forests

Review

Describing and Modelling Stem Form of Tropical Tree Species with Form Factor: A Comprehensive Review

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Abstract: The concept of tree or stem form has been central to forest research for over a century, playing a vital role in accurately assessing tree growth, volume, and biomass. The form factor is an essential component for expressing the shape of a tree, enabling more accurate volume estimation, which is vital for sustainable forest management and planning. Despite its simplicity, flexibility, and advantages in volume estimation, the form factor has received less attention compared to other measures like taper equations and form quotient. This review summarizes the concept, theories, and measures of stem form, and describes the factors influencing its variation. It focuses on the form factor, exploring its types, parameterization, and models in the context of various tropical species and geographic conditions. The review also discusses the use of the form factor in volume estimation and the issues with using default or generic values. The reviewed studies show that tree stem form and form factor variations are influenced by multiple site, tree, and stand characteristics, including site quality, soil type, climate conditions, tree species, age, crown metrics, genetic factors, stand density, and silviculture. The breast height form factor is the most adopted among the three common types of form factors due to its comparative benefits. Of the five most tested form factor functions for predicting tree form factors, Pollanschütz's function is generally considered the best. However, its performance is often not significantly different from other models. This review identifies the "Hohenadl" method and mixed-effects modelling as overlooked yet potentially valuable approaches for form factor modelling. Using the form factor, especially by diameter or age classes, can enhance tree volume estimation, surpassing volume equations. However, relying on default or generic form factors can lead to volume and biomass estimation errors of up to 17–35%, underscoring the need to limit variation sources in form factor modelling and application. Further recommendations are provided for improving the statistical techniques involved in developing form factor functions.

Keywords: stem shape; forest inventory; volume; taper; stem growth; artificial form factor; breast-height form factor; terrestrial laser scanning; machine learning

Academic Editor: Guy R. Larocque

Received: 5 December 2024
Revised: 22 December 2024
Accepted: 24 December 2024
Published: 27 December 2024

Citation: Oluwajuwon, T.V.; Ogbuka, C.E.; Ogana, F.N.; Hossain, M.S.; Israel, R.; Lee, D.J. Describing and Modelling Stem Form of Tropical Tree Species with Form Factor: A Comprehensive Review. *Forests* **2025**, *16*, 29. https://doi.org/10.3390/f16010029

1. Introduction

Tropical forests have been the focus of scientific study and conservation initiatives due to their biodiversity and critical role in the global ecological balance. The multifaceted nature of these forests and their importance in the global carbon cycle have increased the need for forest assessment, monitoring, and sustainable forest management. Central to understanding and managing these ecosystems in the face of climate change is the nuanced exploration of tree characteristics through forest biometrics and inventory [1]. National Forest Monitoring Systems and the United Nations Framework Convention on Climate Change's Reducing Emissions from Deforestation and Forest Degradation (REDD+) require reliable, high-quality data from these forests, which aids in national policy making, effective planning, sustainable developments, and reforestation and carbon project implementations [2–5].

Among the essential forest parameters, volume and biomass stand out for their role in evaluating forest productivity, quantifying growing stock, predicting growth and yield, and assessing the ecological functioning of the forest [1,5]. Tree variables such as diameter at breast height (dbh) and tree height are crucial in estimating tree volume. Due to the different shapes of trees, various inflection points along their length, varying climatic conditions, species composition, ages, and management practices, forests in the tropics could prove difficult in terms of accurate volume and growth estimation [6]. The form factor is a numerical ratio that compares the volume of a tree's stem to the volume of a geometric shape, typically a cylinder. The form factor is determined by dividing the volume of the real stem by the volume of the reference geometric shape. It compensates for tree stem abnormalities and non-cylindrical forms and gives information on stem tapering [7]. Although some countries, such as Nepal [7] and Brazil [8], use form factors of 0.5 and 0.7, respectively, for all tree species in those regions, variability in tree shapes and sizes leads to incorrect volume estimates.

The shape of the tree (stem form) can be quantitatively expressed by stem taper, which is a decrease in diameter from the base to the tip [9]. The stem factor is determined by the crown length and structure, as well as other characteristics such as wind exposure, genotype, species, and silvicultural treatment [10,11]. Stem form differences have an impact on how well the form factor depicts the true volume of the tree. A more tapered or uneven stem may provide a form factor that deviates from unity (1.0), the ideal value for a perfectly cylindrical shape.

Allometric equations and volume tables based solely on dbh and height do not account for the changing shape of the stem along the tree trunk (tapering) and may result in an under- or overestimation of volume and biomass. Thus, additional metrics, particularly the interplay between stem form and form factors, may be required [9,10]. As form factor is a numerical representation of stem form and changes in stem form have a direct impact on the accuracy of volume and biomass predictions, acknowledging and comprehending this link is critical for effective and accurate forestry practices such as projected yield, sustainable management, and carbon sequestration assessments.

This paper explores the conditions associated with modelling and characterizing the stem form of several tropical tree species, with a specific focus on the form factor. The form factor influences include stand, tree, and site features. We also discuss the variation of the form factor with height and diameter along the stem of the tree and its possible implications for the total volume of a single tree. Furthermore, we investigate how form factors can be used in stem form modelling, as well as the potential regression models and attributes that can be derived and their application in volume estimations. We look at real-world applications of form factors, in addition to their theoretical applications, particularly as they relate to efficient, sustainable plantation and climate change management.

Relevant articles were identified through searches in the Google Scholar, MDPI, and Web of Science databases using various keyword combinations in titles and abstracts, including "tropical species", "form factor", "stem form", and "form factor function". The initial search was conducted in July 2022 and was updated on 14 September 2023. Only publications in English were considered, and articles published up to the specified data collection periods were included. No restrictions were imposed on the types of articles to be incorporated. The initial search yielded 653 articles after removing duplicates. The screening process began by reviewing titles and abstracts to exclude records that were irrelevant, resulting in a reduction to 353 articles. These included mostly peer-reviewed publications, with a few important grey literature sources, all providing details about tree stem form in tropical regions. However, not all the articles included or emphasized the form factor specifically as a measure of stem form. Therefore, a full-text review was conducted to screen the content of the remaining articles, retaining those with a substantive focus on form factor, including information on specific species, their geographic location, and their plantation type. In addition to articles specifically addressing form factor, some of the most relevant studies covering stem form were included to offer broader foundational reviews on tree form, its variation, theories, and diverse measurement approaches. Following this thorough process, a final dataset of 83 articles was obtained for further data extraction, evidence summary, and thematic analysis.

