ALLOMETRIC MODELS FOR VOLUME ESTIMATION OF RED CEDAR (*TOONA CILIATA* M. ROEM.) IN THE NORTHWESTERN HIMALAYAS OF INDIA

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Abstract. Allometric equations are often applied to estimate volume and carbon stocks of forest ecosystems. This study focused on formulating or developing allometric equations or models for estimating the volume of standing *Toona ciliata* M. Roem. trees in the red cedar woodlands of Northwestern Himalayas of India. Despite rich floral diversity, there has been a scarcity of such equations for this region. The research involved sampling and measuring 100 red cedar trees across four sites. Dendrometric variables were then measured for each site to create models based on height, diameter at breast height (DBH), and form factor as predictor variables. This work underscores the importance of allometric equations in accurately assessing the volume of red cedar woodlands, as they consider factors like vegetation type, management practices, and environmental conditions. The findings will enhance our grasp of allometric equations and contribute to the development of tools for forest planners, farmers, and researchers, enabling precise prediction of forest resources in terms of volume. This will, in turn, support effective management strategies for red cedar woodlands in the Northwestern Himalayas and similar ecosystems worldwide.

Keywords: *carbon stocks, dendrometric variables, forest ecosystems, prediction, wood*

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Introduction

Allometric equations/models are extensively employed for estimating volume (Chen et al., 2023) and forest carbon stocks (Lima et al., 2017). Precise estimates of woodlands are pivotal for monitoring environmental processes such as nutrient cycling, wood production (Conti et al., 2013) and sustainable forest management (Wang et al., 2006). The volume of a tree can be estimated using a variety of techniques; some are general while others comprise allometric equations that are specific to site and species (Cifuentes et al., 2015). Despite being used extensively, general allometric equations might not be capable of predicting local volume accurately owing to variations in the architecture of the tree viz. stems, age, height, stand density, diameter, site conditions (climate and soils), cultivar, and management practices (Kaonga et al., 2010; Paul et al., 2016). Allometric models are less biased compared to the general models (Feyisa et al., 2018) owing to the effects on tree growth characteristics from the local climate, altitude, soil properties, and land-use history (Yuen et al., 2016). Majority of the formerly formulated allometric equations proved to be costly and time-consuming when implemented across wide strata of woodland owing to the destructive methods involved (Augusto et al., 2003; Roxburgh et al., 2015). In order to make informed decisions it is required to develop models that are site and species-specific along with assessing the aptness of existing allometric equations in order to achieve accurate volume estimation (Chisholm et al., 2023). Numerous allometric equations have been claimed to be suitable for red cedar worldwide. However, owing to the high biological diversity of the Northwestern Himalayas, it is hard to employ a ‘one-fits-all’ model. Despite having high ecological and economic value, the red cedar woodlands in particular in the Northwestern Himalayas have received little attention in terms of formulating species specific allometric models for precise forest volume estimation (Dhanda and Verma, 2001).

Toona ciliata M. Roem. (Red cedar) is a member of the Meliaceae family that can grow up to 40 m in the wild (Dassanayake et al., 1980). *T. ciliata* has the broadest range among the four toona species (Hua et al., 2008) and is one of the long-lived species (Weber et al., 2017) of the Northwestern Himalayas. It grows in small gaps in the forests, where it is either planted or grows spontaneously, mostly on the bunds of agricultural fields and occasionally in pastures (Singh et al., 2023). It can be found in India, Thailand, Bangladesh, Burma, Southern China, the Philippines, Malaysia and Indonesia between 150°N to 250°N latitude, at elevations up to 1500 m above mean sea level. From Jammu and Kashmir eastwards, it can be found in India’s sub-Himalayan tract and outer Himalayan valleys, as well as the plains of Bihar, Assam, West Bengal, Khasi hills, Eastern Ghats valleys in moist places, and the hills of Kurnool, Karnataka, and the Western Ghats. *T. ciliata* is primarily known for its versatile wood, which is used to make high-end items such as furniture, musical instruments, and carvings as well as for constructing houses and ships (Lake, 2015).

