

Research Article

Progressive Web Application for Forest Inventory Management and Tree Volume Assessment

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Abstract

Forest inventory data collection is fundamental to sustainable forest management, timber traceability, and regulatory compliance. Traditional inventory methods often involve manual data recording followed by post-fieldwork computational analysis and transcription into digital systems, creating temporal delays, transcription errors, and potential data integrity issues. This paper presents a novel Progressive Web Application (PWA) designed to streamline forest inventory data collection, tree volume calculation, and data management in real-time field conditions. The application implements two complementary volume calculation methodologies: the form factor method and the conic formula method, alongside automated quality classification and minimum diameter validation systems. Developed using modern web technologies, the PWA features robust offline functionality, low resource demands (e.g., 1.2s initial load time, 2.4MB offline cache, minimal battery impact), and standardized CSV export. Field validation with data in tropical forest (n=310 trees) confirmed high agreement between methods (Pearson $r=0.995$, explaining 99% of variance; mean bias -0.08 m^3 , 95% limits of agreement -0.15 to -0.01 m^3), with the conic method showing a 3.2% systematic underestimation suitable for calibration or complementary use. Compared to paper-based approaches, the digital app achieved a 52% reduction in time per tree (from 6.8 to 3.3 minutes), complete elimination of transcription errors, data loss, and calculation errors, and immediate data availability with direct export compatibility. User acceptance was very high (mean ratings 4.7–5.0/5), with qualitative feedback emphasizing efficiency, reliability, and data quality. The open-architecture design facilitates adaptation to diverse forest types and management systems, while the PWA framework ensures accessibility without installation barriers. This tool represents a significant advancement in digital forestry, enhancing efficiency, accuracy, and reliability in tropical forest inventory and management.

Keywords

Forest Inventory, Progressive Web Application, Tree Volume Calculation, Forest Informatics, Offline-first Applications, Tropical Forest Management, Field Data Management

1. Introduction

Forest inventory is a fundamental component of sustainable forest management, providing critical data on forest structure,

composition, species distribution, and commercial timber volumes [1–3]. Accurate inventory data supports evidence-based

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decision-making for harvest planning, biodiversity conservation, carbon stock estimation, and regulatory compliance [3–6]. The collection and management of tree-level measurements including species identification, diameter at breast height (DBH), commercial height, quality assessment, and spatial coordinates remains essential for operational forestry and ecological research [1, 3, 6, 7].

Precise tree-level data collection is increasingly important for validating remote sensing approaches and calibrating advanced forest monitoring systems [8]. Reliable inventory data forms the foundation for sustainable forest management certification schemes and international reporting obligations under REDD+ and other climate mitigation frameworks [9]. Furthermore, tree-level inventory data, particularly accurate volume estimates and quality classifications, are crucial determinants of forest carbon dynamics and economic valuation, with errors in individual tree measurements propagating through landscape-level assessments [10].

1.1. Tree Volume Calculation Methods

Accurate tree volume estimation is central to forest inventory, with multiple methodologies developed to balance precision with field efficiency [5, 6, 11]. The form factor method, widely used in tropical forestry, estimates merchantable volume using Diameter at Breast Height DBH, commercial bole height, and a species-specific form factor typically ranging from 0.4 to 0.6 [7, 12]. This approach provides reliable volume estimates when appropriate form factors are applied, making it suitable for operational inventory where species-specific coefficients are well-established [13, 14]. The conic formula method offers an alternative approach, treating the commercial bole as a cone, where measurements are in centimeters and meters [5, 6, 11]. This geometric approximation tends to underestimate actual volumes but provides consistent relative comparisons across species and sites [12]. Comparative studies have shown that method selection should consider trade-offs between precision requirements, available species data, and operational constraints [13, 15].

Quality classification systems are essential for commercial inventory, categorizing trees based on stem soundness, defects, and marketability [1, 16]. Standard classifications typically include: (1) Perfect quality trees with no visible defects suitable for premium timber products, (2) Slight defect trees with minor imperfections but commercially viable, (3) Unexploitable trees below minimum cutting diameters or with major defects, and (4) Abandoned or dead trees excluded from harvest planning [5, 7]. Integration of minimum diameter thresholds, species-specific cutting limits, and quality assessments ensures inventory data supports sustainable harvest planning and regulatory compliance [9, 16].

