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Comparative Accuracy and Precision Assessment of Survey Instruments for Teak Tree Height Measurement and Carbon Sequestration Estimation

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Abstract

This study comparatively evaluated the accuracy and precision of three tree height measurement instruments: a Laser Rangefinder, a Total Station in Remote Elevation Measurement (REM) mode, and a Total Station in Coordinate mode. The research also compared their operational efficiency for teak tree height measurement and demonstrated their application in estimating carbon sequestration. This novel field-based validation offers a comparative analysis for commercially and ecologically significant teak (Tectona grandis), directly linking precise height measurements to carbon stock estimation and addressing the practical need for reliable, efficient survey methodologies in tropical forestry. Height measurements were conducted against a precisely determined reference under controlled offset conditions (-0.50, -0.25, 0.00, +0.25, +0.50 m from true vertical). Results indicated the Total Station (Coordinate mode) yielded the highest accuracy, precision, and overall efficiency, considering acceptable error margins. The Laser Rangefinder was the most rapid but exhibited lower accuracy and efficiency. Field measurements of 93 teak heights across all three instruments showed no statistically significant differences at the 95% confidence level, a consistency observed in repeated and inter-user measurements. Carbon dioxide equivalent calculations of 76,554.19 kg revealed Coordinate mode estimates differed by only 1.29% from the Laser Rangefinder and 4.20% from the REM mode.

Keywords: Tree height measurement, Carbon sequestration, Carbon stock, Total station, Laser Rangefinder

1. Introduction

Tree height is fundamental in forest management for assessing growth, timber volume, biomass, and carbon sequestration. Accurate data are crucial for effective forest resource planning, sustainable management, and mitigating greenhouse gas emissions (Brown, 2002). Despite its importance, achieving accurate and precise field measurements remains challenging, often due to varied instrument designs and operational principles. For instance, Laser Rangefinders are designed for forestry, while Total Stations are for broader surveying. Although foundational mensuration is established (Husch et al., 2003), ongoing investigation and validation are needed for modern instrument’s comparative field performance, accuracy, and efficiency, especially Total Station's Remote Elevation Measurement (REM) and Coordinate modes.

Recent technological advancements offer new tools for forest structure assessment, including UAV-based LiDAR, digital aerial photogrammetry, Terrestrial Laser Scanning (TLS), and satellite sensors (e.g., Abegg et al., 2023; Zhou et al., 2023; Coops et al., 2025). While these technologies show potential, a deeper understanding is required before their regular application in national forest inventories. Meanwhile, traditional ground-based Total Stations, particularly their REM and Coordinate modes, are increasingly being applied in forestry to enhance measurement accuracy. Selecting appropriate instruments and measurement protocols is critical for robust biomass and carbon stock assessments, influencing forest conservation and ecosystem restoration (Pretzsch, 2009; Chave et al., 2014). However, relying solely on manufacturer specifications can be misleading, as field conditions (terrain variability, canopy density, tree morphology, operator skill) significantly influence measurement outcomes. Thus, field-based evaluations are crucial for determining practical accuracy, precision, and efficiency under real-world conditions.

A discernible lack of comprehensive comparative studies specifically validating the performance of Total Station's REM versus Coordinate modes for tree height surveys across diverse tree forms remains. This gap is particularly critical for economically significant species like teak (Tectona grandis) in tropical forestry, which this study addresses through empirical field validation. Teak was selected due to its considerable economic importance in Thailand and Southeast Asia, widespread use in plantation forestry, straight bole morphology facilitating height measurement, and substantial contribution to carbon stock via high aboveground biomass and long-term storage capacity.

This research systematically evaluates and compares the accuracy, precision, and operational efficiency of a Laser Rangefinder, a Total Station (REM mode), and a Total Station (Coordinate mode), using teak trees as a case study. The study also demonstrates the practical application of these height measurements in estimating teak's carbon sequestration potential. By providing a rigorous comparative assessment, this research offers valuable insights for instrument selection in various forestry contexts, ultimately contributing to more accurate and efficient methods for forest inventory, biomass assessment, and carbon accounting.

2. Objectives

2.1 To comparatively evaluate the accuracy and precision of a Laser Rangefinder, Total Station (REM mode), and Total Station (Coordinate mode) for tree height measurement under controlled and field conditions.

2.2 To assess and compare the operational efficiency of these methods in measuring teak (Tectona grandis) tree height.

2.3 To demonstrate the practical application of height measurements from these methods in estimating carbon sequestration, providing a relevant case study for tropical forestry and environmental monitoring.

