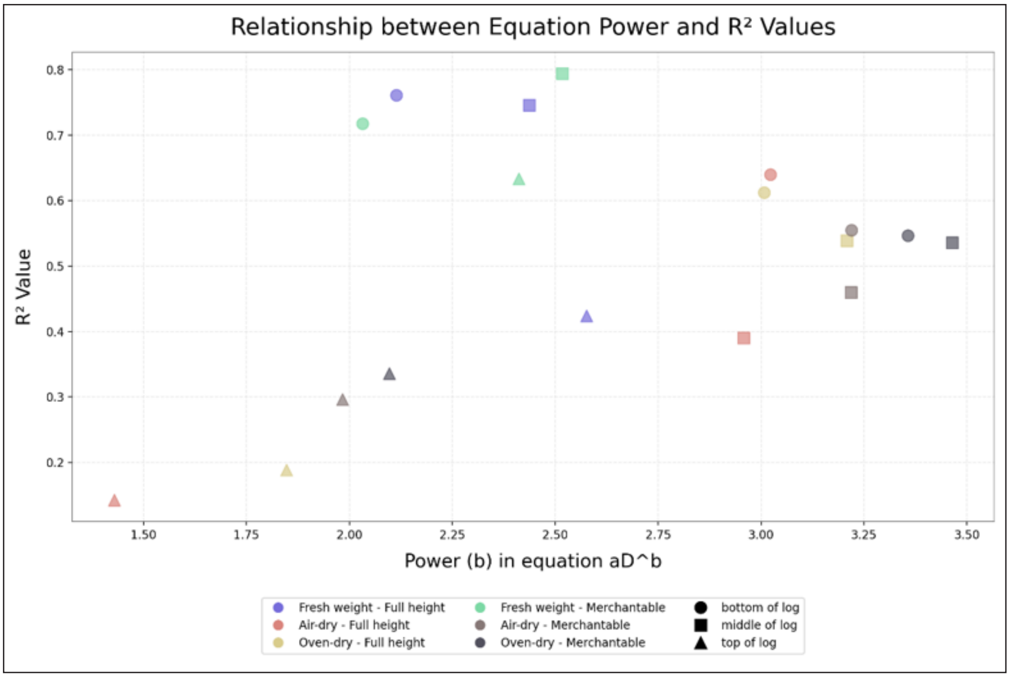

Figure 4. The relationship between the exponent (*b*) and the coefficient of determination (R^2) across different hydration states (fresh, air-dry, oven-dry) and log positions (top, middle, bottom)

Note. Each point is annotated with its corresponding equation value, and different colours and markers indicate the measurement type and position on the log

In contrast, the middle and bottom log sections exhibited a steadier distribution. Moderate *b* values (2.03-2.51) with moderate correlation (R^2= 0.63 - 0.79) for the FW state suggested a more consistent relationship between DBH and biomass. For ADW and ODW states, similar log positions showed the highest *b* values (2.95-3.35) with moderate correlations (R^2= 0.39 - 0.63), suggesting that biomass allocation in these sections is more predictable. Regardless of biomass allocation or log position, the allometric exponent (b>1) reliably exhibits a positive allometric relationship.

Volume for Log Interval and Form Factor Estimation

Newton's formula was adopted to establish an accurate baseline for the observed volume, involving the determination of independent tree variables (DBH and total height). The log volume and log length formed a clear sigmoidal relationship, reflecting the tree's tapering profile and specific wood allocation. The observed and predicted values fit the data well. Smalian's formula obtained the highest R^2(0.771) followed by Newton's (0.770), Huber's

(0.769) and Bruce's (0.759) (Figure 5). Meanwhile, Huber's formula was found to be the most accurate formula, confirmed by the lowest error estimates (Table 4). Specifically, Huber's Mean Bias Error (MBE) and Root Mean Square Error (RMSE) ranged from a minimal magnitude of 10^{-7} m^3 for the lower 0.3 m log intervals to a maximum of 10^{-4} m^3 for the highest log intervals (≥11.3 m).