The purpose of this research is construction of one-way and two-way volume tables by formulating species-specific allometric equation for estimating red cedar volume in the Northwestern Himalayas. While one-way tables offer simplicity and ease of use for quick assessments, two-way tables enhance precision by considering multiple tree characteristics. Besides, it offers an initial assessment of the productivity potential of *T. ciliata*, which shall facilitate researchers/foresters to quantify the yield of toona trees in the mid-hills of the Northwestern Himalayas of India. The objectives of the study can be enumerated as (1) deriving allometric models for selected toona trees in mid-hills of

Northwestern areas of Himachal Pradesh, (2) validating performance of the widely used volume equations for assessing the volume of red cedar woodland, and (3) construction of volume tables for red cedar.

Materials and methods

Study area

In present investigation, the naturally raised trees of *T. ciliata* were chosen from district Kangra in August-September, 2020. The district Kangra is situated between 32.0998°N and 76.2691°E (Govt. of H.P., 2009) in the western part of Himachal Pradesh, India (*Fig. 1*). Sitewise locational data of altitude, latitude and longitude of selected trees were recorded with instrument GARMIN GPS III PLUS (*Table 1*). The district is spread over an area of 5,739 km^2 (10.31% of the total state area) covering about 216,643 ha of land. Out of 195,738 ha is arable land with river Beas flowing through spanning 94.00 km. The soil texture is both sandy and loamy. Seasonal changes in temperature and rainfall are influenced by the topographical features of the area with annual temperatures varying from 0° C to 40° C. Summer temperatures may reach up to 38° C; autumn temperatures vary between 7° C to 16° C (Centigrade or Fahrenheit) while spring temperatures may range from 16° C to 25° C during spring. Winters, however, are harsh with the northern side receiving snowfall (Singh et al., 1994). Precipitation takes place around the year with an approx. annual average rainfall of 1850 mm which is substantially higher than the national average. However, nearly 70 per cent of rain falls during the monsoons (Prakash et al., 2016). The annual precipitation fluctuates from 1200 to 3000 mm across different parts of the district owing to its distinctive topography.

Selection criteria for trees

Tree species were selected for volume estimation by using stem density and basal area (Amaro et al., 2013). 25 trees with highest basal areas and frequencies of occurrence from each site were chosen. The number of trees sampled per site was found to be proportional to the frequency of occurrence or relative density of each tree (Romero et al., 2020). Individuals within each site were sampled based on diameter classes, with the number of trees in each class contributing to the diameter distribution without imposing any limit on tree height.

Table 1. *Altitude, latitude and longitude of collection sites*

Sr. No.	Site	Altitude (m asl*)	Latitude (°N)	Longitude (°E)
1.	Baslag	410	31°44’16”	076°18’5”
2.	Chauli	435	32°11’50”	076°22’16”
3.	Kaloha	478	32°11’57”	076°22’4”
4.	Nihari	552	31°44’59”	076°16’57”