3. Methodology

This study systematically investigated and compared the performance of three widely used instruments and operational modes for tree height measurement: a Laser Rangefinder and a Total Station operating in both Remote Elevation Measurement (REM) and Coordinate modes.

Instrument Specifications:

1) Laser Rangefinder: Nikon Forestry Pro II brand. Supports a 2-point height mode with ±0.3 m precision for distances < 1,000 m. Measures up to 1,600 m; display results with 0.1 m resolution for distances < 1,000 m and 1.0 m for longer distances (Nikon, 2019).

2) Total Station: TOPCON GPT-3005N brand. Features 5 arcseconds angular accuracy and Non-Prism measurements up to 1,200 m. Offers 1 mm display resolution in fine mode. Supports REM and Coordinate modes for flexible, precise measurements (TOPCON, 2005).

3.1 Accuracy and Precision Assessment under Simulated Offset Conditions Accuracy and precision were assessed using a precisely determined 4.247 m reference height. This reference was meticulously measured indoors at Lampang Rajabhat University's Civil Technology Building. Offset distances of -0.50, -0.25, 0.00, +0.25, and +0.50 m from the true vertical were established (Figure 1). The experimental setup ensured horizontal distances exceeded the Nikon Forestry Pro II's minimum of 7.5 m and observation angles (<45 degrees) were within optimal operating range to minimize errors (Bragg, 2007; Bragg et al., 2011).

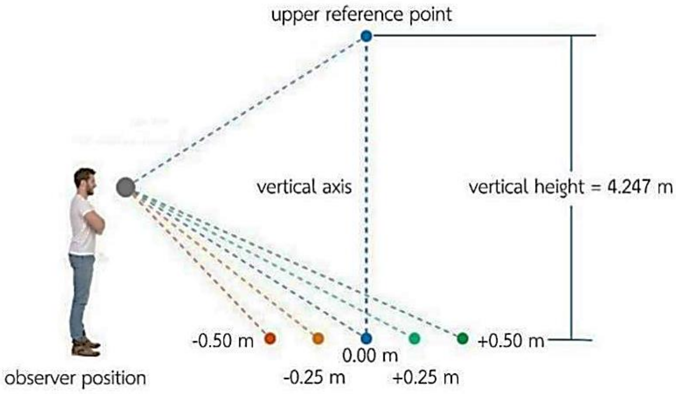

Figure 1 illustrates the height measurement testing method by simulating offset scenarios at -0.50, -0.25, 0.00, +0.25, and +0.50 meters.

3.2 Study Site and Teak Tree Samples, the study was conducted at Lampang Rajabhat University on 93 teak trees (girth > 15 cm). The girth was measured at breast height (1.3 m above ground), following standard forestry practice. Both upright and leaning teak trees with varying heights were included to reflect natural field variability and ensure realistic assessment conditions.

3.3 Field Measurement of Teak Tree Heights Teak tree heights were measured using three instruments:

1) Laser Rangefinder: Employed the 2-point method, standing at least 7.5 m from the tree (Figure 2, left).

2) Total Station REM mode: Positioned at the same location as the Laser Rangefinder, ensuring an unobstructed vertical line of sight from tree base to top (Figure 2, right).

3) Total Station Coordinate mode: Measured 3D coordinates at the tree base and top (Figure 3). Height data from all instruments were used to estimate carbon sequestration in teak biomass.

Figure 2 illustrates the field setups: Laser Rangefinder (left), and Total Station (right).

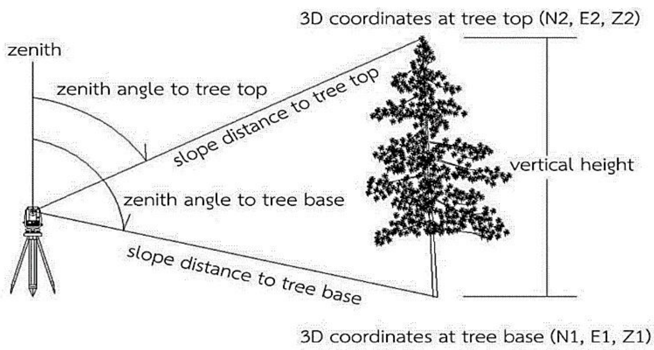

Figure 3 illustrates height measurement using a Total Station in Coordinate mode.