2. Tree Stem Form and Its Variation

Tree or stem form has been a prominent concept in forest research for more than a century and is still evolving, considering the need to accurately define and determine tree (stem) volume and growth. Numerous efforts have been made to study and characterize tree form, aiming to mathematically derive a generic and standardized formula for its estimation [12]. However, the existing methods lack consensus and may not provide consistent accuracy across a wide range of tree dimensions, species, and geographic and stand management [11]. One of the reasons for this limitation has been attributed to the lack of a unified theory that can provide explanations for the variability in stem forms within and among trees of the same species or in a given stand [12]. For example, an individual tree can assume different forms along its axis. Several authors have described trees as being dividable into three to four sections from the apex to the butt, with the possibility of exhibiting correspondingly somewhat distinct forms. Osawa [13] identified a cylindrical treetop next to a cone and a paraboloid, ending in a swollen base. Husch [14] and Newnham [15] had earlier defined a neiloidal butt extending into a paraboloidal bole section and then capped with a conoidal treetop containing the live crown (Figure 1). The effects of these sectional distinctions of tree form variation tend to become more complex and obvious as a result of irregularities potentially caused by certain tree diameter growth aberrations or interruptions from natural (environmental) or mostly biological factors like heart rots, buttresses, cambial injuries, and defoliation [11,12,16]. Hence, the form of a stem may change abruptly from one geometric form to another [15].

Several factors have been widely promulgated to facilitate stem/tree form variation. According to Muhairwe [11], these can be categorized into site, tree and stand factors (Figure 2). Concerning site characteristics, available water and nutrients can affect the form of the trees through their influence on crown development. Trees growing on poor sites often exhibit suboptimal form, explainable by the prominent relationship between tree growth and site quality. In an earlier study, Smith [17] found a comparatively better rate of ring (annual) growth and, consequently, a significant degree of taper and form in young stands of some conifers grown openly in richer sites, compared to those grown in dense stands with poorer quality sites. Tree form also responds to other environmental and climatic variations. For instance, Dudzińska [18] attributed the variations in the stem form of beech (*Fagus sylvatica* L.) to elevation differences, while Schneider [19] highlighted the comparative importance of total summer precipitation and mean winter temperature for balsam fir (*Abies balsamea* [L.] Mill.). Muhairwe [11] asserted that dry pine stands, such as interior lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), tend to exhibit a compacted decurrent form in comparison with the extended, excurrent form of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) grown in wet coastal environments as a drought tolerance mechanism.

Tree and stand characteristics like the tree and stand ages, crown factors (e.g., crown position and size), species variation, stand density, and silviculture also determine the tree stem form variation [11,20–24] (Figure 2). Younger trees tend to assume a more or less conoidal stem form, especially in the upper tree section, which gradually reduces to the cylinder as they increase in age, reduce in height increment, and add less variable diameter growth in their main stems. However, this is variable and may depend on tree species type and stand composition due to species differences in their growth dynamics, in terms of height, diameter, and crown dimensions [7,9,10]. Dominant trees exhibit better growth rates and attain a more conoidal form than the suppressed ones, which typically assume a parabola [11,25]. Regarding crown length, those with shorter crowns tend to assume less taper even if they have the same height and diameter increments compared to those with longer crowns [26]. This correlates with how stand density determines tree form since trees that grow in open stands free of competition tend to possess deeper crowns and more tapering conoidal stems than those in closed stands [11,22]. The genetic variation within and among tree populations and species also influences the variability in their form approximations. Socha and Kulej [27,28] reported the effect of provenance variation on the stem form of *Abies grandis* (Douglas ex D.Don) Lindl. (grand firs) and *Larix decidua* Mill. (European larch), reporting that trees from certain provenances exhibited greater stem cylindricity than those from other provenances.

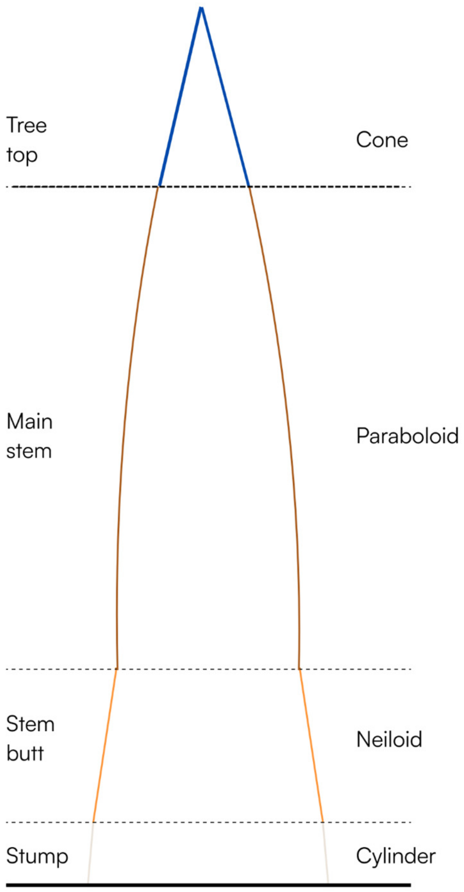

Figure 1. Typical geometric forms of different tree stem sections. Adapted from Ref. [15].

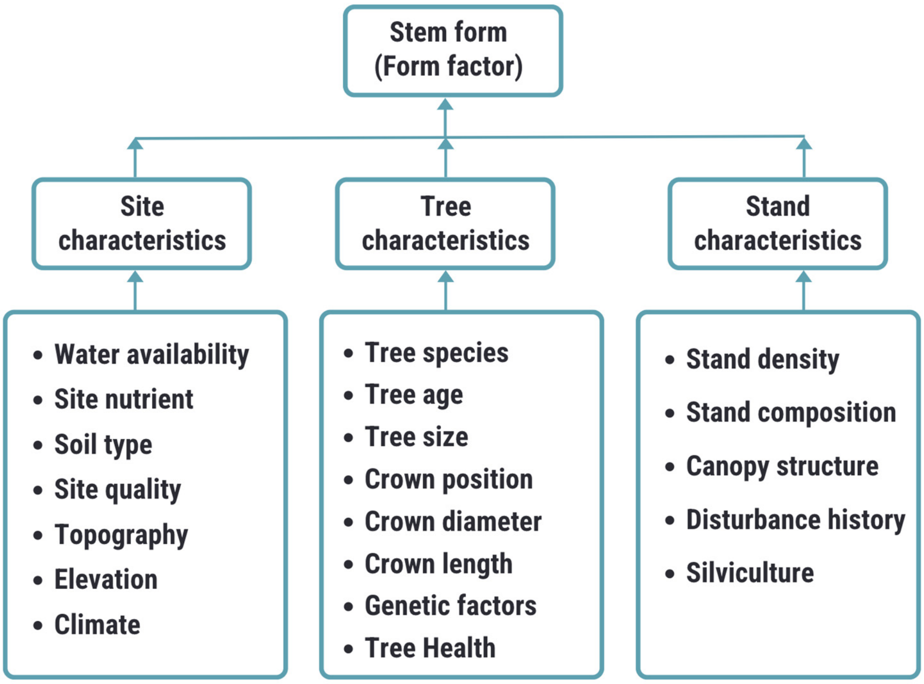

Figure 2. Factors influencing stem form variation identified in this review.

