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Choosing the right close-range technology for measuring DBH in fast-growing trees plantations

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ABSTRACT

Recently, the cultivation of fast-growing tree (FGT) plantations has gained importance due to the growing energy and climate crisis. FGT plantations have the potential to reduce carbon footprints and lower greenhouse gas emissions by utilization of local renewable energy sources. Effective monitoring of above-ground biomass (AGB) is crucial for the successful management of these plantations. Standard methods for estimating AGB rely on easily measurable parameters, such as Diameter at Breast Height (DBH) and tree height, which are highly correlated with AGB. Traditional methods for measuring DBH include measuring tapes and calipers; however, these techniques can be labor-intensive, time-consuming, and limited when assessing large areas. Innovative approaches, such as photogrammetry, terrestrial laser scanning (TLS), mobile laser scanning (MLS), and iPhone LiDAR scanning, can complement these traditional methods by generating point clouds that can be used for extracting dendrometric parameters. This study evaluates the effectiveness of TLS (RIEGL VZ-1000), MLS (Stonex X120 GO), iPhone LiDAR (iPhone 13 Pro MAX), and terrestrial photogrammetry (iPhone 13 Pro MAX) for estimating DBH in a Paulownia plantation. Each technology has limitations: while TLS offers high accuracy, it is also expensive and time-consuming. Similarly, MLS is relatively costly. On the other hand, iPhone LiDAR and terrestrial photogrammetry are more affordable alternatives; however, the iPhone LiDAR has a limited scanning range, and photogrammetry requires considerable time and expertise for data collection and processing. The primary objective of this study was to evaluate these technologies based on their accuracy in DBH estimation, ease of use, data collection, processing time, and cost within the ideal conditions of a Paulownia plantation (characterized by the absence of understory, level ground, and uniform tree shape and spacing). The aim was to determine whether traditional methods could be replaced with more efficient, quicker, easier, and cost-effective alternatives. Results indicated that TLS, MLS, and photogrammetry provided similar DBH estimation accuracies, with root mean square error (RMSE) values between 0.7 and 0.72 cm and relative RMSE values between 2.87 % and 2.95 %. In contrast, the iPhone LiDAR was the least accurate, with an RMSE of 1.7 cm and an rRMSE of 6.96 %. This study demonstrates that all evaluated technologies offer sufficient accuracy for DBH estimation, although TLS and MLS capture additional parameters at a higher cost. Therefore, TLS is impractical for DBH estimation in plantation environments due to its high cost, time, and labor demands. While less expensive, terrestrial photogrammetry also requires significant time investment and operator expertise. Despite its cost, MLS achieved the best results among all the evaluated technologies and proved to be the fastest and relatively simple. If cost is a concern, the best solution for DBH estimation in an FGT plantation environment would be iPhone LiDAR scanning. It represents the most affordable option with satisfactory accuracy and ease of use.

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1. Introduction

Fast-growing trees (FGT) plantation plays a significant role during the energy and climate crisis. The cultivation of FGT offers an opportunity to increase energy security by providing a local source of low-carbon renewable biomass fuel, also reduces greenhouse gas emissions and helps in the economic development of rural communities (Lindegaard et al., 2016).

For efficient cultivation of FGT plantations, it is essential to identify suitable areas for their establishment and focus on monitoring their production characteristics. Monitoring includes various methods, but the non-destructive method of biomass estimation is crucial for developing appropriate harvest logistics, determining the optimal timing of interventions, and planning budgets (Sramek et al., 2023). The most used methods for estimating biomass regression and empirical modelling which typically involve measuring parameters such as tree height and diameter at breast height (DBH). These two parameters are among the most important directly measurable variables in forest inventory, which serve as the basis for deriving other parameters such as wood volume, biomass, and the amount of accumulated carbon (Balenović et al., 2021; Chen et al., 2019).

The traditional methods for measuring DBH of trees are measuring tape and caliper. Over the last period, the evolution of these instruments has mainly involved the integration of a digital display, internal memory, and a data transmission system. The traditional method of measuring DBH is labor-intensive, time-consuming, and becomes limited when measuring large areas (Cabo et al., 2018; Chen et al., 2019).

Alternatively, LiDAR technology could be a step forward and more efficient for measuring DBH. Over the past two decades, tremendous advances have been made in technologies for detailed modeling of objects in three-dimensional (3D) space. Using different types of laser scanners, it is possible to create models with high spatial detail and accuracy (Liang et al., 2022). An alternative to laser scanning is photogrammetry. The field of photogrammetry has also made dramatic advances in recent years. High-performance computing is now available, which, in conjunction with developed algorithms, provides the ability to create 3D objects with accuracy similar to TLS (Mokroš et al., 2018). Laser scanning and terrestrial photogrammetry provide valuable information for decision-making in forest and plantation management practices (Gollob et al., 2021)

The principle of laser scanning (LiDAR - Light detection and ranging) is based on the use of active types of sensors that emit a laser beam and then, after reflecting it from the objects of interest, receive it and infer the position of the reflection. A point is formed at the estimated position of the reflection. The sum of all the points created is called the point cloud, a basic object for further analysis and object parameters extraction. Based on mobility, laser scanning can be divided into static laser scanning (also referred to as terrestrial laser scanning TLS) and mobile laser scanning (Hyyppä et al., 2020).

TLS scans objects of interest from a static position on a tripod (Liang et al., 2016). TLS generates the most precise 3D point clouds and offers the highest level of accuracy in estimating DBH, tree height, and other dendrometric parameters as compared to other technologies (Liang et al., 2018). On the other hand, the initial cost is relatively high, and data collection is time-consuming; TLS can generate high point density, so the processing of the data could be cumbersome and would require powerful computational resources and significant storage capacity because of the precision and level of details in the data. As a result, it is primarily utilized for the detailed monitoring of small areas; perhaps the biggest drawback is the inability to detect all trees in the research plot due to occlusion caused by other objects (e.g., trees, shrubs, understory, branches, etc.) (Kükenbrink et al., 2022; Liang et al., 2016). Occlusion generally increases with the distance between the detected tree and the scanner positions within the plot. Occlusion can be minimized by incorporating more scan positions of TLS (Astrup et al., 2014; Liang et al., 2016).