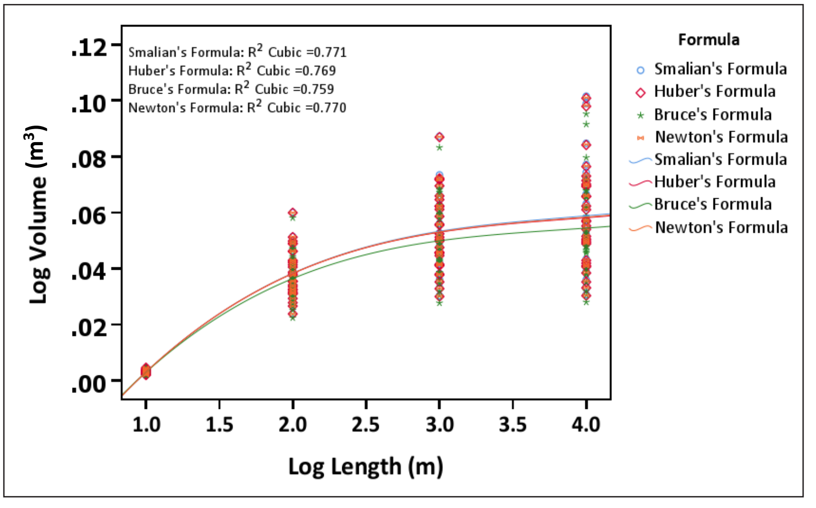

Figure 5. Predicted log volume against log length using Smalian's, Huber's, and Bruce's formulas

Table 4
Statistics of fit of the volume equations tested for 4-year-old Eucalyptus hybrid DH3229

Log Interval/ Formula	**MBE (m^3)**	**RMSE (m^3)**	**SD (m^3)**
0.3 m log interval			
Smalian	-6.10×10^{-7}	6.14×10^{-7}	6.97×10^{-8}
Huber	3.05×10^{-7}	3.07×10^{-7}	3.49×10^{-8}
Bruce	5.17×10^{-5}	5.20×10^{-5}	6.06×10^{-6}
≤ 5.3 m log interval			
Smalian	-7.53×10^{-5}	8.20×10^{-5}	3.32×10^{-5}
Huber	3.76×10^{-5}	4.10×10^{-5}	1.66×10^{-5}
Bruce	1.82×10^{-3}	1.86×10^{-3}	4.13×10^{-4}
9.3 m log interval			
Smalian	-2.29×10^{-4}	2.75×10^{-4}	1.54×10^{-4}
Huber	1.14×10^{-4}	1.37×10^{-4}	7.72×10^{-5}
Bruce	3.16×10^{-3}	3.22×10^{-3}	6.37×10^{-4}
≥ 11.3 m log interval			
Smalian	-4.43×10^{-4}	4.67×10^{-4}	1.52×10^{-4}
Huber	2.22×10^{-4}	2.34×10^{-4}	7.62×10^{-5}
Bruce	3.83×10^{-3}	3.91×10^{-3}	7.88×10^{-4}

The form factor of the individual tree for four-year-old *E.* hybrid DH3229 remained relatively stable across the sampled diameter range (8.10 cm to 12.50 cm). The analysis yielded a mean form factor of 0.579 ± 0.043, with values ranging from 0.480 to 0.704 (Figure 6).

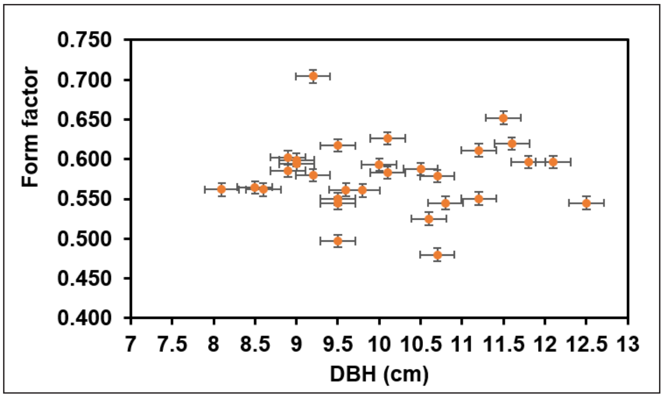

Figure 6. Tree individual form factors and diameter at breast height (DBH) relationships for 30 destructively sampled four-year-old *Eucalyptus* hybrid DH3229 trees