2.1. Tree Form Theories

Since the nineteenth century, different theories have been postulated to describe tree form variation [29,30]. These theories were summarized into four concepts, namely, nutritional, water conduction, mechanistic, and hormonal [12]. Firstly, the nutritional theory proposes that the shape and taper of a tree stem are influenced by its transpirational requirements, which are determined by the rate of early wood formation, especially in the lower part of the stem bole. The water conduction theory similarly hypothesized that physiological requirements for water conduction influences tree shape and stem size. It attributes a cylindrical bole to having equilibrium conduction between root and crown systems. Unlike the first two, the mechanistic theory accords the formation of and variation in stem form to the lateral forces by wind at a certain stem point and the consequent strength requirements and resistance of the stem. This thus influences the variation and functional relationship between stem diameter and height or crown size, which Metzger [30] demonstrated to assume a cubic paraboloid (d^3). In his d^3 rule, he likened tree form to a cantilever beam that is infinitely and inflexibly attached to the ground such that the stem height along any point has a cubic proportion to the stem diameter at that same point. In contrast, Gray [20] later developed a rather quadratic paraboloid (d^2/h) model and theory to explain the mechanistic requirement and form of a typical tree stem, based on the observation that the tree-ground attachments allow a more flexible interaction than the firm system postulated by Metzger's beam theory. The mechanistic theory has gained the most recognition in describing tree form (see [31,32]). Lastly, according to the hormonal theory, stem form variation is envisaged to be determined by growth hormones like auxins produced and conducted from the tree apices. The distribution of these growth substances is expected to influence the radial growth and shape along the stem bole.

Over the past 40 years, some contemporary tree form theories have been described [33,34]. Most of these recent theories find their basis in the mechanistic principles, such as "resistance to bending and elastic buckling from wind and gravity at the expense of vertical growth and competitive advantage for light" [35]. King [33] introduced a theory based on the stability safety factor (SSF), which emphasizes the relationship between tree stability and stem form, particularly focusing on how variations in tree form influence its ability to withstand external forces like wind, snow loads, and other environmental stressors. He described SSF as a measure of the safety margin of a tree's structure against failure due to bending or buckling. Niklas [34] further theorized how stem form development and variation are influenced by the density-specific mechanical properties of key stem tissues, especially those that provide structural support to the tree.

2.2. Measures of Tree Stem Form

Stem form is mostly considered synonymous with stem taper or profile, as they are often used interchangeably in the literature. However, they mean different things. While taper indicates the relative rate of change (decrease) in stem diameter as the tree height increases along the stem from the base to the tip, stem form rather implies the typical (geometric) shape of a solid assumed by the tree stem [1,11,12]. Several 'mathematical' concepts and measures have been developed and used to express stem form. These commonly include form factor, form quotient, form point, and incorrectly attributed taper measures, each with varying levels of accuracy and significance in tree volume approximation or estimation at different forms [1,12,32,36].

The form factor is expressed as the ratio of the volume of a tree to that of a specified geometric solid with a similar cross-sectional area (or diameter) and height. These geometric solids could be cylindrical, conoidal, paraboloidal, or neiloidal. However, the volume of a cylinder is most prominently adopted. Form point refers to "the percentage ratio of the height to the centre of wind resistance on the tree, approximately at the centre of gravity of the crown, to the total tree height", and the higher the form point, the more cylindrical the tree form. Nevertheless, it is rarely adopted in forest inventory [36].

On the other hand, the form quotient (q), which simply implies the ratio of a diameter taken at a certain upper height relative to the diameter at the breast height itself, is a commonly used variable. It can be considered in two different forms, depending on the height at which the upper diameter is measured. The first is the normal form quotient ($q_{0.5}$), which considers the upper diameter at half of the total height of the tree ($d_{0.5h}$), and the other, the absolute (q_a), takes the midpoint between the tree height and breast height ($d_{1/2(h\text{-}1.3)}$). It is widely noted that form quotient, especially q_a, reduces with increasing tree diameters and heights [36].

Studies suggest that the form quotient is preferred over the form factor because it is easier to estimate, being a simple ratio between the diameters at different points, while form factor requires more complex volumetric measurements and computations [37,38]. Despite this, form factor is considered a better summary for stem shape. However, in Brazil, no significant difference has been found in the volume estimation efficiency between form factor and form quotient, as demonstrated with Caatinga trees [39]. Other taper measures used to estimate tree form included taper curves and formulas, taper tables, and taper functions [36]. Myriads of taper equations have been developed for different tree species in various forest stands and conditions, mainly to profile the stems (i.e., to estimate tree diameters at any point on the stems) and, by application, for accurate estimation of merchantable and total stem volumes [32,40–42]. These equations range from single to segmented to variable exponent taper functions [6,32,43]. Many times, there exists a direct relationship between stem form and taper with respect to tree growth. As the diameter decreases with increasing height, the taper becomes greater, resulting in a lower form factor [11].

3. Form Factors

Form factor, as earlier indicated, is one of the essential measures with which the shape or form of a given tree is expressed for a more correct and accurate determination of the tree/stem volume and surface area towards sustainable forest management decisions and planning. Form factors can be broadly categorized into those for stem volume and those for stem surface area [44,45]. However, form factors for stem volume are more commonly discussed in the literature and are widely applied in forest management. Therefore, this synthesis focuses on stem volume form factors. Typically, there is a direct proportional relationship between the form factor for stem surface area and the square root of the form factor for stem volume [45].

Form factor captures the overall shape of a tree stem and provides a basis for most log volume estimation methods [11,36,46]. It is also considered valuable for evaluating stem biomass and its variation among tree species of the same diameter and height [47], although with variable predictive effects [35]. Characteristically, a tree form is likened to the shape of a nearest-similar standard geometric solid, such as a cylinder, considering the similarity in their height and basal area/diameter. A form factor is therefore used as a deduction or correction factor of the geometric shape to the real tree form [11,36,48]. This is simply done by obtaining the ratio of the tree volume to the volume of the specified geometric solid. Often, a cylinder is the most commonly used geometric shape when estimating the form factor of trees. Hence, the general name for most form factors regardless of their specificity is a "cylinder form factor" [49]. Form factor, which typically takes a value within the range of 0–1, can be mathematically derived as follows:

$$F = \frac{V_{Tree}}{V_{Cylinder}} = \frac{V_{Tree}}{BA \times h} = \frac{V_{Tree}}{(\pi \times d^2/4) \times h} \tag{1}$$

where V_{Tree} is the real tree stem volume (m^3) obtained from log cross-sectional areas; $V_{Cylinder}$ = tree cylindrical volume (m^3) derived from the product of the basal area (BA, m^2) and height (h, m) of the (cylindrical) tree. BA is calculated by multiplying pi (3.142) by the square of half of the reference diameter (d, m). It is considered that the higher the value of the stem form factor, the more cylindrical it is. Although the shape of a tree stem can take different forms, a default form factor (0.5) assuming a quadratic/cubic geometric shape is generally used [50]. Table 1 presents a description of the likely stem shapes corresponding to form factor values.