The occlusion effect can be mitigated with MLS because the data collection method is not static and can capture the objects of interest from multiple perspectives. Scanners are typically carried in the hand (HMLS), on a backpack, or various other platforms attached to the moving objects (e.g., various vehicles, tractor, etc.). MLS devices most commonly use SLAM (Simultaneous Localization and Mapping) technology to link individual scans (Balenović et al., 2021; Bauwens et al., 2016). SLAM determines the location and orientation of a device in the local coordinate system at a specific moment in time using the detected objects, and also produces a map of the surroundings (Mokroš et al., 2021).

The main advantage of MLS is the fast data collection with no need to calibrate the equipment, neither to place reference spheres, targets, or tripod (Gollob et al., 2020). The device is lightweight and easy to carry, allowing easy movement even in more rugged terrain as compared to TLS (Balenović et al., 2021). On the other hand, MLS has lower spatial accuracy and low point density compared to TLS, due to presence of noise in the point clouds the possibility of false tree detection and duplications occurs, especially in denser stands (Mokroš et al., 2021).

Both technologies (MLS and TLS) are still relatively expensive. A more affordable alternative to these technologies might be iPhone LiDAR technology or terrestrial photogrammetry (Liang et al., 2022). iPhone with built-in LiDAR sensor offers a cost-effective alternative to MLS and TLS systems. This innovative technology allows the visualization of point clouds in colour. However, it is important to acknowledge that the scanning range of these devices is limited to five meters. While this range may prove inadequate for capturing more complex dendrometric parameters, it can still be effectively utilized for the tasks such as DBH estimation. (Gollob et al., 2021; Mokroš et al., 2021).

There are several applications available for Apple LiDAR devices that enhances the measurement and analysis of dendrometric parameters. For instance, the 3D Scanner App by Laan Labs allows users to create 3D point clouds, which can be easily saved and shared. However, additional software is needed to extract dendrometric parameters such as DBH. Another noteworthy application is Arboreal Forest developed by Arboreal (Sweden). This app automatically calculates DBH along with other dendrometric parameters, including basal area, tree density, volume, and carbon capture (Howie and De Stefano, 2024). The ForestScanner application also offers capabilities to estimate stem diameters and spatial coordinates through real-time instance segmentation and circle fitting. Users can visualize, verify, and share their scanning results in situ (Tatsumi et al., 2023). All these applications enable the measurement of DBH in a shorter timeframe compared to conventional methods, achieving satisfactory results in terms of accuracy (Borz et al., 2024; Howie and De Stefano, 2024; Tatsumi et al., 2023).

Point clouds obtained by terrestrial photogrammetry have recently gained much interest among researchers. The main advantage is the inexpensive acquisition of tree parameters such as tree position and DBH; it is even possible to detect small temporal tree trunk changes (Mokros et al., 2020). The basic principle is to construct a 3D point cloud from highly overlapping 2D images using a dense image matching algorithm (Liang et al., 2022). Terrestrial photogrammetry uses a different sensing method. Often the "stop and go" and the mobile methods are used. In the “stop and go method”, the operator takes images in a static position, moves to another position, and takes more static images. The second approach is the mobile method. The operator holds the camera and automatically captures images while moving (burst mode) (Mokroš et al., 2018).

Currently, several publications (Gollob et al., 2021; Kükenbrink et al., 2022; Mokroš et al., 2021) compare the accuracy of estimating various dendrometric parameters using different technologies, such as TLS, MLS, photogrammetry, and iPhone LiDAR. However, to the best of the authors’ knowledge, no study has comprehensively compared the accuracy of DBH estimation, cost, ease of use, and time requirement for data collection and processing of these technologies, in ideal environment of tree plantation.

This study aims to compare four different technologies: TLS (RIEGL VZ-1000), MLS (Stonex X120 GO), iPhone LiDAR (iPhone 13 Pro Max), and terrestrial photogrammetry (utilizing iPhone 13 Pro Max) under ideal conditions in a Paulownia plantation (same thickness class, regular trunk without branches at the bottom, flat terrain, no understory vegetation). This research investigates the accuracy of DBH estimation, the ease of use, the total duration for data collection and processing, and the respective costs comparing four different technologies

2. Methodology

2.1. Study site

The study was done in the plantation of Paulownia situated in the south-west of Slovakia (47.79°N, 18.45°E) in the Danube Lowland, close to village Búč. The plantation was established in the spring of 2015 on flat terrain at an altitude of 108 m above sea level. Two hundred containerized seedlings of the hybrid Paulownia elongata × fortunei (*Paulownia cotevisa*) were planted in rows with a spacing of 4 × 4 m (625 seedlings.ha-1). One year after planting, the seedlings were cut to the ground to obtain one straight healthy trunk among several shoots that emerged from the stump at the beginning of the second growing season (Pástor et al., 2022). At the time the data collection was conducted the mean DBH within the research plots was 24.3 cm, ranging from a minimum of 17 cm to a maximum of 36.5 cm. The mean tree height was 14.27 m, with heights ranging from 11.3 m to 16.4 m

2.2. Reference data collection

The plantation size is 4.7 ha; 3 research plots (Fig. 1), A, B, and C, with dimensions of 30 × 30 m, were established. Each plot corner point was secured on the terrain using plastic geodetic points as ground control points (GCP). The coordinates of these points were established using a Topcon 9000 total station to enable georeferencing and enhance spatial orientation during data collection. The DBH of every tree for each plot was directly measured using a diameter measuring tape measuring at 1.3 m high. In this experiment, calliper was not use, despite its ability to facilitate faster and easier data collection compared to a diameter tape. This decision was based on the specific ellipsoidal shape of the Paulownia tree trunk, which could affect the DBH estimation accuracy by the selected devices, while this error would be on the side of the reference data, whereas with the diameter tape, it is certain that the reference data were determined correctly. Measuring the DBH of trees in one research plot using a diameter tape took two people (one measuring, the other recording in a notebook) for approximately 17 to 20 min. The meticulously recorded data was used as a reference for the validation of the parameters obtained from the point clouds collected by the chosen technologies.