DISCUSSIONS

Biomass Estimation and Hydration Dynamics of *Eucalyptus* Hybrid DH3229

Topographical conditions and low-maintenance silviculture of the study site suggested the weak correlation observed between DBH and total tree height (R^2 = 0.097). Caldeira et al. (2023) studied the mean basal area of 3.5-year-old *Eucalyptus* trees were higher (35 $m^2 ha^{-1}$) at the bottom of the slope compared to the trees at the top of the slope (27 $m^2 ha^{-1}$). A higher significant correlation was found between the DBH variable and volume (r = 0.92, p < 0.001) than those between the H variable and volume (r = 0.82, p < 0.001) at four years of age of *Eucalyptus* hybrid was also reported by Wu et al. (2011). This high variability in height growth justifies relying on the DBH variable in biomass prediction.

While a sample size of 30 trees represents a structural limitation, normal distribution of DBH range and the highly robust coefficient of determination (R^2= 0.86) for total aboveground fresh biomass, confirming the sufficiency of sample size to capture stable allometric relationships. This approach is well-supported by a previous study by Abdul-Hamid et al. (2022), which successfully developed a single-variable DBH allometric equation for a natural mangrove forest by destructively harvesting 15 tree samples, yielding R^2= 0.9892 when validated to 1000 stand data trees.

Aboveground biomass of trees with DBH >10 cm exhibited approximately twice as high than those with DBH ≤10 cm. Although fast-growing species prioritise vertical development over horizontal expansion, larger tree diameter still accumulates greater biomass due to allometric relationships in tree volume, which is influenced by both diameter and height (Abdul-Hamid et al., 2022). Wu et al. (2011) reported that 19 hybrids of *Eucalyptus* exhibited different growth traits and wood properties between clones and sites in China. The exponential scaling between diameter and biomass renders DBH a more influential factor in biomass accumulation than height (Mohamad Ismail et al., 2020).

Small variation between FW, ADW, and ODW at full height (FH; R^2 = 0.7972) and merchantable height (MH; R^2= 0.7817) observed were attributed to the canopy development and non-merchantable stem tip (Abiri et al., 2020; Wirabuana et al., 2021). The insignificant R^2 values observed between FH and MH suggest only a slight increment in biomass of the highly tapered upper log of FH. These findings emphasise that stem taper remains a relevant factor to consider in biomass estimation for both upper and lower logs, even in fast-growing species like *Eucalyptus*.

The FW models demonstrated greater performance ($R^2 \approx$ 0.80) across all log positions compared to ADW and ODW weight models. In its fresh state, the measurement was done under highly controlled, uniform conditions (same age, same day, same site), which minimises the moisture variation and sample deterioration. Zhuang et al. (2024) studied the effects of water treatment on plant growth and reported R^2 values of 0.95 and 0.98 for two power functions used to establish allometric equations. On the contrary, the ADW exhibited a 32%-38% reduction compared to FW, while ODW declined progressively, exhibiting a 46%-52% reduction from FW and a 20%-24% reduction from ADW.

Allometric Equation Using aD^b for Top, Middle, and Bottom Parts of the Log

The drying process revealed distinct positional fluctuations in model accuracy. Despite moderate R^2 values (0.60 - 0.70) of middle and bottom logs in the dried states, the top log predictability declined significantly. This positional variance is further supported by the allometric exponents (b). The b value consistently demonstrated positive allometry ($b > 1$) across all measurements, but the lowest b value was yielded in the top log sections for both dried models. This reveals the stem taper effect, where progressive diameter reduction resulted in minimised biomass allocation in apical regions (Poorter et al., 2012), whilst highest b values confirmed primary biomass allocation to the lower stem segments.