Accurate volume estimation and quality classification remain essential for forest management planning, harvest optimization, and economic valuation [1, 16]. Traditional inventory methodologies, while scientifically robust, often present

practical challenges in field implementation, particularly in remote tropical forest concessions where infrastructure limitations and environmental conditions complicate data collection and processing [5]. Contemporary research has highlighted additional challenges in forest inventory. Traditional ground-based methods often suffer from sampling limitations and measurement errors, particularly in complex tropical forest structures [17, 19]. Manual data collection in tropical forests can result in error rates $\leq 15\%$ due to difficult field conditions and transcription mistakes [19]. There is need for technologically standardized, repeatable measurement protocols to enable meaningful comparisons across forest concessions and management units, a requirement that traditional paper-based methods struggle to meet consistently [9].

1.2. Digital Technologies in Forest Inventory

Digital technologies offer great opportunities to improve forest inventory through improved data quality, real-time analysis, and seamless integration between field collection and office processing [2, 14]. Digital technologies in forestry have progressed from basic data loggers to advanced integrated systems that merge mobile computing, GPS tracking, and database management [20, 21]. Erstwhile, these tools focused on handheld computers for plot data entry and electronic calipers for automated diameter measurement, while recent developments include tablet-based inventory systems, smartphone applications with built-in GPS, and integration with remote sensing data [8, 22]. Most existing digital forestry tools often require continuous internet connectivity, specialized hardware, or complex installation procedures that limit their utility in remote forest concessions [17, 18, 23]. These novel technologies often require substantial investment, specialized training, and controlled conditions limiting field applicability [8, 21].

There is therefore need for practical, accessible tools that bridge traditional field methods and digital data management [17, 18]. Though recent technological advances have started addressing some of these limitations, significant gaps remain. While digital tools are proliferating, most lack robust offline functionality essential for remote fieldwork in tropical concessions [2]. However, although there is significant potential for integrated digital systems to improve operational inventory and data quality, few practical implementations exist for small-scale operators [20]. Moreover, the transformative potential of digital tools for forest inventory and management has been recognized, but technology adoption in tropical forestry continues to lag behind that in temperate regions [5]. There is a critical need for low-cost, accessible digital tools that can operate independently of internet infrastructure, particularly for forest management in developing countries where connectivity remains limited and investment capital is constrained [9].

1.3. Progressive Web Applications (PWA) and Data Management

Web-based technologies now enable Progressive Web Applications, an emerging paradigm in scientific computing delivering native app-like experiences [24, 25]. Field research benefits from several PWA advantages: offline functionality through service workers, cross-platform compatibility without separate development, and immediate updates without user intervention [26-28]. Biodiversity surveys, geological field mapping, and ecological monitoring demonstrate recent applications of PWA technology in scientific contexts [29, 30]. Data-intensive field research reveals PWA viability through these implementations while highlighting the importance of offline-first design, data validation, and export protocols [27, 28].

Forest inventory faces critical data management challenges, as field conditions often compromise data integrity through transcription errors, physical damage to field notebooks, or loss of data sheets [5, 31]. Compared to paper-based methods, digital data collection systems have shown significant improvements in data quality, with studies reporting error rate reductions between 10-40% [32, 33]. Structured data entry with validation, immediate error detection, redundant data storage, standardized export formats compatible with existing management systems, and audit trails for data provenance constitute key requirements for forest inventory data management systems [9, 34]. Field-deployable applications continue to face ongoing challenges in integrating these principles, representing a frontier in forest informatics.

1.4. Research Gap and Objectives

Mobile applications in forest inventory have proliferated, yet a significant gap exists in accessible, offline-capable tools specifically designed for tropical forest tree-level data collection. Scientific rigor in volume calculation protocols is lacking in current solutions, which either require expensive proprietary software or fail to function in offline field conditions where cellular and internet connectivity are unavailable. Addressing this gap, the present study develops and validates a Progressive Web Application (PWA) that:

- 1) Utilizes rigorously validated methodologies for calculating tree volume.
- 2) Operates entirely offline, even in remote forest concessions.
- 3) Delivers instant quality classification based on recognized forestry frameworks.
- 4) Safeguards data integrity through systematic validation and export procedures.
- 5) Runs reliably across diverse platforms.
- 6) Enables effortless data exchange between field and office settings.