2.3. Data acquisition by innovative close-range technologies

2.3.1. Terrestrial laser scanning

A TLS was employed to scan the plot, utilizing the multi-scan method. Each research plot was scanned from nine positions to minimize occlusion. During the post-processing phase, these scans were merged into a single final scan. The scanning process of one research plot with changing positions and setting the scanner took approximately 21 min. A scheme showing the locations of the scanner within the research plot is shown in Fig. 2.

2.3.2. Mobile laser scanning

MLS trajectory was employed wherein the operator, with the scanner carried in his hand, walked around the edges and through the centre of the plot, as shown in Fig. 3. During scanning, the operator stopped at each GCP and logged its position into the device, which enabled the

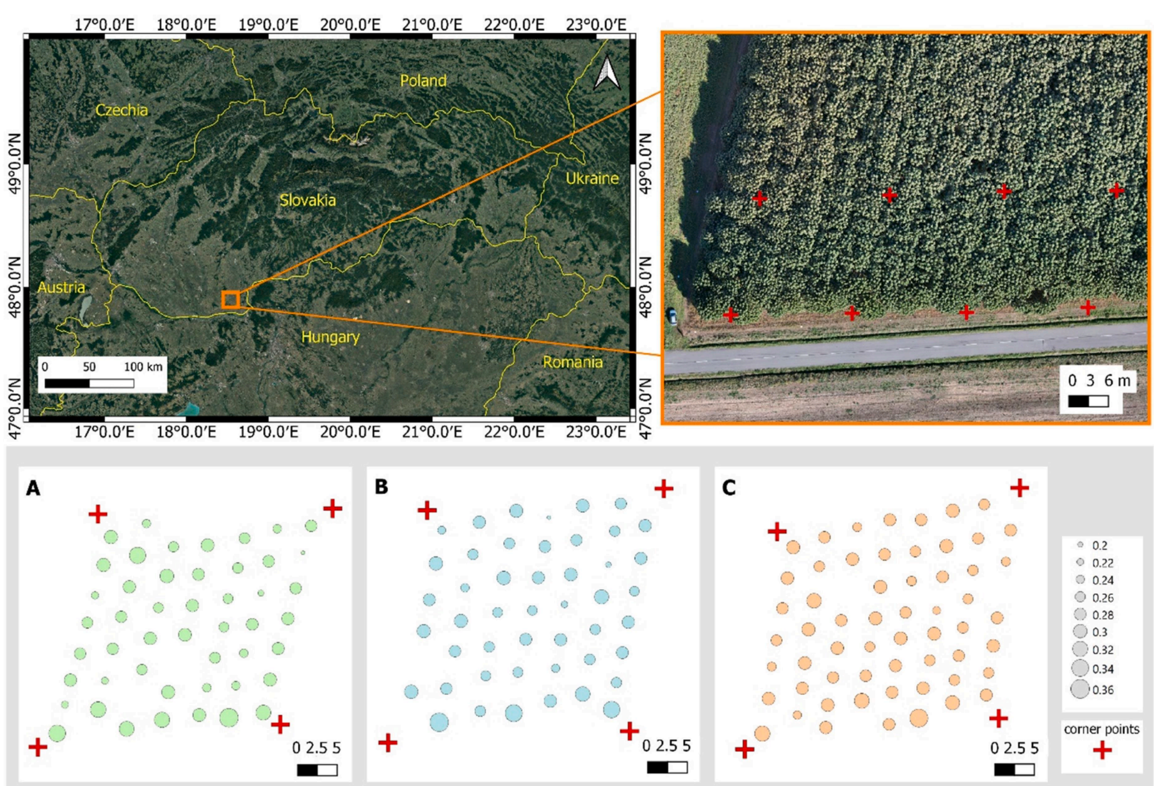

Fig. 1. Plantation of Paulownia - Búč. The position of the site within Slovakia, together with a detailed orthomosaic of the Paulownia plantation, is shown on the top left and right, respectively. On the bottom, A, B, and C are three plots displayed with tree position. The circles represent the variation in DBH.

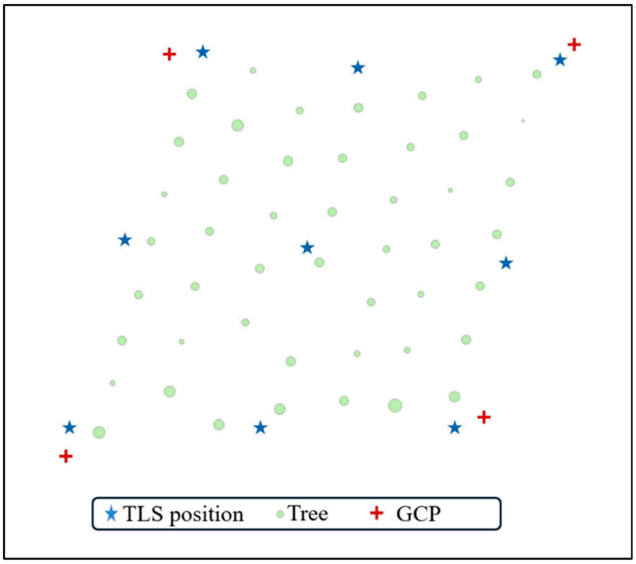

Fig. 2. Scheme of TLS positioning within research plot A.

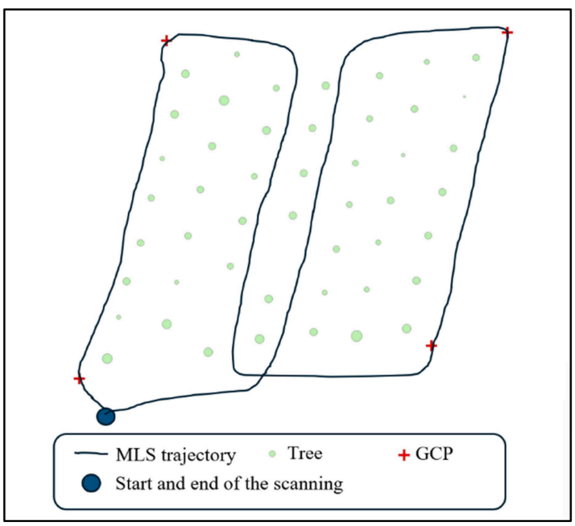

Fig. 3. Trajectory of MLS scanning within research plot A.

point clouds to be georeferenced. Initialization of the scanner before starting each scan took 1 min. The scan itself took approximately 4 min.