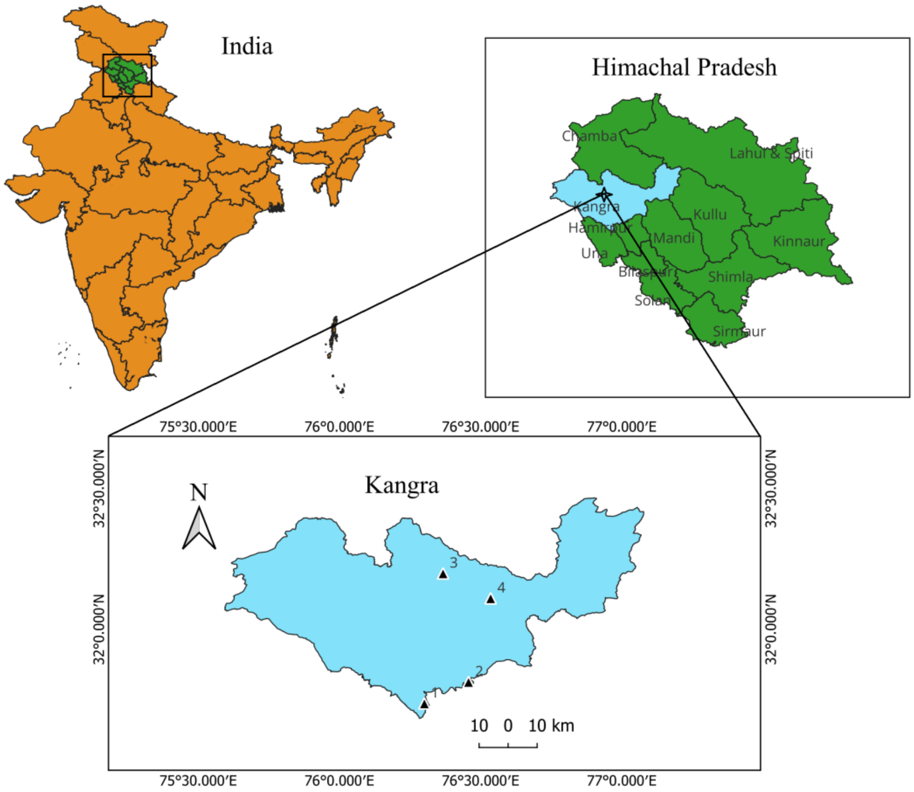

Figure 1. *Graphical representation of selected sites under study*

Measuring principle and method

Measuring principle consisted of accurate measurement of standing tree without causing any damage to the tree with the help of a vernier caliper, measuring tape, and ravi multimeter.

1. The diameter at breast height (DBH) for each selected tree was recorded using a vernier caliper (Analog type, manufactured by Royal Nauticals) and measuring tape. Breast height was marked by the means of a measuring stick on standing trees at 1.37 m above the ground level. The data for two sides at right angles were recorded, an average of which was considered as diameter over bark (dob) in centimeters. Consequently, girth over bark was recorded using measuring tape which was then converted into diameter using a formula.
2. The height of each selected tree was measured as an ocular estimate with the help of a ravi multimeter (Analog type, manufactured by Royal Nauticals). Two sides of trees were selected and observations were recorded from the point where the tree's top and base were visible. The average of these readings was taken as the tree height in meters.
3. The form factor for four different sites was computed using the formula derived from the equations given by Pressler (1865) and Bitterlich (1984). *Equation 3* was used to compute the form factor.

According to Pressler (1865), the volume of the standing tree is:

$$V = f \times h \times g \tag{Eq.1}$$

where: V = volume in cubic meters; f = form factor; h = tree height in meters; g = Basal area in square meters.

According to Bitterlich (1984), the volume of the standing tree is:

$$V = \left(\frac{2}{3}\right) h_1 g \qquad \text{(Eq.2)}$$

where: V = volume in cubic meters; h_1 = height at which the diameter is half of the dbh; g = basal area in square meters.

By using the *Equations 1* and *2* we have:

$$f = \frac{2h1}{3h} \qquad \text{(Eq.3)}$$

Determination of volume

Volume estimation was done using the parameters recorded from the standing trees viz DBH, height, and form factor.

Tree volume was calculated using the following formula:

$$V = \frac{\pi d2}{4} hf$$

where: V = volume in cubic meters; h = tree height in meters; f = form factor; d = diameter at breast height.

Volume model evaluation method

It has been stressed by various authors and have underscored the role of model evaluation in analyzing the model’s predictive ability prior to applying it (Goulding, 1979; Reynolds et al., 1981; Tewari et al., 2000). Eight models (three linear and five nonlinear) were tested to assess the commercial aboveground volume (V, in m^3) using DBH (D, in cm) and height (H, in m) or a combination of D and H as independent variables (*Table 2*). Allometric linear models were derived using least-squares regression analysis for volume estimation (Draper et al., 1966; Gunst, 1999; Shewhart et al., 1967). The estimated linear allometric equations were evaluated for volume using coefficient of determination (R^2) and the root mean square error (RMSE) as goodness-of-fit criteria. R^2 is the variation proportion in the dependent variable as explicated by regression equation. The average distance between observed and predicted values (using regression equation) was calculated using RMSE. The best linear or non-linear equations were selected using the RMSE. All statistical analyses were carried out in R software, version 3.4.21, “stats package”.