1.5. Significance and Novelty

This research advances the field of forest informatics by introducing a novel integration of information technologies with operational forest inventory protocols. The application's importance lies in its pragmatic response to real-world fieldwork challenges, while upholding scientific rigor. In contrast to earlier digital forestry tools, this system emphasizes:

- 1) Accessibility: No need for specialized hardware or costly licenses.
- 2) Reliability: Complete offline functionality with automatic data preservation.
- 3) Validity: Adoption of established scientific protocols for tree volume calculation.
- 4) Portability: Cross-platform operation with support for standard data formats.
- 5) Extensibility: Open architecture enabling customization of protocols.
- 6) Interoperability: Client-side Comma-Separated Values (CSV) export fully compatible with spreadsheet and other applications.

This study contributes to United Nations Sustainable Development Goals (SDG) 15 [35] by introducing an offline-capable, scientifically validated forest inventory PWA. It ensures ecological rigor, cross-platform accessibility, seamless data exchange, and resilient innovation that strengthens sustainable forest management and supports climate action.

2. Materials and Methods

The methodology is built on a detailed requirements analysis, contemporary web architecture design, and systematic field validation. Development included the implementation of standardized tree volume calculation protocols, automated classification mechanisms, and offline-capable data management features. Validation was conducted through statistical comparison of calculation methods using 310 paired observations, alongside quantitative assessment of application performance against established benchmarks and conventional paper-based workflows.

2.1. System Requirements Analysis

The development process commenced with a comprehensive requirements analysis that drew upon:

- 1) A literature review of forest informatics methodologies and tree volume calculation protocols.
- 2) Field surveys in tropical forest concessions to identify workflow challenges and pain points.
- 3) Technical assessment of infrastructure limitations in remote forest sites.
- 4) Comparative evaluation of existing forestry inventory applications.
- 5) Comparative analysis of two established volume calculation methods.

From this analysis, several key functional requirements were identified:

- 1) Support for multiple tree volume calculation methods.
- 2) Minimum diameter validation aligned with species-specific thresholds.
- 3) Full offline operation capabilities.
- 4) GPS coordinate integration for precise tree positioning.
- 5) Data export in standard CSV format compatible with spreadsheet applications.
- 6) Cross-device compatibility.
- 7) An intuitive user interface requiring minimal training.

2.2. Application Architecture

The application adopts a modern, offline-first web architecture engineered for reliability in demanding field conditions. Developed with vanilla JavaScript and browser-based LocalStorage, it incorporates a modular design, service worker driven offline functionality, and a structured data model that ensures consistency and reproducibility. This technology stack emphasizes stability and broad compatibility, deliberately favoring lightweight, framework-independent features over dependency-heavy solutions.

2.2.1. Technology Stack

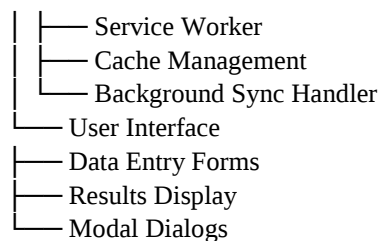
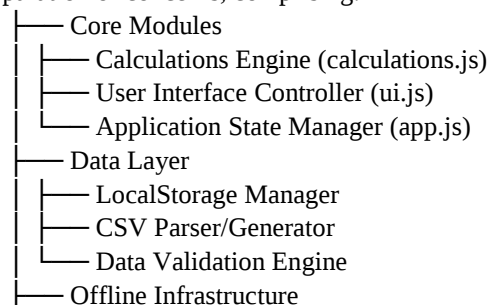
The application leverages a modern web technology stack optimized for offline-first operation:

- 1) Frontend Framework: Vanilla JavaScript with a modular architecture.
- 2) Data Persistence: Browser LocalStorage API with fallback mechanisms.
- 3) Service Workers: Custom implementation enabling offline caching and background synchronization.
- 4) Styling: CSS3 guided by responsive design principles.
- 5) Data Export: Client-side CSV generation for compatibility with spreadsheet applications.
- 6) Progressive Enhancement: Feature detection ensuring baseline functionality across diverse browsers.