2.3.3. iPhone LiDAR scanning

In the case of the iPhone LiDAR scan, the mobile 3D Scanner App from Laan Labs was used for the scan. The scanning trajectory had to be adjusted to the maximum range of the iPhone LiDAR, which is 5 m. Fig. 4 shows the scanning trajectory using the iPhone 13 pro MAX. The operator, carrying the device in hand, walked along the rows, passing by every tree. Due to the complexity of the scanning process on the device memory, it was not possible to scan the research plot all at once, so 1–2 rows were scanned. In the post-processing phase, these scans were merged into one final scan for each plot (A, B, C) using CloudCompare software. Scanning of one research plot took approximately 8 min.

2.3.4. Terrestrial photogrammetry

The iPhone 13 pro Max was also used in the collection of terrestrial photogrammetry data. Prior to the start of photography, photogrammetric targets generated by Agisoft Metashape Professional 2.0.3 were placed next to the tree, later these targets were used for the scale adjustment in the post-processing phase. A stop-and-go

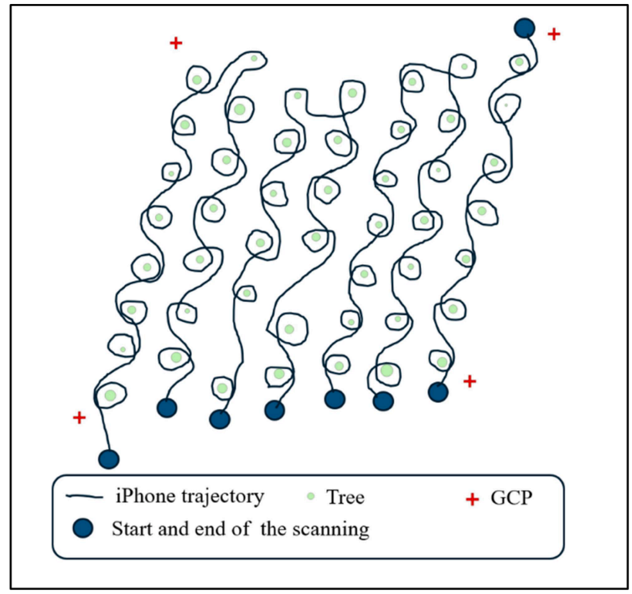

Fig. 4. Trajectory of iPhone LiDAR scanning within research plot A.

photogrammetric method was used, the operator moved around the tree, with each step taking a picture of the tree until the circle was closed. For each individual tree, 22 to 29 photos were taken. It took approximately 60 min to collect all photos for one research plot. Fig. 5 shows the process of data collection using terrestrial photogrammetry.

2.4. Processing of point clouds and DBH extraction

To extract point clouds from the TLS and MLS, raw data were pre-processed using the software provided by the scanner manufacturer. RIEGL VZ-1000 data was processed using RiSCAN PRO 2.1.2 software. Data from Stonex X120 GO were pre-processed by software GOpost. In the case of iPhone scanning, this step is eliminated, and the point cloud can be exported directly from the mobile device. To create the point cloud from photographs for terrestrial photogrammetry, Agisoft Metashape Professional 2.0.3 was utilized. Photo alignment was set with high accuracy, with the key point limit set to 80,000 and the tie point limit to 8000. High quality settings were used for building the point cloud, and depth filtering was set to 'Mild'. Scaling was done using known distances between targets generated from Agisoft, which were placed around the tree. The point cloud of individual trees and cross-section of stems from each device are depicted in Fig. 6.

The estimation of DBH was done by open source, fully automated 3DFin (3D Forest Inventory) plugin (*3DFin/3DFin*, 2023/2023; Laino et al., 2024). This tool is integrated as a plugin in CloudCompare software. The point cloud was processed using the default settings of the tool. The output includes the DBH estimation, tree height, the spatial coordinates of the individual stems, a digital terrain model, and the stem thicknesses in sections divided by 20 cm and more. DBH estimation by this tool is taken at 1.3 m from the terrain. The tool calculates diameter by fitting a circle to the points around the breast height of each tree trunk

2.5. Statistical evaluation

For each technology, estimated DBH was evaluated. The Root Mean Squared Error (RMSE) (Eq. (1)), relative Root Mean Squared Error (rRMSE) (Eq. (2)), and Correlation coefficient (R^2) (Eq. (3)) were calculated to compare results obtained from used technologies and field reference data. The statistical analysis was conducted using R software.

Equations used for DBH evaluation and calculation of error are mentioned below:

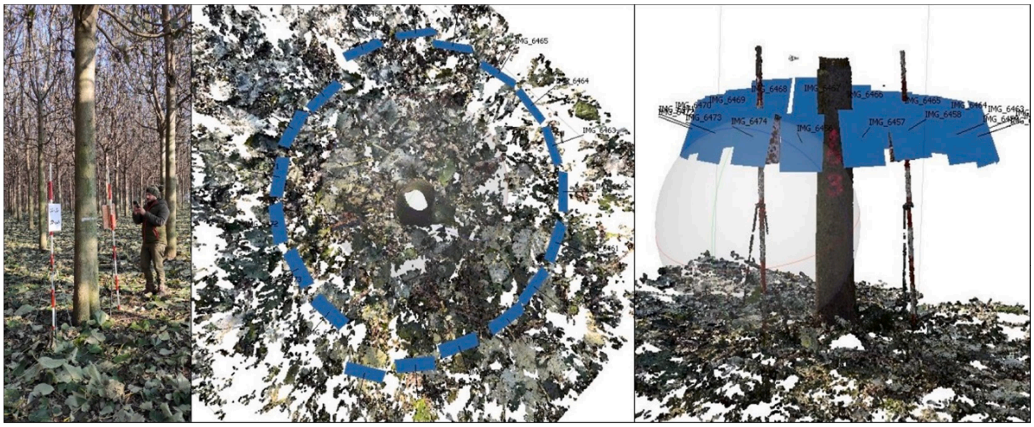

Fig. 5. Pictures captured using Terrestrial photogrammetry and the camera position.