Results

Volume model results

Volume equations are important tool for the projection of total and commercial volume at different stages (thinning and final harvest) as the plantations mature (Cordero et al., 2003). Different volume models were evaluated for the tree species investigated using the ordinary least squares method as summarized in *Table 2*.

Table 2. *Volume equations compared in the study for volume table construction*

No.	Name of the equation	Equation
1	Linear	$Y = \alpha + \beta X$
2	Logarithmic	$Y = \alpha + \beta \ln(X)$
3	Inverse	$Y = \alpha + \frac{B}{X}$
4	Quadratic	$Y = \alpha + \beta_1 X + \beta_2 X^2$
5	Cubic	$Y = \alpha + \beta_1 X + \beta_2 X^2 + \beta_3 X^3$
6	Compound	$Y = \alpha \beta^X$
7	Power	$Y = \alpha X^\beta$
8	Exponential	$Y = \alpha e^{(\beta * X)}$

New volume model and accuracy analysis

To further check the accuracy and applicability of the fitted volume model, the models were evaluated and analyzed. For this purpose, the coefficient of determination (R^2) and the root mean square error (RMSE) were used, and the relevant parameters have been summarized *Tables 3* and *4*.

The combined variable equation (*Eq. 7* given in *Table 2*) offered a more precise estimate as demonstrated by the values of R^2, adjusted R^2, and root mean square error (RMSE) and was, hence, considered a better option for volume prediction. *Equation 7* in *Table 2* displayed negligible error between the measured and the predicted volume. The RMSE (0.008) and high value of R^2 (0.984) respectively, presented in *Table 3* indicated the appropriateness of the power model ($V = 7.888 \text{ X } D^{2.548}$).

The estimates of various parameters and goodness of fit statistics of different linear and non-linear functions were tested for assessing the volume based on D^2H for *T. ciliata* in *Table 3*. The high value of R^2 (0.998), with a minimum RMSE (0.001) of the power model provided positive results for the volume assessment of *T. ciliata* as presented in *Table 4*.

Table 3. *Parameter estimates and regression statistics for all the models tested for one-way volume table*

No.	A	B	β_1	β_2	β_3	SE	R^2	RMSE
1	-0.944	4.473	-	-	-	0.123	0.926	0.015
2	2.233	1.1472	-	-	-	0.185	0.833	0.034
3	1.976	-0.430	-	-	-	0.244	0.709	0.060
4	0.259	-	-2.421	9.218	-	0.063	0.981	0.004
5	-0.393	-	3.411	-7.043	14.299	0.061	0.982	0.004
6	0.039	1379.636	-	-	-	0.151	0.956	0.023
7	7.838	2.548	-	-	-	**0.087**	**0.984**	**0.008**
8	0.039	7.230	-	-	-	0.151	0.956	0.023

Table 4. *Parameter estimates and regression statistics for all the models tested for the two-way volume table*

No.	A	B	β_1	β_2	β_3	SE	R^2	RMSE
1	-0.006	0.2888	-	-	-	0.019	0.998	0.0003
2	0.314	0.577	-	-	-	0.182	0.838	0.033
3	1.091	-0.542	-	-	-	0.318	0.505	0.101
4	0.002	-	0.280	0.001	-	0.019	0.998	0.0003
5	-0.0003	-	0.2846	0.0004	0.0001	0.019	0.998	0.0003
6	0.200	1.524	-	-	-	0.282	0.846	0.080
7	0.284	1.003	-	-	-	**0.015**	**0.998**	**0.001**
8	0.200	0.421	-	-	-	0.282	0.846	0.080