3.4 Statistical Data Analysis Statistical analysis was conducted in two parts:

1) Measuring the reference height of a building to analyze accuracy and precision, considering Bias, E %, SD, precision, and EE values as following:

(1) Bias, or the difference between the measured value and the actual height value, obtained from all three types of instruments, as shown in Equation 1:

$$\text{Bias} = \text{Measured value} - \text{Actual value} \tag{1}$$

(2) Mean Absolute Percentage Error (E%), as shown in Equation 2:

$$\mathrm{E}\% = \frac{1}{\mathrm{n}}\sum\frac{(\text{Measured value}-\text{Actual value})}{\text{Actual value}} \times 100\% \tag{2}$$

where n is the number of data points, and the lowest E% value indicates the most accurate measurement.

(3) The statistics used to indicate the precision of the measurement can be analyzed from the Standard Deviation (SD) and the measurement precision, according to Husch et al. (2003), as shown in Equation 3:

$$\text{Precision}^2 = \text{Accuracy}^2 - \text{Bias}^2 \tag{3}$$

The statistics used to analyze the efficiency and time consumption of all three types of instruments are considered from the Efficient and Error-Tolerant (EE), which can be obtained from Equation 4 (Bonyad and Mirzaei, 2016):

$$\mathrm{EE} = \mathrm{E\%}^2 \times \mathrm{T} \quad (4)$$

where T is the total time used for the measurement. A calculation result that yields a low EE value is considered cost-effective in terms of time spent and measurement error.

2) Teak Tree Height Measurement: Statistical differences were analyzed using One-way ANOVA.

3.5 Carbon Sequestration Estimation Tree height (from three instruments) and circumference at breast height (approx. 1.3 m above ground, by a measuring tape) were collected. These data were applied to estimate aboveground biomass and carbon sequestration using allometric equations (Ogawa et al., 1965; Thailand Greenhouse Gas Management Organization, 2023).

4. Results

This study evaluated the accuracy, precision, and efficiency of tree height surveying instruments. Results are presented in two main sections: 1) instrument assessment under controlled conditions, and 2) comparative analysis of teak tree height measurement in the field, including operational efficiency and an illustrative example for carbon sequestration.

4.1 Instrument Accuracy and Precision

1) Accuracy

Table 1 presents the direction of systematic error, and the Absolute Mean Bias (AMB), reflecting the overall magnitude of measurement deviations regardless of direction. The Total Station in Coordinate mode consistently provided average height values closest to the reference value of 4.247 m. When accuracy was evaluated using Percent Error (E%), the Total Station in Coordinate mode demonstrated the lowest average E% (0.020%). In contrast, the Total Station in REM mode and the Laser Rangefinder exhibited higher average E% values (2.235% and 4.717%, respectively).

Table 1 Comparison of height measurement instrument accuracy against the 4.247 m reference value under simulated offset scenarios.

Offset from reference point	Laser Rangefinder			Total Station Mode REM			Total Station Mode Coordinate		
	$\bar{h} \pm \sigma$ (m)	AMB	E %	$\bar{h} \pm \sigma$ (m)	AMB	E %	$\bar{h} \pm \sigma$ (m)	AMB	E %
-0.50	4.000±0.058	0.247	5.816	4.093±0.000	0.154	3.634	4.248±0.000	0.001	0.016
-0.25	3.967±0.033	0.280	6.601	4.169±0.001	0.078	1.829	4.248±0.001	0.001	0.024
0.00	4.100±0.058	0.147	3.461	4.249±0.001	0.002	0.047	4.247±0.000	0.000	0.008
+0.25	4.167±0.067	0.116	1.892	4.328±0.000	0.081	1.907	4.247±0.001	0.001	0.008
+0.50	4.000±0.058	0.247	5.816	4.407±0.000	0.160	3.760	4.245±0.000	0.002	0.047
Average	**4.047±0.055**	**0.207**	**4.717**	**4.249±0.000**	**0.095**	**2.235**	**4.247±0.000**	**0.001**	**0.020**

2) Precision evaluated as Standard Deviation (SD) of height measurements under each offset condition was shown in Table 2. Both Total Station modes showed high precision (low SD values). The Laser Rangefinder, however, exhibited greater measurement variability, indicating lower precision (higher SD values). For instance, the average deviation from the 4.247 m true height of 4.247 m was minimal for Coordinate mode (0.000 m) and REM mode (-0.001 m), while whereas the Laser Rangefinder's average was 0.006 m lower.

Table 2 Standard deviation (SD) and deviation from true value of mean height measurements from the reference point at various distances.