Table 1. Geometric descriptions of stem form factor and range (in brackets).

Stem Geometric Form	Stem Form Factor
Cylinder	1.00 (>0.9)
Neiloid	0.25 (0.2–0.3)
Conoid	0.33 (0.3–0.45)
Quadratic paraboloid	0.50 (0.45–0.55)
Cubic paraboloid	0.60 (0.55–0.65)

3.1. Types of Form Factors

Different types of form factors in relation to stem volume have been developed and adopted over the years. Based on the height of measurement of the (cylindrical) basal area or diameter, this classification is divided into three: breast height or artificial ($F_{1.3}$), absolute (F_a), and normal (F_N) [51], as shown in Figure 3.

1. Absolute form factor

For the absolute form factor, its cylindrical volume is estimated based on the sectional area at any convenient height close to the ground level. It is described as the ratio of the volume of the tree to the cylindrical volume taken above a specified measurement point at the tree base. Previous studies have used different height reference points as base heights for calculating this form factor, due to factors such as variations in tree buttress formation, tree morphology, and practical measurement considerations. Tiryana et al. [46] measured the cylindrical volume at 0.2 m above ground while estimating the absolute form factor for *Swietenia macrophylla* King in some Indonesian community forests in Central Java. Subedi et al. [7], in *Shorea robusta* Roth forests in Nepal, selected 0.8 m above the ground as the convenient height point for the form factor.

2. Normal form factor

Normal or Pressler's form factor is based on the cross-sectional area at a relative height. It is described as the ratio of tree volume to the cylindrical volume taken at some percentages or proportions of the tree height. According to Brack [31], these sectional area (i.e., diameter) proportions are generally measured in a sequence of 0.1, 0.3, 0.5, 0.7, and 0.9 of the total tree height, though Philip [51] prescribed the suitability of just considering 0.9 of the tree height. However, many studies have used different proportions, including one-tenth, 0.1 [52], 0.05 [28], and 0.3 [27] of the total tree heights. This form factor is also called the natural form factor [53,54] and is mostly regarded as the real or true form factor [28,36]. However, it is not usually adopted because a prior tree height measurement is needed before selecting a relative measurement point.

3. Breast height form factor

Breast height form factor is based on the sectional area (diameter) measured at breast height and the stem/bole height of the tree. This considers that the height of a cylinder is the same as that of the stem and that the area of the cylinder is equal to the stem's basal area at breast height. Other terms for this form factor are 'artificial form factor' [10,51,53], 'false form factor' [36], and 'real form factor' [55]. Regardless of the naming inconsistency, breast height form factor is considered the most common and useful method of determining form factors.

Most of the existing literature on form factor mensuration has adopted the breast height form factor, whether singly (e.g., [23,53,56]) or together with other types [7,46]. One of the reasons for its extensive use is the convenience of defining and measuring a common breast height, thus facilitating its easier and more comparable computations [57]. Another and possibly the most important feature is that it gives higher and more precise estimates of volume. For instance, Subedi et al. [7] reported a mean value of breast height form factor of 0.43 against 0.40 for absolute form factor in *Shorea robusta* forests. Similarly, Tiryana et al. [46] determined 0.68 and 0.46 as the averages of the breast height and absolute form factors for *Swietenia macrophylla*. The mean of breast height form factors for European larches (0.47) was also greater than that (0.43) of the normal form factor taken at 0.05 of the height [28]. However, uncertainties still exist about how significant these differences are and how accurate the breast height form factor could be at predicting tree volumes relative to other form factors. This is demonstrated by the contrasting findings of Oluwajuwon et al. [58] and Tiryana et al. [46]. While the former affirmed the superiority of the breast height form factor (0.48) over the absolute (0.40) in *Paraserianthes falcataria* (L.) Nielsen plantation, the latter reported that the breast height form factor yielded a high negative bias and overestimated the bole volume of the mahogany trees when used with the total height, thereby recommending use of the absolute form factor.

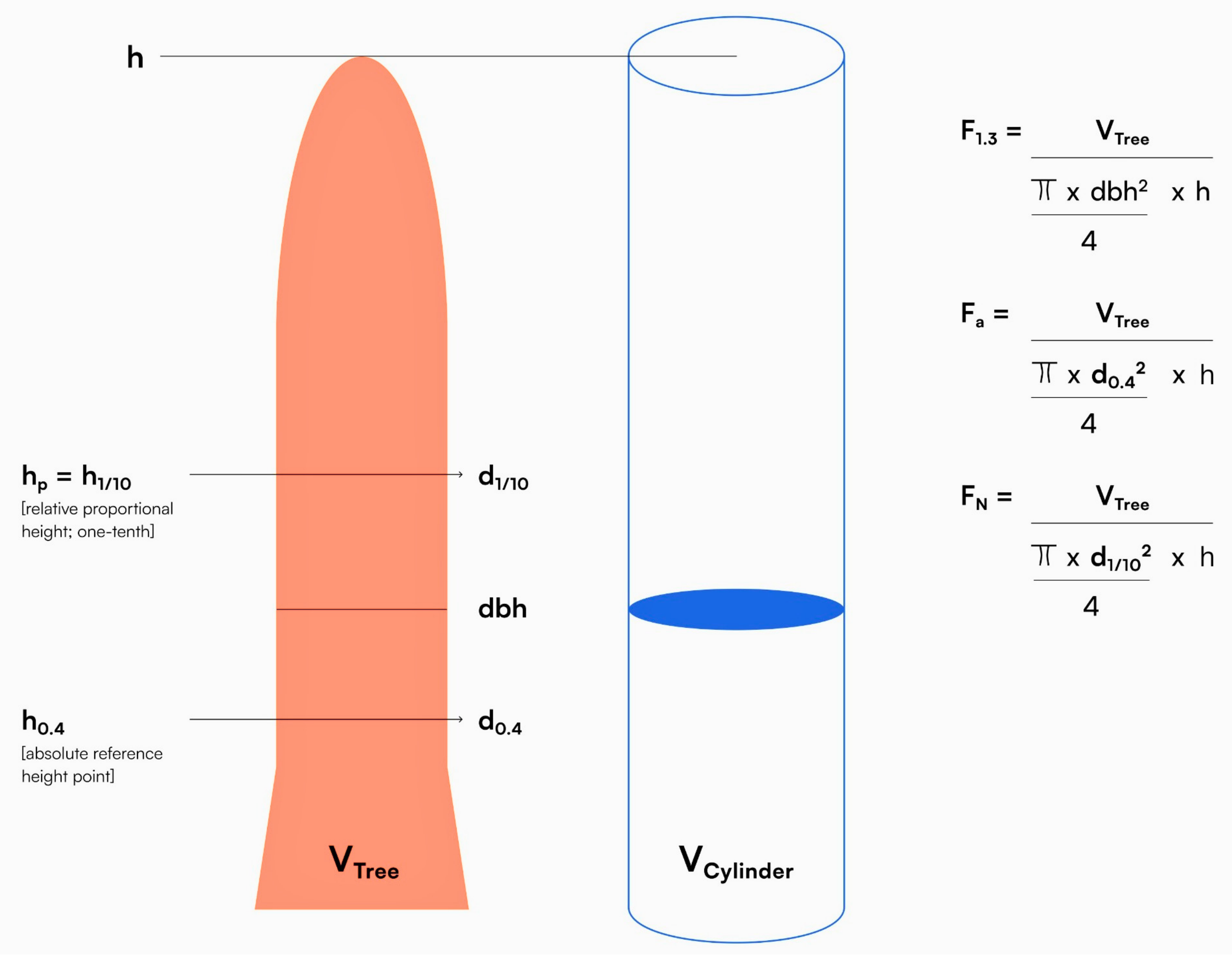

Figure 3. Calculations of various form factors along the stem of a tree at different heights and diameters, adapted from Ref. [38]. $F_{1.3}$ refers to the breast height form factor; F_a represents the absolute form factor; and F_N denotes the normal form factor.