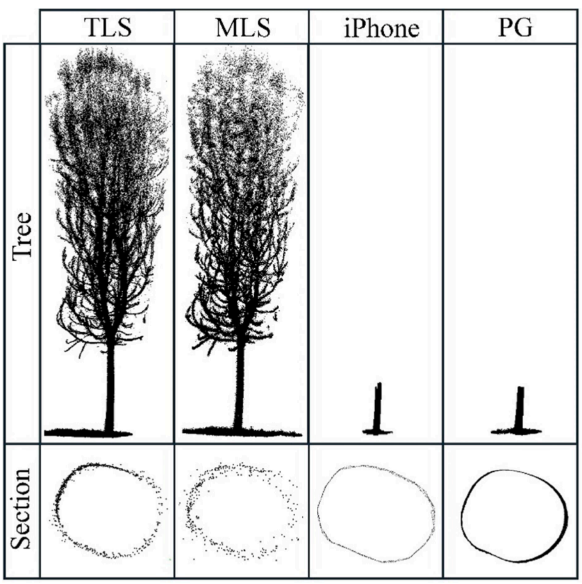

Fig. 6. Example of point clouds from all devices and Cross-section thickness (5 cm) at DBH. PG - (photogrammetry).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - \widehat{Y})^2} \quad (1)$$

$$rRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - \widehat{Y})^2}}{\frac{1}{N}\sum_{i=1}^{N}Y_i} \times 100 \quad (2)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \widehat{Y})^2}{\sum_{i=1}^{N}(Y_i - \overline{Y})^2} \quad (3)$$

Where, Y_i is the actual observation (m), $\widehat{Y}$ is the estimated observation (m), N total number of observations.

2.6. Evaluation of price and ease of use

The prices of the equipment and software required to create point clouds suitable for extracting selected dendrometric parameters were considered in the price evaluation. Prices were obtained from distributors' quotations or purchase invoices from individual manufacturers and may vary from country to country depending on the supply of distributors to individual institutions.

The ease of use of the equipment and software was evaluated based on a set of specific criteria from the operator's perspective. This evaluation considered factors including (1) the level of prior experience or specialized knowledge required to operate the equipment, (2) the training duration needed for a novice to reach basic proficiency, (3) the intuitiveness of the software interface, and (4) whether the software allows automated evaluation of selected parameters without extensive user adjustments. These factors were rated using a simple scoring system to support consistent evaluation across equipment and software.

3. Results

3.1. Statistical validation of estimated DBH

The correlation between the reference and estimated DBH was highest for photogrammetry ($R^2 = 0.951$) and lowest for iPhone LiDAR scanning ($R^2 = 0.725$). Both the TLS and MLS achieved the same correlation value ($R^2 = 0.949$). The variability of the data was evaluated by the standard deviation of DBH estimation. The lowest standard deviation was achieved with TLS and photogrammetry, both at 0.70 cm, followed by MLS at 0.72 cm. The highest variability was observed with iPhone LiDAR, at 1.7 cm. RMSE obtained was highest with iPhone LiDAR scanning, 1.7 cm, with rRMSE of 6.96 %. The lowest RMSE of 0.70 cm, with the rRMSE of 2.87 %, was achieved using TLS. For MLS, the RMSE obtained was 0.72 and rRMSE was 2.95 %, and for photogrammetry, RMSE was 0.7 cm with rRMSE of 2.89 %. The plots representing the correlation and error values are shown in Fig. 8.

From Fig. 9 and Table 1, it is evident that TLS, MLS, and photogrammetry provide the most accurate measurements of DBH; results are very similar, and there is no significant difference, with minimal deviation. Refer to Table 1. The errors for iPhone LiDAR are spread out more, with a distribution extending further into both negative and positive error ranges, compared to TLS, photogrammetry, and MLS, indicating a wider range of deviations.

In summary, TLS, photogrammetry, and MLS provide the most accurate and precise DBH measurements, with minimal errors that are consistently close to zero . iPhone LiDAR has the highest variability, indicating it is the least reliable for precise DBH measurements among

Table 1
Statistical analysis of evaluated methods.

Method	Range of error (cm)	Minimum error (cm)	Maximum error (cm)	Standard error (cm)	Standard deviation (cm)
TLS	7.738	−3.413	4.324	0.057	0.702
MLS	6.64	−5.14	1.5	0.058	0.718
iPhone LiDAR	12.97	−5.27	7.7	0.138	1.7
PG	6.8	−3.4	3.4	0.057	0.702

all the devices tested. However, with RMSE 1.7 cm it is still reliable for inventory purposes with other benefits over TLS, MLS, and photogrammetry.

3.2. Comparison of evaluated technologies

All the technologies studied were compared according to criteria, considering the cost of the equipment and software required to process the data collection, the time required for data acquisition and processing, the ease of use of the technology, and the accuracy of the DBH estimation. A graphical evaluation of the examined criteria for the investigated technologies is shown in Fig. 9.

3.2.1. TLS

The accuracy of DBH estimation achieved by TLS - Riegl VZ-1000 was very similar to that of MLS and photogrammetry; the scanner was released in 2010 and is no longer available. Currently, the prices for alternative TLS devices from Riegl, such as the VZ-400i or VZ-600i, range from approximately €90,000 to €130,000, including the proprietary software. Regarding time requirements, approximately 21 min were spent scanning one plot with nine positions, this time would be shorter with newer version of Riegl TLS, however, it would still exceed the time required for data collection with MLS or iPhone LiDAR.. Processing the raw data from the TLS technology, and merging multiple scans into a final composite scan within the research plot using RiSCAN Pro software took approximately 26 min. During this process, operator input was needed to merge individual scans, specify the number of key points, apply filtering, and other adjustments. Newer RIEGL TLS models like the VZ 400i and VZ 600i, equipped with RTK modules and inertial units, offer pre-registered scans, which would reduce processing time. Nevertheless, operator input is still required, and the total data processing time remains longer than that of MLS or iPhone LiDAR data. Specific knowledge and skills are required for operating the TLS. Prior exposure and expertise are required to handle the device, which incorporates proper placement of the tripod, scanning parameters, as well as determining the position and number of scans in the plot. Additionally, processing the raw data and merging the scans into a final point cloud using RiSCAN pro software necessitates a basic understanding of the software. Consequently, this technology is not suitable for non-professional users.