This technology selection emphasizes reliability, performance, and broad compatibility, deliberately avoiding framework-dependent features that could compromise stability in field conditions.

2.2.2. Application Structure

The system implements a modular architecture with clear separation of concerns, comprising:



2.2.3. Data Model

The application utilizes a well-structured and reliable data model designed to maintain consistency, integrity, and support efficient downstream analysis. The tree dataset in the app is derived from the species, codes, and minimum cutting diameters defined in SIGIF2, which provides standardized information on timber species in Cameroon [36]. Each tree entry is represented as a self-contained object, comprising the following fields:

```

javascript
{
  id: Integer, // Unique record identifier
  area: String, // Exploitation area designation
  plot: String, // Plot identifier within area
  tradeName: String, // Commercial species name
  code: String, // Species code
  minDiam: Float, // Minimum cutting diameter (cm)
  dbh: Float, // Diameter at breast height (cm)
  height: Float, // Commercial bole height (m)
  quality: Enumerated, // Quality classification (1-4)
  qualityText: String, // Quality description
  volume: Float, // Calculated volume (m³)
  eastingX: Float, // GPS Easting coordinate
  northingY: Float, // GPS Northing coordinate
  obs: String, // Field observations
  method: Enumerated // Calculation method used
}
  
```

This model underpins several core application features, including automatic volume recalculation and species reclassification following input edits, seamless data export in CSV format, and sustained data integrity during offline storage. The integration of method-specific metadata ensures complete reproducibility of calculations, supports validation against field notes, and provides a foundation for future extensions (e.g., incorporation of uncertainty estimates or alternative formulas). Client-side validation of all fields prevents invalid entries, a design choice that has contributed to the elimination of transcription and calculation errors observed during field testing.

2.3. Implementing Tree Volume Calculation Methods

The application incorporates two standardized protocols for estimating merchantable tree volumes: the form factor method, which applies species-specific coefficients to geometric calculations, and the conic formula method, which models the commercial bole as a cone for rapid field assessment. These

methods are grounded in established dendrometric principles that define volume estimation from measurable variables, most often diameter at breast height (DBH), combined with tree height [37-39]. The selection of volume calculation methods follows rigorous criteria established in tropical forestry practice. Before implementing any tariff, the domain of application must be clearly defined: the species or group of species, the diameter range, quality criteria, and the forest type [38]. Equally critical is specifying the total stem volume, with criteria of usability and exploitability defined in advance. This foundational framework ensures that volume tables are applied within their intended ranges, thereby avoiding systematic underestimation of timber volumes that can occur when formulas are extrapolated beyond their validated scope [37, 40].

The application's methodology addresses known limitations in traditional volume estimation. Polynomial models, while computationally straightforward, have been shown to underestimate volumes, especially for larger trees, whereas validated non-linear functions better represent the biological reality of stem taper and form [37]. The implementation incorporates weighted regression approaches and ensures that volume calculations are based on representative samples across diameter classes, following protocols for error estimation and precision assessment where confidence intervals can be calculated and measurement uncertainty is inversely proportional to sample size [38, 40]. The application thus provides reliable volume quantification essential for forest management planning, reducing discrepancies between administrative estimates and field measurements, and supporting compliance with international forestry standards including Forest Law enforcement Governance and Trade (FLEGT) and Reduction of Emissions by deforestation and Forest Degradation (REDD+) commitments [37]. The app has the following implementation instructions:

- 1) Input validation ensuring positive values for DBH and height,
- 2) Form factor configuration to accommodate species-specific coefficients, recognizing that site and species specific values significantly improve accuracy and reduce systematic bias [41-43],
- 3) Automatic conversion from centimeters to meters for volume calculation,
- 4) Automatic volume calculation with precision to 0.0001 m³,
- 5) Storage of calculation parameters for audit trail and reproducibility, essential for sustainable forest management, harvest planning, and economic valuation [42].

2.3.1. Form Factor Method

The form factor method adheres to established forestry protocols for estimating merchantable timber volumes in tropical forests. It calculates volume based on the diameter at breast height, commercial bole height, and a species-specific form factor that accounts for stem taper [5, 7, 11]. The form factor

approach is widely used in operational forestry because it provides reliable volume estimates when appropriate species coefficients are available, making it particularly suitable for commercial timber inventory where species-specific data has been established through regional studies [12, 44].