Reference Point Offset (m)	Laser Rangefinder (m)		Total Station REM Mode (m)		Total station Coordinate Mode (m)	
	SD	Precision	SD	Precision	SD	Precision
-0.50	0.100	4.239	0.001	4.244	0.001	4.247
-0.25	0.058	4.237	0.001	4.246	0.001	4.247
0.00	0.100	4.244	0.001	4.247	0.001	4.247
+0.25	0.115	4.245	0.000	4.246	0.002	4.247
+0.50	0.100	4.239	0.001	4.244	0.000	4.247
Average	**0.055**	**4.241**	**0.000**	**4.246**	**0.001**	**4.247**
Deviation from True Value		-0.006		-0.001		0.000

3) Efficiency and Error-tolerance (EE) The Laser Rangefinder was the quickest instrument, averaging 3.22 minutes per series under controlled conditions (Table 3). It exhibited the lowest overall efficiency and highest error susceptibility (EE = 71.647). Both Total Station modes demonstrated significantly higher efficiency. The Coordinate mode achieved the lowest EE (0.00325), highlighting its superior balance of accuracy and time, followed by REM mode (EE = 41.222) (Table 3).

Table 3 Comparison of Efficiency and Error-tolerance (EE) of height measurement instruments.

Instrument	Average E %	Time (min)	EE
Laser Rangefinder	4.717	3.22	71.647
Total station in REM mode	2.235	8.25	41.222
Total station in Coordinate mode	0.020	7.80	0.00325

4.2 Teak Tree Height Measurement Comparison

1) Statistical Analysis of Field Height Measurements.

Table 4 presents the statistical results of height measurements from 93 teak trees using three instruments. The Total Station in REM mode yielded the highest average height (14.036 m), followed by the Coordinate mode (13.485 m) and the Laser Rangefinder (13.275 m). REM mode also recorded the lowest standard error (0.010 m) and standard deviation (0.029 m), suggesting high precision in this context. However, it exhibited the widest data range (17.118 m), indicating greater susceptibility to field conditions or tree form variability affecting individual measurements.

Table 4 Statistical analysis results of teak tree heights measured by the three instruments.

Statistical Values / Height Measurement Instruments	Height (m)		
	Laser Rangefinder	Total station Mode REM	Total station Mode Coordinate
Mean	13.275	14.036	13.485
Standard Error	0.085	0.010	0.035
Standard Deviation	0.254	0.029	0.104
Range	16.056	17.118	15.863
Minimum	7.378	7.625	7.794
Maximum	23.433	24.744	23.657

2) Comparison of Statistical Differences in Teak Tree Heights

One-way ANOVA analysis revealed a P-value of 0.33, which is greater than the significance level of 0.05. This leads to the acceptance of the null hypothesis that the mean teak tree heights measured by the three instruments do not differ significantly at a 95% confidence level (Table 5). Furthermore, tests for differences in repeated measurements by each individual measurer and between different measurers using the same instrument also yielded P-values greater than 0.05. These results suggest that, under the conditions of this study, neither repeated measurements by the same operator nor operator variability (among trained individuals following the same protocol) significantly affected the obtained height values at the 95% confidence level.

Table 5 Statistical test results considering variance caused by the instruments.

Source of Variation	SS	df	MS	F	P-value
Between Groups	28.708	2	14.3542	1.1143	0.3296
Within Groups	3,555.518	276	12.8823		
Total	**3,584.227**	**278**			

3) Illustrative Application for Carbon Sequestration Estimation, a moderate linear relationship (R^2= 0.5145) was observed between tree height (Coordinate mode data) and diameter at breast height (DBH) (Figure 4). When estimating carbon sequestration, results from the three instruments were similar: Laser Rangefinder (75,564.77 kgCO_2eq), Total Station REM mode (79,771.64 kgCO_2eq), and Coordinate mode (76,554.19 kgCO_2eq). Compared to the Coordinate mode reference, REM mode was 4.20% higher, while the Laser Rangefinder was 1.29% lower. These differences are considered acceptable, reflecting that all three instruments can reliably measure height for carbon sequestration estimation.