Volume tables

One-way (DBH) and two-way volume tables (DBH and height) were constructed with the help of the best-fitted models. The appropriateness of the power model ($V = 7.888 \text{ X } D^{2.548}$) for the construction of a one-way volume table for *T. ciliata* is presented in *Table 5*. The power model ($V = 0.284 \text{ X } (D^2H)^{1.003}$) was employed for constructing the two-way volume table of the *T. ciliata*, as presented in *Table 6.*

Relationship between variables

The volume tables were generated based on DBH and height, individually as well as combinedly, suggested that there might be some variations and relationships between the variables. *Figure 2* depicted strong and positive correlation between DBH and height with r = 0.86, volume and DBH with r = 0.96 and volume vs height with r = 0.86 (R software, version 3.4.21; ‘corr’package).

Table 5. *One-way volume table (Overbark) for T. ciliata based on power model ($V = 7.888 \times D^{2.548}$)*

Diameter (cm)	Volume (m^3)	Diameter (cm)	Volume (m^3)	Diameter (cm)	Volume (m^3)
15	0.0078	30	0.0458	45	0.1286
16	0.0092	31	0.0498	46	0.1360
17	0.0108	32	0.0540	47	0.1437
18	0.0125	33	0.0584	48	0.1516
19	0.0143	34	0.0630	49	0.1598
20	0.0163	35	0.0678	50	0.1682
21	0.0184	36	0.0728	51	0.1770
22	0.0208	37	0.0781	52	0.1859
23	0.0233	38	0.0836	53	0.1952
24	0.0259	39	0.0893	54	0.2047
25	0.0288	40	0.0953	55	0.2145
26	0.0318	41	0.1015	56	0.2246
27	0.0350	42	0.1079	57	0.2349
28	0.0384	43	0.1146	58	0.2456
29	0.0420	44	0.1215	59	0.2565

Table 6. *Two-way volume table (Overbark) for T. ciliata based on power model (*$V = 0.284 \times (D^2H)^{1.003}$*)*

Height (m)	Diameter (cm)									
	15	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
10	0.0654	0.1165	0.1822	0.2627	0.3579	0.4678	0.5925	0.7319	0.8861	1.0551
11	0.0720	0.1281	0.2005	0.2890	0.3938	0.5147	0.6519	0.8053	0.9750	1.1609
12	0.0785	0.1398	0.2188	0.3154	0.4297	0.5617	0.7113	0.8788	1.0639	1.2668
13	0.0851	0.1515	0.2371	0.3418	0.4656	0.6086	0.7708	0.9522	1.1528	1.3727
14	0.0916	0.1632	0.2554	0.3681	0.5015	0.6556	0.8303	1.0257	1.2418	1.4786
15	0.0982	0.1749	0.2737	0.3945	0.5375	0.7025	0.8898	1.0992	1.3308	1.5846
16	0.1048	0.1866	0.2920	0.4209	0.5734	0.7495	0.9493	1.1727	1.4198	1.6905
17	0.1114	0.1983	0.3103	0.4473	0.6093	0.7965	1.0088	1.2462	1.5088	1.7965
18	0.1179	0.2100	0.3286	0.4737	0.6453	0.8435	1.0683	1.3197	1.5978	1.9025
19	0.1245	0.2217	0.3469	0.5001	0.6813	0.8905	1.1279	1.3933	1.6868	2.0085
20	0.1311	0.2334	0.3652	0.5264	0.7172	0.9375	1.1874	1.4668	1.7759	2.1146
21	0.1376	0.2451	0.3835	0.5529	0.7532	0.9845	1.2469	1.5404	1.8650	2.2206