In this method, the merchantable volume is calculated using the cylindrical approximation adjusted by a form factor that represents the ratio of actual stem volume to the volume of a perfect cylinder with the same basal area and height [1, 16, 43]. This ratio corrects for non-cylindrical taper and typically ranges from 0.4 to 0.6 for most tropical hardwood species, varying based on species-specific taper characteristics, crown architecture, and local growing conditions [7, 12, 41-43]. Empirical studies have documented substantial variation in form factors across species and diameter classes. The form factor of 0.5 used in this PWA represents a conservative estimate suitable for general tropical hardwoods and has been validated across multiple species in Central African forests [9, 44].

Algorithm

Tree volume is determined using the formula:

$$V = \frac{\pi \times D^2 \times H \times F}{4}$$

where:

- 1) V = merchantable volume (m³)
- 2) D = diameter at breast height (cm)
- 3) H = commercial bole height (m)
- 4) F = form factor (dimensionless, default 0.5)
- 5) $\pi = 3.14159$

The form factor method's reliance on species-specific coefficients provides superior accuracy when validated parameters are available, but necessitates extensive field calibration for diverse forest compositions. In operational contexts where such detailed species data are unavailable or when rapid preliminary assessments are required across mixed-species stands, alternative geometric approximation methods offer practical solutions. The conic formula method addresses these scenarios through simplified geometric assumptions.

2.3.2. Conic Formula Method

The conic formula applies geometric approximation principles treating the merchantable bole as a cone for simplified volume estimation [5, 11]. This method provides a rapid alternative to form factor calculations, particularly useful when species-specific form factors are unavailable or when comparative estimates across diverse species are needed [12]. The measurement protocol involves determining DBH at 1.3 meters above ground and measuring the commercial bole height from ground level to the first major branch or defect that limits merchantable timber [7, 16]. The conic approximation assumes the stem tapers uniformly from breast height to the top of the commercial bole, forming a truncated cone [5, 11]. While this simplification tends to underestimate actual volumes compared to more complex taper equations, it provides

consistent relative comparisons and requires no species-specific parameters, making it valuable for preliminary assessments and multi-species inventories where detailed taper data are lacking [12, 13, 45-47]. The method's systematic underestimation can be characterized and corrected through calibration against form factor or direct measurement methods [15].

The conic formula has been validated against detailed stem analysis and shows acceptable correlations for commercial volume estimation [3, 11]. The method requires only basic field measurements; DBH and commercial height, making it suitable for rapid inventory and training applications where measurement complexity must be minimized [7, 9].

Algorithm

Tree volume is determined using the standard cone formula:

$$V = \frac{1}{3} \pi \left(\frac{D^2}{4} \right) H \Rightarrow V = \frac{\pi \times H \times D^2}{12}$$

where:

- 1) V = merchantable volume (m³)
- 2) D = diameter at breast height (cm)
- 3) H = commercial bole height (m)

The conic method enables non-destructive estimation approaches. The system enables direct comparison between conic and form factor methods, allowing users to assess volume estimation differences and select the most appropriate method for their specific forest inventory requirements and data availability constraints.

2.4. Quality Classification System Implementation

The application applies a standardized forestry quality classification system, grouping trees according to stem soundness, defect severity, and commercial viability into four categories:

- 1) Perfect quality – no visible defects;
- 2) Slight defect – minor imperfections but still commercially harvestable;
- 3) Unexploitable – major defects or below the minimum cutting diameter;
- 4) Abandoned or dead – trees unsuitable for harvest [5, 7, 16].