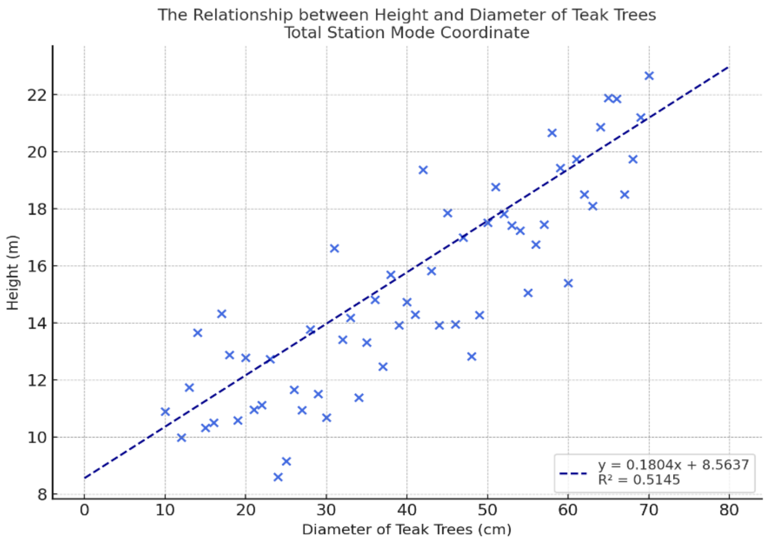

Figure 4 Relationship between height and diameter at breast height of teak trees.

5. Discussion and Conclusions

5.1 Discussion

1) Comparison of Instrument Accuracy and Precision under Controlled Conditions

The Total Station provided the highest height measurement accuracy and precision against the 4.247 m reference (Table 1, Table 2). Its superior performance (lowest E% of 0.020%, minimal deviation) aligns with the total stations' capabilities for precise positional determination (Simonjan and Shendyapina, 2020). Coordinate mode's reliance on 3D coordinate calculations, similar to the sine method, offers greater robustness against errors for inclined targets (Bragg et al., 2011). The Laser Rangefinder (Nikon Forestry Pro II), using its 2-point mode, also relies on trigonometric principles for vertical height differences.

Conversely, Total Station (REM mode) (avg. E% = 2.235%) and Laser Rangefinder (avg. E% = 4.717%) exhibited lower accuracy in these tests. REM mode's tangent function dependence makes it susceptible to errors with leaning targets, causing over/underestimation (as shown previously in Section 2)). The Laser Rangefinder, though convenient and fast (Pretzsch, 2014), showed the lowest accuracy. Total Station's significantly higher resolution (0.001 m distance, 0.001 degrees angle) and stable tripod mounting versus the handheld Laser Rangefinder contribute substantially to these accuracy and precision differences.

2) Field Performance and Factors Influencing Measurements

Field measurements of teak height revealed the REM mode yielded the highest average height (14.036 m), exceeding coordinate mode (13.485 m) and Laser Rangefinder (13.275 m), despite coordinate mode's superior controlled accuracy. Tree inclination, explored through simulated offset conditions, strongly explains this discrepancy. While teak generally has straight boles, subtle leans are common. If the crown apex leans towards the instrument, REM mode's trigonometric calculations will overestimate true height. Coordinate mode, by determining precise 3D coordinates, is less susceptible to such lean-induced errors.

Interestingly, the Laser Rangefinder (lower controlled accuracy, E% of 4.717%) produced mean field heights (13.275 m) closer to Coordinate mode (13.485 m) than REM mode (14.036 m). This may stem from its 2-point method, which, while prone to random sighting errors, might be less affected by systematic overestimation from forward tree lean. Its simpler operation could also contribute to more consistent apex sighting compared to REM mode.

Despite instrument-specific tendencies, one-way ANOVA showed no statistically significant difference ($P=0.33$) among mean tree heights measured by the three instruments in the field at a 95% confidence level (Table 5). This suggests comparable average height estimations for practical field applications, indicating operational robustness. Consistency in repeated and inter-user measurements further supports this interchangeability for average height estimation.

3) Implications for Carbon Sequestration Estimation

The relationship between tree height and DBH yielded a moderate $R^2=0.5145$ (Coordinate mode data). This implies that biomass and carbon estimates relying heavily on DBH, or on heights predicted from DBH, will inherently carry uncertainty. Direct incorporation of accurately measured tree height (e.g., from Coordinate mode) into allometric equations (Chave et al., 2014; Ogawa et al., 1965) can reduce this uncertainty and improve carbon stock assessment precision.

Carbon sequestration estimates (CO_2 equivalent) from the three instruments were relatively similar: Coordinate mode differed by only 1.29% from Laser Rangefinder and 4.20% from REM mode indicating consistency in carbon sequestration estimates. While these overall differences appear minor at this study's scale, instrument and method choice become critical for large-scale inventories or high-precision carbon accounting. Systematic biases, like REM mode's potential overestimation, could accumulate to significant discrepancies in total carbon stock over extensive forest areas.