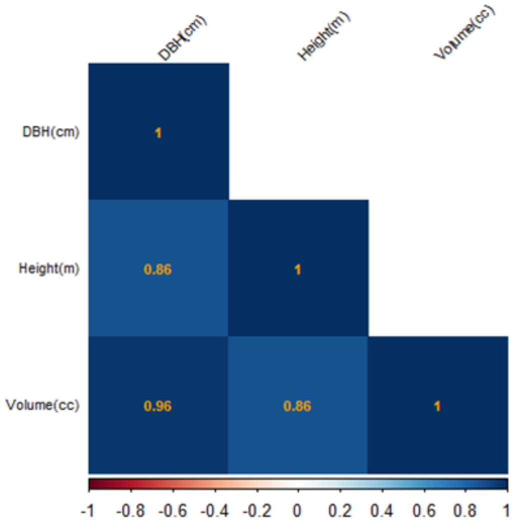

Figure 2. *Simple correlation between dendrometric variables and volume of Red Cedar*

There was a relationship between the volume estimated and the height of red cedar trees as shown in *Figure 3*. Moreover, the estimated volume and diameter at breast height (DBH) showed an increasing trend concerning each other (*Fig. 4*).

Discussion

In the present study, the allometric equations were fitted for volume estimation with DBH and height, individually as well as combined. In previous studies, DBH as an independent variable was also used to construct a one-way volume table (Tewari et al., 2018; Jain et al., 1996; Negi et al., 1998; Sharma et al., 2017). Dhanda et al. (2001), Iew et al. (2001), and Dogra et al. (2003) used a combined variable of DBH and height to generate a two-way volume table. Linear and non-linear equations were used to model the relationship of total volume (V) with DBH, and height. A total of 8 volume equations, which were used in present investigation on red cedar, were selected from the literature based on their wide application to test in this particular study (Tewari et al., 2003, 2006, 2007, 2013).