3.2. Existing Form Factors for Different Tree Species and Their Variations

Different forest mensuration studies have estimated form factors for varying numbers of tree species across Asia, recognizing the need for an approximate knowledge of the typical form of any tree species. Table 2 summarizes some of these studies while substantiating the possible variations in this essential dendrometric variable for tree volume estimation and sustainable forest management planning.

The review reveals that the values of form factors can be influenced by site, tree, and stand characteristics, which include factors such as species, age, genetic and climatic conditions, management regimes, stand density, etc., in the same manner they impact tree form. For instance, Cardoso et al. [25] studied the effects of pruning on the form factor of some pines and reported better values for the pruned stands than the unpruned ones. Among the nine commercial tree species considered in Bhutan, three were *Pinus* spp. and three *Quercus* spp., with different mean form factors ranging from 0.34 to 0.45 for the broadleaves and 0.48 to 0.55 for the conifers [9]. Form factor could also respond to the stand density of the forest. Peng et al. [38] evaluated how thinning affects the trunk form factor of 9-year-old *Liquidambar formosana* Hance trees and reported a positive interaction, i.e., there was an increase in the form factor with increasing thinning intensity and reduced stand density. The average form factor of trees in stand densities of 1200 trees ha^{-1} and 600 trees ha^{-1} were 0.40 and 0.48, respectively. Conversely, Gao [59] found that an increase in the stand density of poplar plantations occasioned an increase in the stem form factor. The effect of thinning and spacing on the dendrometric form variable could also be statistically insignificant or absent, as reported by Socha [60] for Scots pine (*Pinus sylvestris* L.), Pérez and Kanninen [61] for teak trees, and Özbayram and Çiçek [54] for narrow-leaved ash trees (*Fraxinus angustifolia* Vahl.).

Regarding the influence of tree age, the stem form of *P. pseudostrobus* Lindl. stand was found to vary widely across different ages, with 10-year-old and 20-year-old plantations of the species having form factors of 0.42 and 0.51, respectively [62]. In *S. robusta*, saplings had higher form factors (0.59) compared to older trees (0.56) [63]. Other species studied by Thakur [63] in the Parbat district of Nepal included *Schima wallichii* (DC.) Korth. (F = 0.58), *P. roxburghii* Sarg. (F = 0.63), and *Castanopsis indica* (Roxburgh ex Lindl.) A. DC. (F = 0.59). However, Petrin and Bogdanov [56] reported quite a unique trend of not much tree form variation with age in different species investigated in Bulgaria. For instance, they found 44-year and 122-year-old Turkey oak (*Quercus cerris* L.) trees had the same form factor (0.49). Furthermore, form factors can be estimated over and under the bark [7,64], likely depending on tree bark thickness and its expected effect on stem form variation. The authors confirmed that form factors calculated over the bark are superior to those calculated under the bark. However, this may yield an opposite outcome in terms of actual stem volume estimation, given the comparative relevance of diameter under bark in characterizing actual product volume [6]. This tendency for stem form to change with tree growth has led to the emphasis on tree diameter classes when using the form factor to estimate stem volumes [65], especially in forests with diverging tree growth patterns.

Tree form and its form factor could also change significantly from site to site, that is, the growth environment as shown in Table 2 with three average form factors found for *S. robusta*, across different sites and districts in Nepal.

Table 2. A summary of some average form factors of different tree species in Asia.

S/N	Species	Country (District)	Stem form Factor (Mean)	Forest Type	Reference
1	*Albies densa*	Bhutan	0.56	Plantation	[9]
2	*Castanopsis indica*	Nepal	0.59	Moist Forest	[63]
3	*Dalbergia sissoo*	Nepal	0.50–0.56	Moist Forest	[66]
4	*Mallotus philippensis*	India	0.57	Moist Forest	[23]
5	*Paraserianthes falcataria*	Indonesia (Java)	0.65	Plantation	[67]
6	*Paraserianthes falcataria*	Indonesia (Kalimantan)	0.48	Plantation	[58]
7	*Pinus roxburghii*	Nepal	0.63	Moist Forest	[63]
8	*Pinus spinulosa*	Bhutan	0.50	Plantation	[9]
9	*Pinus wallichiana*	Bhutan	0.49	Plantation	[9]
10	*Schima wallichii*	Nepal	0.58	Moist Forest	[63]
11	*Shorea robusta*	Nepal (Banke)	0.43	Moist Forest	[7]
12	*Shorea robusta*	Nepal (Nawalparasi)	0.51–0.65	Moist Forest	[66]
13	*Shorea robusta*	Nepal (Bara)	0.33	Moist Forest	[64]
14	*Shorea robusta*	Nepal (Parbat)	0.59	Moist Forest	[63]
15	*Swietenia macrophylla*	Indonesia (Central Java)	0.68	Plantation	[46]
16	*Swietenia macrophylla*	Indonesia (East Java)	0.46	Plantation	[68]
17	*Tectona grandis*	India	0.44	Moist Forest	[23]
18	*Terminalia alata*	Nepal	0.52–0.66	Moist Forest	[66]
19	*Terminalia elliptica*	India	0.42	Moist Forest	[23]
20	*Tsuga dumosa*	Bhutan	0.48	Plantation	[9]

4. Form Factor Functions

Over the last century, several parametric functions have been developed to serve as the basic models for easier and more accurate determination of the form factors of different tree stems [9,69,70]. Generally, measuring cylinder form factors in the field is considered challenging, which is why most foresters and forest managers avoid the direct use of form factors in volume estimation. Instead, they opt for volume equations that involve only dbh or together with height as explanatory variables [49]. The form factor functions give the form factor of a tree stem by regressing it with more measurable tree characteristics, i.e., diameter at breast height and tree height, which significantly influence the stem form variation among trees and even of the same species. Developing these functions also sought to avert the volume estimation errors from generic usage of a form factor for individual tree of the same tree species within a similar stand or forest type and area.