4) Practical Implications, Efficiency, and Instrument Selection

It is interesting to note that the measurement time using the Laser Rangefinder was the fastest, averaging 3.22 min/tree, making it attractive for rapid field assessments. However, it exhibited a higher error efficiency (EE = 71.647) compared to the Total Station (REM and coordinate modes). Total Station (Coordinate mode), though slower (avg. 7.80 min/tree), demonstrated superior accuracy (avg. E% = 0.020%) and the lowest EE (0.00325). This positions the Coordinate mode as preferred for research or inventories demanding high-fidelity data (Hummel et al., 2011). In contrast, REM mode offered intermediate performance (avg. 8.25 min/tree and EE = 41.222).

A pragmatic cost-benefit perspective is essential for instrument selection in diverse forestry contexts. For large-scale inventories, community forestry initiatives, or situations with limited budgets and personnel, the significantly lower cost and rapid deployment of Laser Rangefinders may outweigh their lower intrinsic accuracy, particularly if average estimates over many trees can mitigate some individual measurement errors. However, it is crucial to acknowledge the potential for higher variability and bias. Conversely, when the objective is to develop precise allometric models, monitor subtle changes in forest structure, or for carbon projects demanding high accountability and verification, the higher initial investment and operational time associated with the Total Station in Coordinate mode are justified by its superior data quality. The Total Station in REM mode might serve as a practical compromise where a Total Station is available, and a balance between speed and accuracy-better than that of a Laser Rangefinder but less time-consuming than full Coordinate measurements is sought, provided users are cognizant of and can potentially account for its bias related to tree inclination. For instance, conventional

Total Stations requiring a prism for distance measurement would necessitate using REM mode to avoid climbing trees to place a prism at the top, thereby enhancing safety and convenience in such scenarios.

5) Limitations of the Study and Future Research

This study has several limitations that should be considered when interpreting the results. First, the instrument evaluation was limited to specific models (Nikon Forestry Pro II and TOPCON GPT 3005N), so findings may not generalize to devices with different specifications or technologies. Second, the field site at Lampang Rajabhat University, while representative of local teak plantations, did not reflect broader conditions such as steep terrain, dense understorey, complex canopies, or leaf-on periods in deciduous forests - factors that may further affect measurement accuracy. Third, despite the use of standardized protocols (Section 3.3), variability in operator skill and judgment -particularly when identifying tree bases and tops in complex field settings - may still contribute to measurement uncertainty. Future research should address these limitations by developing calibration or correction models to reduce errors from tree inclination and sighting challenges. Broader comparisons across more device models, forest types, and species are also needed to improve generalizability. Furthermore, integrating height data from efficient ground-based methods with emerging remote sensing technologies - such as UAV-LiDAR, terrestrial laser scanning, or satellite sensors (e.g., Zhou et al., 2022; Abegg et al., 2023; Coops et al., 2025) - could support the development of more robust and scalable systems for forest inventory and carbon monitoring. Such hybrid approaches are essential for improving local forest management and strengthening contributions to global climate change mitigation.

5.2 Conclusion

This comparative study evaluated the accuracy, precision, and operational efficiency of tree height measurement tools in the context of teak plantation forestry, focusing on a laser rangefinder (Nikon Forestry Pro II) and a total station (TOPCON GPT-3005N) operated in both Remote Elevation Measurement (REM) and Coordinate modes. Under controlled conditions, the Coordinate mode consistently yielded the most accurate and precise results, with the highest efficiency index. The Laser rangefinder was the fastest method but showed lower accuracy, while the REM mode exhibited sensitivity to tree inclination. Field measurements of 93 teak trees revealed no statistically significant differences in mean tree height among the three methods ($P = 0.33$), suggesting practical interchangeability for average height estimation. Estimates of carbon sequestration were similarly consistent, with only slight variations observed among the different measurement methods. This study provides practical value as a field validation of existing height measurement tools. The results highlight real-world trade-offs between measurement accuracy, operational speed, and equipment cost-critical considerations for forestry practitioners and carbon monitoring initiatives operating under resource and logistical constraints. These insights are especially relevant to tropical plantation forestry, where rapid yet reliable data collection is essential. While the Coordinate mode is recommended for applications requiring high precision or the generation of reference data, the laser rangefinder offers an efficient alternative for routine surveys. The findings thus offer actionable guidance for tool selection and contribute useful recommendations for optimizing measurement strategies in applied forestry. Future work should explore correction models for faster methods and expand testing across diverse forest types and species.

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