3.2.2. MLS

In terms of accuracy, MLS technology shows the same potential as TLS and photogrammetry. The differences in DBH estimation accuracies among the three technologies are minimal (see Fig. 7). The cost of the Stonex X120GO MLS scanner, including the necessary software for data processing, ranges approximately from €30,000 to €35,000. Data collection from a single research plot took <5 min, while processing the raw data using the proprietary software GOpost took approximately 20 min. Initial parameter settings were required at the start of the processing, after which the software automatically processed the scans without further operator input.From a user's perspective, this technology is much less cumbersome than TLS. The scans are operated by a mobile phone or tablet, and Ground Control Points (GCPs) can also be entered. The application is relatively simple and intuitive. Creating a point cloud from raw data using the GOpost software requires minimal parameter setting knowledge. After brief training, this technology could be effectively used even by non-professionals.

3.2.3. Photogrammetry

Photogrammetry provides a very similar DBH estimation as TLS and MLS. Additionally, among the technologies examined in this study, including iPhone LiDAR scanning, it is one of the most cost-effective options. An iPhone 13 Pro Max, priced between €850 and €1200. Besides the device cost, the software is required to generate 3D point clouds from photographs. This study used Agisoft Metashape Professional, with an academic license costing approximately €800 and a commercial license costing up to €3200. Data collection from one plot, where each tree was individually photographed, took approximately 62 min. Hence, it requires more time. Data processing in Agisoft Metashape Professional, including photo alignment, 3D point cloud creation, and scaling with photogrammetric targets, took up to 5.5 h. User interaction was required to scale point clouds for each tree in the research plots. After scaling, processing a single tree took from 4 to 5 min without

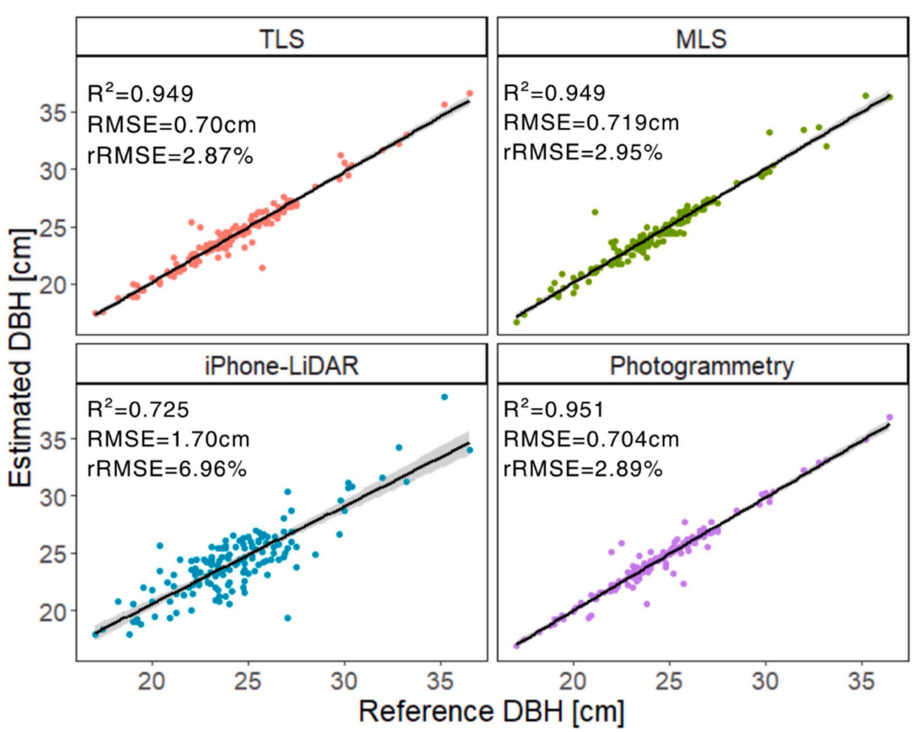

Fig. 7. Correlation plots depicting the statistical error values (RMSE, rRMSE).

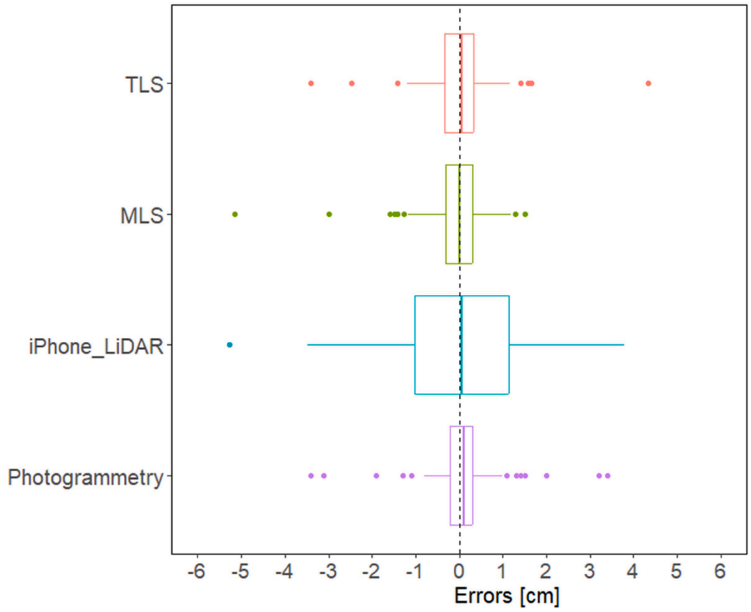

Fig. 8. Boxplots displaying absolute errors show the interquartile range from the 25th to 75th percentiles, with whiskers extending 1.5 times the interquartile range. The median is indicated by a line within each boxplot, and outliers are represented by dots.