Historically, the need to improve the Austrian Forest Inventory and obtain the highest possible accuracy in volume determination for the economic tree species in 1961 led to the research of more accurate methods of measuring the stem form considering its significance in volume inventory. Pollanschütz [69] developed an arithmetic form factor function based on the relationship between a normal form quotient and the breast height form factor. However, this function was limited in predicting form factor and volume for trees across different forest conditions. According to the author, this was also the case with the arithmetic functions of Naslund [71,72], including the Swedish functions mostly for pine, birch and spruce, and Meyer's form factor function [73]. Although the additional input of crown ratio (i.e., the percentage of a tree's total height occupied by its live foliage) in the Large Swedish function reduced the estimation error, Pollanschütz demonstrated the need for a standard logarithmic form factor function with different combinations of the common input variables (dbh and h) for more accurate predictions. Evert [74] later developed another arithmetic form-class function adapted to Australian forest growing conditions. Rosset [70] further developed a simple power regression method but with a log-linear transformation of both the response (f) and input (dbh and height) variables. All of these are summarized in Table 3. The five most commonly tested or adopted tree form factors for accurate tree volume estimation or standard volume table construction include Pollanschütz's, Short Swedish's, Meyer's, F. Evert's (Australian), and Rosset's form factor functions.

Table 3. A summary of some major candidates of parametric form factor functions in stem form modelling.

S/N	Form Factor Function	Regression Equation	Source
1	Large Swedish's	$f = a + b_1 \times \frac{1}{h} + b_2 \times \frac{1}{dbh} + b_3 \times \frac{1}{dbh^2} + b_4 \times \frac{h_k}{h}$	[72]
2	Short Swedish's	$f = a + b_1 \times \frac{1}{h} + b_2 \times \frac{1}{dbh} + b_3 \times \frac{1}{dbh^2}$	[71]
3	Meyer's	$f = a + b_1 \times \frac{1}{dbh^2 \times h} + b_2 \times \frac{1}{dbh \times h} + b_3 \times \frac{1}{dbh} + b_4 \times \frac{1}{h} + b_5 \times \frac{1}{dbh^2}$	[73]
4	Pollanschütz's	$f = a + b_1 \times ln^2(dbh) + b_2 \times \frac{1}{h} + b_3 \times \frac{1}{dbh} + b_4 \times \frac{1}{dbh^2} + b_5 \times \frac{1}{dbh \times h} + b_6 \times \frac{1}{dbh^2 \times h}$	[69]
5	F. Evert's Australian	$f = a + b_1 \times \frac{1}{dbh^2 \times h} + b_2 \times \frac{1}{h} + b_3 \times \frac{1}{dbh^2}$	[74]
6	Rosset's	$ln(f) = a + b_1 \times ln(dbh) + b_2 \times ln(h)$	[70]

NB: f is the form factor; ln is the Napierian/natural logarithm; dbh and h are in decimetres in function (4), while in other equations, dbh is in centimetres and h is in decimetres; h_k is the crown ratio—the percentage of a tree's total height occupied by its live crown.

Form Factor Functions Tested for Different Tropical Species

In our literature search, we found that unlike taper equations which have been extensively developed for several tropical tree species, especially for the economic plantation species [6], only a few studies have tested form factor models to evaluate the stem form of tropical tree species. Nevertheless, in these studies, the form factor regression equations stated above have been applied, in different combinations, for some tree species of different forest types (Table 4). Tenzin et al. [9] selectively fitted and evaluated Pollanschütz's, Short Swedish's, Meyer's, and F. Evert's functions with datasets of four tree species—*Tsuga Dumosa* (D.Don) Eichler, *Picea spinulosa* (Griff.) A. Henry, *Abies densa* Griff., and *Pinus wallichiana* A.B. Jacks—in Bhutan. Other studies [75,76] examined the five functions for *Acacia decurrens* Wild. and *Eucalyptus camaldulensis* Dehnh. in different forest areas in Ethiopia. Pollanschütz's function is widely regarded as the best owing to its consistency and lack of bias in predicting form factors [9,10,58], though its performance is sometimes comparable to other models [75]. However, the accuracy of the functions still varies with tree species and forest sites considered. For instance, Pollanschütz's equation had the best fit rank for *P. wallichiana* and *T. dumosa*, whereas Evert's for *A. densa*, and the Short Swedish for *P. spinulosa* using the rank sums of the fit statistics [9], although the authors subjectively selected the Pollanschütz's model options for all the species due to predictions' consistency.

Studies have attempted to model form factor without using a standard function and have obtained variable prediction performances, from low (21%) to high (83%) explained variances. Baral et al. [64] developed second-order polynomial functions using the ordinary least squares (OLS) modelling technique to estimate the form factor of *S. robusta* based on either diameter or height measurements. These simple 'non-standard' models could be attributed to comparatively lower prediction accuracy than functions typically fitted with the reciprocal inverses of the tree growth variables. However, Felipe et al. [53] used relative diameter measurements along stem height and recorded a significant effect in explaining the growth–form relationship. This approach somewhat follows the principle of Hohenadl's method of stem form assessment, which employs form quotient at percentual fractions of the total height (e.g., diameters at 0.3 and 0.5 of total height) [77] and could reduce the standard deviation of form functions [78]. Therefore, we recommend standardizing this function as a suitable candidate for further form factor modelling studies and propose the name "Hohenadl's form factor function".

Most existing form factor models have traditionally incorporated only dbh and total height [53,58,64], as is also common in stem taper equations [32]. However, in recent years, form factor modelling studies have started to include additional covariates, such as crown size, stand density, and species mixture, to better capture the attributes influencing stem form and enhance estimation accuracy. For example, Chapagain and Sharma [79] incorporated tree-level and stand-level variables, including crown ratio, relative diameter, and the basal area proportion of the species of interest, in modelling form factors for *S. robusta* using a mixed-effects modelling approach. This approach is well-suited for accounting for hierarchical and nested stem form data, as it better captures tree-level and stand-level variability as well as random effects. Therefore, mixed modelling should be increasingly considered for fitting form factor functions in future studies.

Table 4. Some form factor functions fitted for a few tropical tree species and their attributes.