Intrinsically, the dried models explained only ≤60% of biomass variation, implying that predictability is influenced by physiological, environmental and anatomical factors, including wood density, age-related and position-specific moisture dynamics during drying (Elustondo et al., 2023; Khan et al., 2025; Ribeiro et al., 2015). Top logs contain younger, less lignified tissue with predominant sapwood (characterised by higher initial moisture content), while middle and bottom logs feature greater proportions of dense heartwood with lower initial moisture content (Ren et al., 2023). This structural gradient creates non-uniform drying responses, with top logs undergoing more substantial physical transformations during moisture loss, thereby reducing the stability of dry-weight predictions compared to the more robust FW estimates.

Eucalyptus Hybrid Volume and Form Factor Estimation

The sigmoidal relationship between log volume and log length highlights progressive volumetric changes, attributable to tree tapering. Despite the high sensitivity of Smalian's formula for shorter logs (0.3-5.3 m), it consistently underestimated volumes as the log position approached the canopy due to its inability to capture pronounced stem taper. In contrast, as stem taper became more pronounced, Huber's formula maintained consistent accuracy with minimal error, thereby minimising bias in whole-stem volume estimates. Particularly, the RMSE and SD by Huber's formula demonstrated higher precision than values reported by Hernández-Ramos et al. (2017) for *E. urophylla*. This indicates a substantial methodological improvement in volume prediction accuracy and consistency across log positions.

The current study sufficiently quantified the aboveground biomass and a reliable preliminary form factor for four-year-old *E.* hybrid. Based on the integration of 30 destructively sampled trees, real volume estimation employing Newton's formula resulted in a form factor of 0.579, surpassing the values reported in earlier studies. Corresponding studies for older (five- to nine-year-old) and larger DBH classes of *Eucalyptus* species by Japarudin et al. (2020) recorded form factors for *E. grandis*, *E. pellita*, *E. urophylla* and *E*. hybrid were in the range 0.365 to 0.379 in Asia while 0.466 was reported in Africa (Gezahagn et al., 2020). This disparity primarily reflects the differences in tree age and diameter ranges, emphasising the importance of age-specific quantification; younger, fast-growing trees possess different stem tapers and volume distributions before reaching optimal mature wood density (Curvo et al., 2024).

Study Limitation and Scope of Application

While this study provides valuable baseline allometric equations and empirical form factors for early-age *Eucalyptus* hybrid DH3229, there are methodological constraints inherent to the experiment design that must be addressed. First and foremost, the destructive sampling was based on a sample size of 30 trees harvested from a single plantation site. While a sample size of 30 trees spanning a stratified diameter range is practically sufficient for developing preliminary site-specific models, it intrinsically limits the broader statistical generalizability of the findings.

Furthermore, it is important to consider that the sampling was restricted to a single age class (four years old) under a low-intensity silvicultural management regime on sloped terrain. Consequently, the mathematical relationships and form factors determined here reflect the specific growth dynamics, site quality, and microclimate of this study area. Therefore, these findings underscore the need for circumspection when applying these models to different geographic regions, varied silvicultural regimes, or older age classes. Although independent field validation across multiple sites was beyond the scope of the present study, empirical validation and testing across broader environmental gradients are strongly recommended before these models are employed as exploratory references for operational forest inventory or commercial yield projections in other settings.

CONCLUSION

Precise tree height measurements continue to present operational challenges. This study provides foundational information for early-age *Eucalyptus* hybrid DH3229 trees, showing that diameter at breast height (DBH) is the primary driver of biomass allocation, and that accurate biomass determination was obtained when measurements were taken in the fresh state. Even though the empirical form factor derived in this study is higher than those reported in previous studies, this finding emphasises the necessity of age- and site-specific quantification when developing mathematical expressions.

RECOMMENDATIONS

Future research should utilise a larger sample size and extend the study sites to encompass a wider array of geographical locations and early-age sequences (e.g., 2-5 years old) to refine these models. This will help clarify the developmental shifts in empirical form factors prior to rotation maturity. Furthermore, future studies should incorporate wood density variables and develop component-specific equations. This framework will reduce uncertainty in allometric relationships, offering reliable tools for short-rotation plantation inventory.

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