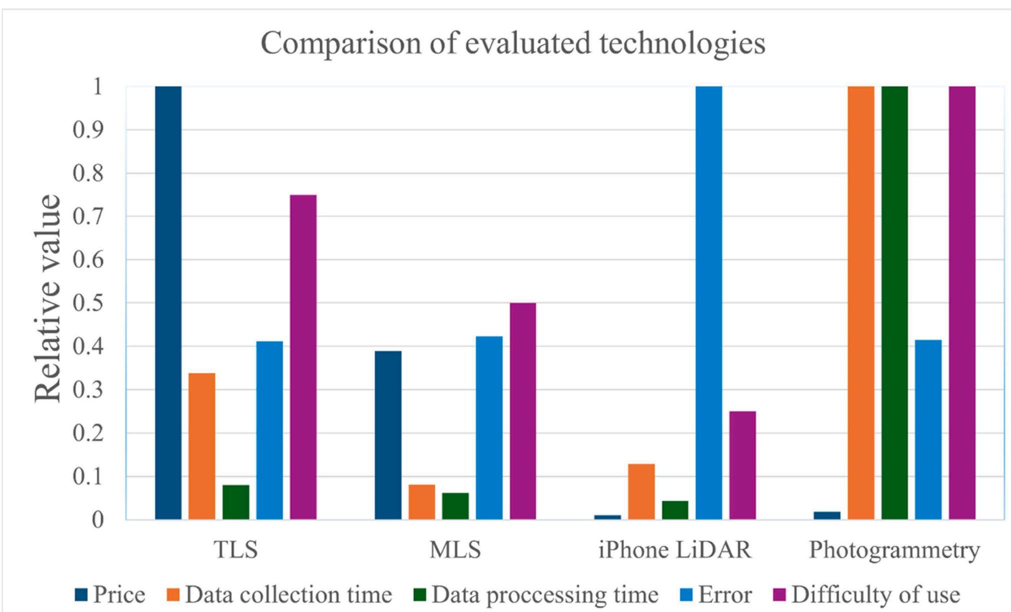

Fig. 9. Bar chart for comparison of evaluated technologies where values are relative calculation against the highest value in the group.

further operator input before starting on the next tree.This technology is also very demanding from the user's perspective. The camera settings must be carefully managed, and the operator must take photographs in a manner that ensures sufficient overlap. Additionally, the photos must be sharp, which requires a certain level of expertise. Besides aligning the photos and creating the point cloud, it is necessary to create a scale, which also requires specialized knowledge. Consequently, this technology is not suitable for non-professionals as well.

3.2.4. iPhone LiDAR scanning

The lowest DBH estimation accuracy was achieved using iPhone LiDAR technology. However, it is the least expensive among the technologies investigated. An iPhone 13 Pro Max, priced between €850 and €1300, and no additional software is needed. Point clouds are generated directly on the device using the 3D Scanner App and can be exported directly to a computer. The data collection time is relatively low, requiring <8 min per plot. Since the iPhone produces processed point clouds in real-time, it eliminates data processing time. From a user perspective, this is the most accessible technology, as most users are familiar with mobile phones in their everyday lives. However, it is important to consider the scanner's range, which is only 5 m. Nevertheless, this device can be used by non-professionals and does not require specific skills.

4. Discussion

This study demonstrates that all the technologies investigated are applicable to DBH estimation in Paulownia FGT. To the best of the authors' knowledge, no similar study on the evaluation of the mentioned technologies for DBH estimation in an FGT plantation setting has been published yet. Therefore, the obtained results were compared with publications either from homogenous or two-species forest plantation (Chiappini et al., 2022; Sun et al., 2015; Tsuchiya et al., 2023; Wang et al., 2019) Or from forest stands environments (Gollob et al., 2021; Guenther et al., 2024; Kükenbrink et al., 2022; Mikita et al., 2016; Mokroš et al., 2021).

Among all the selected studies, Wang et al. (2019), estimated DBH and tree height in a Ginkgo plantation using a low-cost TLS device, which most closely resembles the investigated paulownia plantation in terms of tree thickness, stand structure, and plantation spacing. The RMSE and rRMSE for DBH estimation in the study were 1.27 cm and 10.52 %, respectively. In the plantation, four research plots of 10 × 10 m dimensions were established and scanned using single-scan methods from the centre of each plot. They reported a tree detection rate (TDR) ranging from 86.36 % to 100 %, with an average TDR of 92.75 %.

In contrast, this study achieved a 100 % TDR with each investigated technology, and no trees were falsely detected. This difference in tree detection rates is observed due to the implementation of different scanning methods. The present study utilized a multi-scan method for TLS, where nine positions per plot were used in 30 × 30 meter plots.

Tsuchiya et al. (2023) also reported a 100 % TDR using backpack MLS equipment across all five study plots of Japanese cedar and cypress, with RMSE and rRMSE of DBH estimation reported as 2.6 cm and 8.5 %, respectively.

In a study by Mokroš et al. (2021), low-cost technologies for forest inventory were explored as alternatives to TLS. The research encompassed eight mixed forest plots measuring 25 × 25 m. The highest accuracy was achieved by TLS, with the Faro Focus S70 having an RMSE of 1.45 cm and an rRMSE of 5.18 %. Using the MLS GeoSLAM ZEB Horizon, the achieved RMSE was 6.2 cm, and the rRMSE obtained was 17.63 %. Also, a prototype device named "MultiCam," which featured four cameras for terrestrial photogrammetry, was tested, achieving a DBH with RMSE of 6.98 cm and rRMSE of 22.86 %. Furthermore, also included iPad LiDAR scanning with RMSE 3.31 cm and rRMSE 10.3 %. TDR in their study recorded was TLS 95.15 %, MLS 67.91 %, multi-camera photogrammetry 64.18 %, and iPad 77.24 %.

Similarly, Kükenbrink et al. (2022) explored various technologies in a mixed temperate forest. Their results were divided for the individual plots, achieving TDR values from 60 % to 92.2 % for TLS FARO Focus 3D S120, 28 % to 79 % for MLS GeoSLAM ZebRevo RT, and from 29.8 % to 45.6 % for GoPro photogrammetry. Further details are mentioned in Table 1.