Species	Parameters							n	Max dbh (cm)	RMSE	R^2	Forest Type	Reference
	a	b_1	b_2	b_3	b_4	b_5	b_6						
Pollanschtz′s function : $f = a + b_1 \times ln^2(dbh) + b_2 \times \frac{1}{h} + b_3 \times \frac{1}{dbh} + b_4 \times \frac{1}{dbh^2} + b_5 \times \frac{1}{dbh \times h} + b_6 \times \frac{1}{dbh^2 \times h}$													
Abies densa	0.5367	−0.016	ns	ns	−0.097	14.752	ns	45	60.3	N/A	0.45	* C. plantation	[9]
Paraserianthes falcataria	0.416	−0.070	8.085	−0.034	−0.001	5.485	−0.154	24	28.3	0.051	N/A	* S. plantation	[58]
Pinus spinulosa	0.4505	ns	−16.412	0.281	−0.153	14.270	ns	58	75.3	N/A	0.57	* C. plantation	[9]
Pinus wallichiana	0.6384	−0.023	−39.308	ns	−0.086	43.190	−7.639	59	95.8	N/A	0.43	* C. plantation	[9]
Tsuga dumosa	0.5425	−0.019	−5.847	ns	ns	4.994	ns	89	107.4	N/A	0.32	* C. plantation	[9]
Meyer′s function : $f = a + b_1 \times \frac{1}{dbh^2 \times h} + b_2 \times \frac{1}{dbh \times h} + b_3 \times \frac{1}{dbh} + b_4 \times \frac{1}{h} + b_5 \times \frac{1}{dbh^2}$													
Acacia decurrens	−2.812	34,386.117	−6841.019	67.464	325.494	−332.262	-	58	14.0	0.037	0.23	Woodlots & * S. plantation	[75]
Non − standard function : $f = a + b_1 \times dbh + b_2 \times dbh^2$													
Shorea robusta	0.2302	4.927×10^{-3}	-4.753×10^{-5}	-	-	-	-	100	112.7	N/A	0.23	* S. plantation	[64]
Non − standard function : $f = a + b_1 \times h + b_2 \times h^2$													
Shorea robusta	0.0307	0.028	-6.04×10^{-4}	-	-	-	-	100	36.5 **	N/A	0.21	* S. plantation	[64]
Non − standard "Hohenadl′s" function : $f = a + b_1 \times \frac{d_{0.3}}{dbh^2} + b_2 \times \frac{1}{dbh^2} + b_3 \times d_{0.5}$													
Tectona grandis	0.0926	6.677	−3.014	0.012	-	-	-	120	26.55	N/A	0.83	* E. plantation	[53]

n means sample size; R^2 indicates coefficient of determination; * S. plantation represents smallholder or community-managed forests; * C. plantation indicates commercial plantation, while * E. plantation represents experimental plantation. *ln* = Napierian logarithm; *f* = breast height form factor; $d_{0.3}$ & $d_{0.5}$ = Hohenadl's relative diameter at 0.3 and 0.5 of tree height (cm); *dbh* = diameter at 1.3m height (decimetre in Pollanschütz's, but centimetre in other functions); *h* = tree height (decimetre in Pollanschütz's and Mayer's functions, but metre in other functions); ns = non-significant; N/A = not available; ** indicates that the value is the maximum height (m).

5. Tree Growth and Form Factors

The form of a stem is inextricably influenced by tree growth, as demonstrated by the fundamental (mechanistic) theories. The two most important tree growth variables that directly define the shape of a tree stem and its segment include the diameter at breast height and tree height. Several studies have therefore examined the relationship between form factors and each of these vital growth variables [7,53,58,80,81]. This is usually to understand how changes in individual tree characteristics can influence the stand volume (estimation). Overall, the common trend observed in these studies depicts a negative correlation, whereby there is a decrease in form factors with dbh and height increments (see [7,53,80–82]). However, the trend is not entirely consistent throughout the studies.

According to Subedi et al. [7], there are initial increases in form factors of *S. robusta* as the tree dbh and height increase to a certain threshold when the form values become constant before starting to experience a downward slope with a further increase until they again stabilize. The authors reported the threshold before the form factor reduction to be about 60 cm dbh or 30 m in height. However, this depends on some factors, including the tree species, site quality or the structure of the stand. By implication, it is evident that there is a non-linear change in stem form with respect to tree dbh. The small-sized and big trees will record the lowest form factors, while trees in the middle-diameter classes exhibit the highest values.

In contrast, most other studies found no obvious distinction between the small-sized and mid-sized trees but rather a gradual decrease in the form factors, with the large trees having the lowest values [53,80,81]. In this case, the form factor reduction from small to big trees in the stand remains constant at a certain dbh or age point but varies with tree and site attributes. While Tenzin et al. [9] reported this occurred at 60 cm dbh across nine commercial tree species, in *Pinus taeda* L., it occurred at 40 cm dbh [81], and similarly in an 18-year-old *Tectona grandis* L.f. stand [53]. Therefore, the variation in tree height and dbh tends to influence the accuracy of the volume estimated using the form factor. However, in extreme cases, the form factor may not exhibit any significant and strong relationship with the tree variables, whereby the same form value can be applied to estimate tree stem volumes for trees of different sizes and heights without any observable error [46,68]. Also, only in rare instances were form factors positively correlated with tree growth (i.e., an increase in form factor with increasing tree diameter or height), as reported for *S. robusta* and *Fraxinus angustifolia* by Chapagain and Sharma [79] and Özbayram and Çiçek [54], respectively. These possible trends of the form factor–growth relationship are visualized in Figure 4.

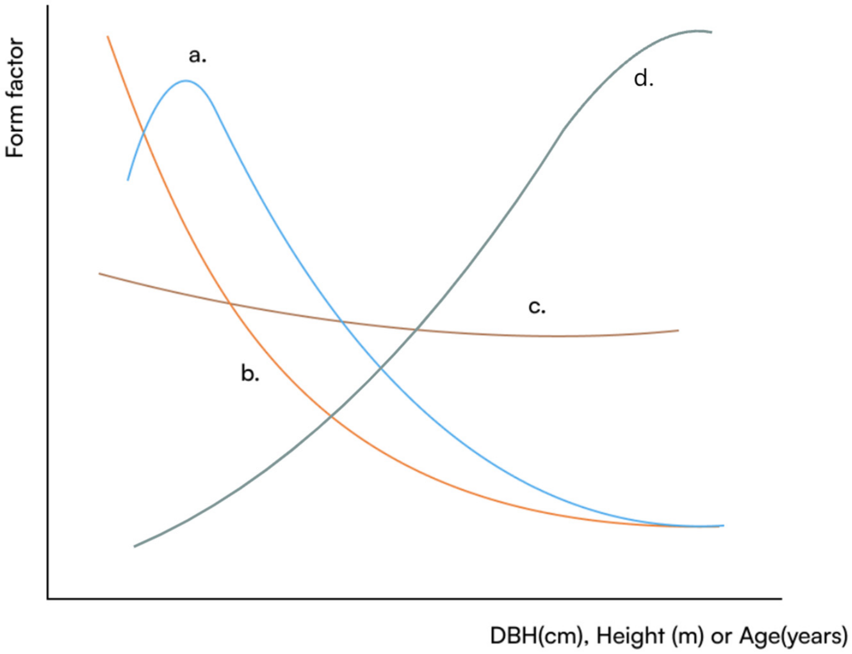

Figure 4. The relationship between form factor and growth of a tropical tree species takes one of the three trends: (a.) an initial increase in form factor to a constant point before a gradual decrease until the bottom growth or age peak; (b.) a gradual decrease in form factor without any initial increase until no further change is observed at a certain diameter or age, hence remains consistent; (c.) no visible trend is observed in the form factor variation with changes in the growth or age of the tree; (d.) a rare, gradual increase in form factor with increasing growth or age, reaching a peak point.