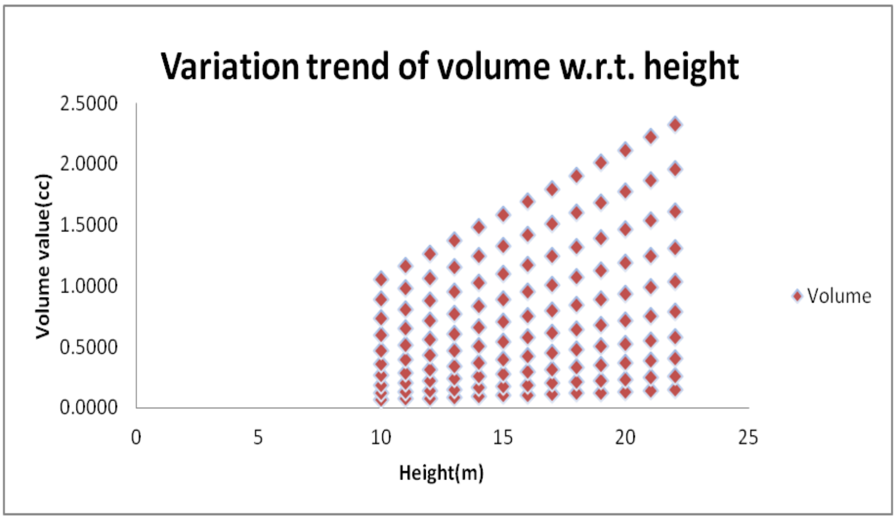

Figure 3. *Variation trend of volume concerning height for Red Cedar*

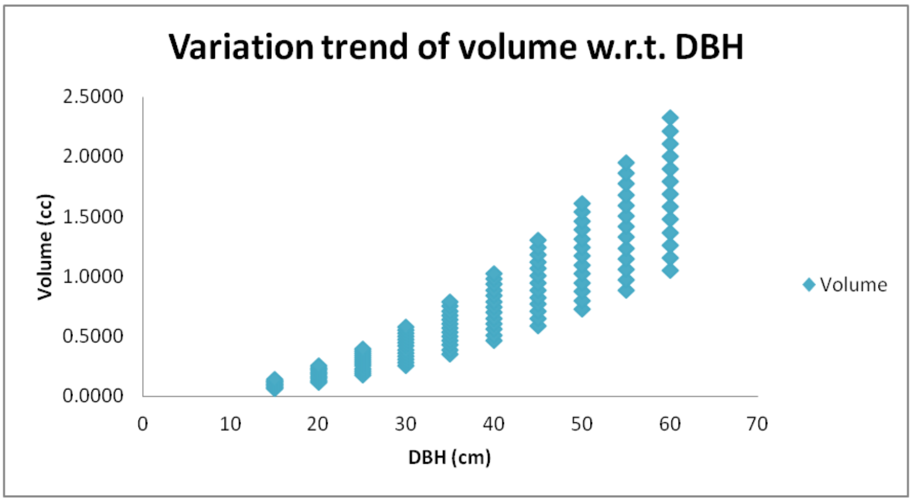

Figure 4. *Variation trend of volume concerning DBH for Red Cedar*

The application of volume equations is promising for estimating yield in future studies whilst avoiding destructive sampling (Nunifu et al., 1999). There is a need to have design models that rely on conveniently and inexpensively measured tree parameters (Phillips, 1995) and ease of operation is an important consideration for the use of volume tables. Fit statistics should not be the sole criterion for establishing the superiority of a model. Quantitative evaluation of models was employed to compare 8 volume equations and select the most suitable model. As previously stated that R^2 is a significant measure of the amount of variation about the mean explained by the model (Unjia, 2021) and also the root mean square deviation (RMSD) or root mean square error (RMSE) forecast by a model were commonly used criteria (Sonal et al., 2010) to evaluate the results.

For constructing a one-way volume table, the power model ($V = 7.888 X D^{2.548}$) was found to be the best fit based on the highest R^2 value of 0.984 and the lowest root mean square value of 0.008. On the other hand, the power model ($V = 0.284 X (D^2H)^{1.003}$) was found to be the most appropriate fit for constructing a two-way volume table, based on the maximum R^2 value (0.998) and the minimum root mean square error value (0.001). The findings of the present investigation are in line with the results obtained by Aman et al. (2020) and Giri et al. (2019) and they recommended the power model to construct local volume tables. The present results are also in conformity with the findings of Shrestha et al. (2018) who observed a strong and positive relationship between diameter at breast height and height of the tree. Bai (2023) also found statistically considerable correlations between volume and height; volume and DBH of the trees. Estimation of volume using the allometric models generated through non-destructive methods, in turn, will help the farmers and commercial growers of toona trees (Rodda et al., 2023; Luoma et al., 2021; Bilous et al., 2017).

Conclusion

Due to the recent focus on biomass and carbon storage, the application of volume tables has increased. This study provides four different advantages in addition to the great precision as described in the aforementioned experimental results in the region of the Northwestern Himalayan regions of India. Firstly, the non-destructive method was used in the study, since it deviates from the traditional approaches that involve felling trees and analytic segmentation. This non-destructive method is very cheap to use as compared to traditional methods that involved analytical work requiring plenty of manpower and material resources which makes them expensive and also time consuming as they entails a sequence of activities such as clearance of the surroundings, environmental damage, felling of sample trees, cutting twigs and removing leaves, segments of the trunk, disc, drying and analyzing. Technological advancement is also a major advantage as, various advanced equipments are being continuously introduced to calculate the volume of standing trees. Great efficiency and accuracy comprise the fourth benefit of our model.

Nonetheless, this method does have a few shortcomings. In high-density forest zones, the instrument observation visibility is disturbed which adversely affects the accuracy of tree trunk observation and measurement of volume. This limitation, however, can be overcome by altering the observation site position or appropriate sparse tree occlusion. The equations provided in this study represent a promising contribution towards developing tools to assist forest planners, farmers, and researchers in predicting forest resources in terms of volume more accurately compared to traditional methods. Owing to the increased interest in the use of toona trees in industries, the ability to predict its yield using stem volume data will be greatly valued.

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Conflict of interests. The authors declare no conflict of interest.

Data availability statement. The data presented in this study are available upon request.

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