The 100 % detection rate in the present study can likely be attributed to several factors. Notably, there were no thin trees in the study plots, with the thinnest tree having a DBH of 17 cm and a mean DBH of 24.34 cm. The area features relatively flat terrain devoid of undergrowth with trees planted at a consistent 4 × 4 meter spacing. In contrast, other studies were conducted in mixed forests, with varying DBH categories starting from 7 cm, various tree species, uneven tree growth, and rugged terrain with undergrowth were considered (Kükenbrink et al., 2022; Mokroš et al., 2021).

In this study, the terrestrial photogrammetry was conducted individually for every tree, eliminating the uncertainty and error in the tree detection. Conversely, in other studies, photogrammetry was conducted plot-wise. All the above-mentioned factors appeared to influence the RMSE and rRMSE, resulting in comparatively lower values than those observed in other studies. Further details are mentioned in Table 2, which presents a compilation of the publications alongside other relevant studies focusing on selected technologies for DBH estimation, including a comparative analysis of their results with the key findings of the studies.

5. Conclusion

This study comprehensively evaluated the efficiency of four different methods, namely Terrestrial Laser Scanning, Mobile Laser Scanning, iPhone LiDAR scanning, and terrestrial photogrammetry, for the estimation of DBH in a Paulownia plantation. The accuracy of each method, ease of use, data collection, processing time, and costs were meticulously assessed.

The results showed that TLS, MLS, and photogrammetry are the most accurate and precise in DBH estimation compared to iPhone LiDAR.

TLS can Additionally be utilized for fine-scale dendrometric parameters, such as tree height, tree location, carbon stock, and biomass of branches and leaves, which can also be estimated. The generated high-quality point clouds are suitable for detailed analysis of the sub-twig level. However, this technology is the most expensive, requires a high level of expertise, and necessitates multiple scan positions to minimize occlusion, which increases the overall time; therefore, it is not practical to use for inventory in plantations, as the device is too heavy to move around, and data collection time is much higher comparatively. Nevertheless, it is suitable for fine-scale measurement of the tree parameters at the sub-twig level.

In contrast, the MLS (Stonex X120 GO) requires the least time for data collection, and data processing is also relatively quick. DBH estimation is much faster for larger areas than a clipper or diameter tape. It can provide satisfactory precision for other parameters, such as estimating tree height, tree position, crown parameters, etc. From a user

Table 2
Comparison of results with other studies.

Reference	Study area	technology	RMSE (cm)	rRMSE (%)	r^2	TDR
(Mokroš et al., 2021)	Mixed temperate forest	TLS	1.45	5.18	0.996	95.15
		MLS	6.2	17.63	0.897	67.91
		iPad LiDAR	3.31	10.3	0.973	77.24
		MultiCam PG	6.98	22.86	0.799	64.18
(Gollob et al., 2021)	Mixed temperate forest	MLS	1.59	-	-	97.3
		iPad LiDAR	3.64	-	-	99.5
(Kükenbrink et al., 2022)	Mixed temperate forest	TLS	1.6–3.7	2.6–4.51	0.973–0.983	60–92.2
		MLS	2.4–3.8	3.7–4.28	0.972–0.977	28–79
		GoPro PG	1.4–3	1.98–6.88	0.840–0.972	29.8–45.6
(Guenther et al., 2024)	Mixed Boreal Forest	iPad LiDAR	1.5	8.6	–	
(Chiappini et al., 2022)	Black Pine Forest plantation	MLS	2.7	10.8	0.747	
(Wang et al., 2019)	Ginkgo and pine plantation	Low-cost TLS	1.27	10.52	0.78	92.75
(Sun et al., 2015)	Chinese Fir plantation	TLS	0.37	2.1	0.987	
(Mikita et al., 2016)	Old spruce forest	PG	0.911	–	0.984	
(Tsuchiya et al., 2023)	Japanese cedar and cypress plantation	Backpack MLS	2.6	8.5		100
This study	Homogenous, FGT, Paulownia plantation	TLS	**0.70**	**2.87**	**0.949**	**100**
		MLS	**0.72**	**2.95**	**0.949**	**100**
		PG	**0.70**	**2.89**	**0.951**	**100**
		iPhone LiDAR	**1.70**	**6.96**	**0.725**	**100**

perspective, MLS is relatively simple to use; however, it is still one of the more expensive technologies available. If cost is not an issue, considering all other evaluated aspects, this technology is the best choice.

The most affordable technology examined is iPhone LiDAR scanning, followed closely by photogrammetry, which incurs a slightly higher cost due to image processing software. Both methods utilized the iPhone 13 Pro Max. Terrestrial photogrammetry offers a slightly higher accuracy in DBH estimation. However, this technology is impractical for data collection and processing using the above methodology as it requires extensive operator knowledge. The data collection and processing time with this technology exceeded all other technologies evaluated in this study. And with the same methodology, it has no practical application.

In comparison, iPhone laser scanning has high potential, primarily due to its ease of use, availability, and low time consumption. Additionally, there is no need for any additional software to create a point cloud. However, it is important to note that there are limitations concerning the range of the LiDAR scanner. This study demonstrates that iPhone LiDAR is the best low-cost solution for estimating DBH in 'tree-structured' plantations."

In conclusion, each of the technologies investigated provides satisfactory results in estimating DBH for inventory in “tree-structured” FGT plantations. MLS and iPhone LiDAR scanning provides a more efficient device for estimating DBH in terms of time and labor intensity, especially in larger areas. TLS and photogrammetry are not practically applicable in DBH estimation. However, TLS finds its application in detailed mapping and monitoring of the forest or plantations to detect annual increments of the trunk. Perhaps is also usable to get dendrometric parameters at the sub-twig level. Future research could investigate different methods of data collection using these technologies, possibly using them in differently structured plantations (coppice plantations), estimating other dendrometric parameters, and temporal analysis of the dendrometric parameters.

CRediT authorship contribution statement

Michal Skladan: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Juliána Chudá:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Arunima Singh:** Validation, Formal analysis, Data curation, Conceptualization. **Matej Masný:** Writing – review & editing, Data curation. **Martin Lieskovský:** Formal analysis. **Michal Pástor:** Data curation. **Martin Mokroš:** Writing – review & editing. **Jozef Vyboštok:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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