6. Applications of Form-Factor Approach in Volume Estimation

The volume of a tree stem can be estimated using either sectional methods or volume functions [62,83]. Sectional methods encompass the form-factor approach, which allows for estimating standing tree volume as the product of basal area from *dbh* (m), height (m), and form factor (unitless), without relying on volume or taper models.

$$V = \frac{\pi\, dbh^2}{4} \times h \times f$$

Although many volume inventory efforts use regression equations and taper/profile functions to estimate stem volumes [36,84,85], the use of form factor to calculate volume is common in practice by forest managers, attributed to certain comparative advantages [58,86,87]. Regression models based on diameter at breast height (*dbh*) and/or tree height can produce prediction errors. For instance, Stinglwagner et al. [88] found calculation errors of up to 15% even with accurate measurements of dbh and height. Therefore, the form-factor approach is needed to provide more accurate stem volume estimates for whole-tree stem or at any desirable point or section of measurement, considering its respective form along the tree stem [89].

The form-factor method has been recommended for tree volume prediction for its simplicity, flexibility, and analytical advantages, at least, over the least-squares volume regression techniques. Evert [86] demonstrates this in early testing research using black spruce (*Picea mariana* [Mill.] B.S.P.) trees. He noted that using the form-factor approach yielded more valid and accurate estimates for small trees. The resulting variances of tree volumes from the form-factor application are homogenous for both large and small trees, whereas weighted least-squares methods often exhibit low variances for small trees and high variances for larger trees. Beyond establishing the comparison on tree sizes, Sanquetta et al. [81] directly evaluated the performance and fitting superiority of form factor and volume regression models using 146 *Pinus taeda* trees and found that mean form factor, especially by diameter or age classes, gave the most accurate volume estimates. Other studies have similarly shown the form-factor method outperforming selected volume models and considered a simple and robust technique for quick tree and stand volume inventory [90,91]. Conversely, some studies have reported volume models to generate better tree volume estimation than the simple “V = BA × H × F” equation, although mostly without any significant differences [46,67,92].

7. Concerns Associated with Using Default or Generic Form Factors in Volume Estimation

The default form factor is a unique value (i.e., 0.5) presumed by many forest managers to have been globally recommended to describe tree stem form. A generic form factor refers to any value generally adopted from published studies with or without similarity in the sites or tree stands evaluated. Using default or generic form factors is prevalent amongst several commercial timber companies and government and community forestry officials worldwide in estimating standing tree volume for production, carbon stock inventory and forest planning. An example is the case of Nepal, where the usual default form factor (0.5) is recommended and adopted for all tree species in community forest mensuration, regardless of individual tree variations in growth and form [93]. Similarly, in Indonesian community forests, most communities lack adequate knowledge of timber volume estimation and, consequently, often rely on external agents who typically use a generic form factor for economic or ecological valuations of their standing trees [46]. Most agents or foresters in the country choose a general artificial form factor of 0.6 or 0.5 [94].

The use of either default or non-specific form factor value is often predicated on the absence of species- and site-specific form factors, apart from the fact that such practice permits flexibility for predicting tree volume [46,94,95]. Meanwhile, as previously justified, form factors vary with tree species, site conditions and silvicultural management practices. Therefore, applying a default form factor or such that has been estimated from different plantation forest, species, or site is attributed to volume prediction error. In a comparative volume mensuration study, Subedi et al. [7] found that the default form factor (0.5) and two other regional form factors resulted in an overestimation of the actual standing volume of *S. robusta* trees by up to 35%. Oluwajuwon et al. [58] reported a volume overestimation of up to 17% in *Paraserianthes falcataria* smallholder plantations. These estimation errors often have a direct implication on expanded biomass/carbon estimation from volume. Henry et al. [96] found a significant bias in biomass estimates converted from volumes computed using a generic form factor of 0.6 across some African tropical forests. Nevertheless, the trend and significance of estimation errors from alternative values vary and may be dependent on relative variability in methodologies, species architecture, site, stand, and management conditions compared to the forests from which the form values were originally obtained.

8. Conclusions, Recommendations, and Opportunities for Future Research and Development

The study provides a comprehensive review of form factor as a crucial measure for stem form and volume modelling, aimed at enhancing forest management and planning. The review highlights various factors, including site, tree and stand factors, that influence tree form variations. Many of these factors have not been adequately integrated into form factor modelling in previous studies and could be explored more in future research, for instance, by using a mixed modelling approach that accounts for greater tree-level and stand-level variability and effects. The parametric "Hohenadl" method highlighted in this review, which incorporates relative diameter measurements, could be further investigated and standardized for future form factor modelling. This study recommends that forest managers and decision-makers utilize specific form factors for volume estimation rather than default values to maximize forest volume and carbon stock valuation, given the observed dynamic relationship between stem form and tree growth over time.

Form factor and stem form can be estimated both over-bark and under-bark using over-bark and under-bark diameters, respectively. While there is typically a linear relationship between these two forms of diameter, form factor can vary considerably [7]. Until now, much attention has been focused on measuring diameter over bark for describing stem form and estimating stem volume. Meanwhile, providing information on or developing techniques to easily measure diameter under bark may improve actual stem form and volume characterization and provide more accurate merchantable stem wood valuation [6]. Non-destructive advanced technologies, such as ground-penetrating radar, terrestrial stereoscopic photogrammetry, ultrasonic testing, terrestrial laser scanning (TLS), and resistance drilling methods, have the potential to profile tree form and structure by distinguishing different wood parts and diameter under bark for improved measurement accuracy. Such technologies offer a comparative advantage over manual tree profile assessments and can efficiently supplement them [6,22,32]. Jacobs et al. [22] recently modelled form factors for tree stems using TLS, achieving improved estimation accuracy.

Generally, the application and development of form factor and its function in tree form and forest modelling have been quite limited compared with taper functions. Despite recent advancements in the use of non-parametric techniques, such as machine learning (ML) algorithms, in modelling tree form and taper over conventional parametric fitting methods [6,97,98], there is a dearth of studies like [99] that have integrated these contemporary ML approaches specifically in modelling form factors. Research efforts could therefore be directed toward exploring the potential of fitting and modelling form factor and its volume prediction using techniques like random forest (RF) regression trees, artificial neural networks (ANNs), and k-nearest neighbour (k-NN). These approaches can effectively complement traditional modelling practices in developing form factor equations with much better predictive accuracy.

Author Contributions: Conceptualization, T.V.O. and M.S.H.; methodology, T.V.O. and M.S.H.; writing—original draft preparation, T.V.O., C.E.O. and R.I.; writing—review and editing, T.V.O., F.N.O. and D.J.L.; visualization, T.V.O. and C.E.O.; validation, T.V.O., F.N.O., R.I. and D.J.L.; funding acquisition, D.J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work received funding support to cover its publishing costs from the Forest Research Institute, University of the Sunshine Coast.

Data Availability Statement: No new data were created or analysed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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