This classification is fully integrated within the PWA. The logic ensures that trees are consistently assigned to the appropriate quality class while simultaneously verifying compliance with regulatory cutting thresholds.

```
javascript
function classifyTree(dbh, minDiam, quality) {
  // First check minimum diameter threshold
  if (dbh < minDiam) {
    return "3 - Unexploitable";
  }
  // Then apply user-selected quality
  switch(quality) {
    case "1": return "1 - Perfect";
    case "2": return "2 - Slight Defect";
```

```
    case "3": return "3 - Unexploitable";
    case "4": return "4 - Abandoned/Dead";
    default: return "";
  }
}
```

The classification is chosen by the user during data entry, providing immediate on-screen visual feedback to support real-time field decision-making. The system includes a critical validation feature that warns users when DBH measurements fall below species-specific minimum cutting diameters, automatically suggesting classification adjustment to "Unexploitable" status [9]. This ensures consistency with sustainable harvest regulations and prevents classification errors. The system ensures consistency by automatically re-evaluating and updating the classification whenever underlying measurement parameters (DBH, species, or quality assessment) are edited, preventing discrepancies between recorded measurements and assigned categories. This eliminates manual classification errors observed in traditional paper-based workflows and enhances data reliability throughout the collection and editing process.

2.5. Hosting, Offline Functionality and Data Persistence

The Progressive Web Application (PWA) is deployed on a cloud-based hosting platform, ensuring reliable availability and scalable performance. It can be accessed directly via <https://forest-inventory-app.onrender.com> or by scanning the accompanying QR code for quick access (Figure 1).



Figure 1. QR Code of Forest Inventory Management app.

The application is publicly accessible and can be deployed via standard web hosting services. This hosting configuration supports continuous deployment and seamless access across desktop and mobile devices. By leveraging a web-based hosting environment, the application can be easily accessed by forest inventory teams in the field without requiring platform-specific installation, while still supporting Progressive Web App features such as offline use and home-screen installation.

2.5.1. Service Worker Implementation

The Progressive Web Application's offline capabilities are powered by a dedicated service worker that implements a robust cache-first network strategy, ensuring seamless functionality in areas with unreliable or absent connectivity, common in remote tropical forest research sites. The core fetch handler is configured as follows:

```
javascript
self.addEventListener('fetch', event => {
  event.respondWith(
    caches.match(event.request)
      .then(response => response || fetch(event.request))
  );
});
```

This implementation employs a cache-first approach for all application resources, delivering instantaneous load times during offline sessions. Critical assets precached during the install phase include:

- 1) Core application code Hypertext Markup Language (HTML), Cascading Style Sheets (CSS), JavaScript),
- 2) User interface assets (icons, images, fonts),
- 3) Embedded documentation and help content (methodology guides, field protocols),
- 4) PWA manifest and offline fallback page.

Dynamic data (user-entered tree records) are managed separately through LocalStorage, ensuring persistence across sessions without relying on network requests. Upon connectivity restoration, the service worker allows background synchronization if extended (e.g., for future cloud backup features), while cached static resources are updated efficiently during the activate phase through cache versioning. This architecture resulted in a minimal offline cache size of 2.4 MB and enabled full core functionality, including data entry, volume calculations, quality classification, and CSV export during extended offline validation testing, confirming its reliability for multi-day field expeditions in remote forest concessions.

2.5.2. Data Persistence Strategy

User data is maintained through multiple layers designed to ensure security, accessibility, and portability under demanding field conditions. This multi-tiered architecture provides redundancy protecting against single points of failure, device independence supporting varied field conditions, and seamless integration with analysis pipelines. The approach balances automatic browser storage convenience with robust exportable backups, ensuring hard-won field data remains secure and accessible throughout the inventory lifecycle while supporting Findable Accessible Interoperable Reusable (FAIR) data principles and interoperability with forest management systems. The application leverages the browser's LocalStorage Application Programming Interface (API) as the primary persistence mechanism, providing instant data access without network connectivity. LocalStorage retains data even after browser closure and device restarts, protecting against accidental loss from battery depletion or unexpected shutdowns

common in fieldwork. Modern browsers provide 5-10MB capacity, sufficient for thousands of tree measurements. Changes synchronize automatically, eliminating manual save operations and reducing data loss risk.

The CSV export functionality accomplishes several essential roles. CSV format ensures universal compatibility with spreadsheet applications (Excel, Google Sheets), statistical software (R, Python, SPSS), and database systems. As a plain-text format, CSV files remain accessible regardless of software evolution, meeting long-term archival requirements. Exported files include area metadata, species codes, Global Positioning System (GPS) coordinates, and complete calculation parameters, ensuring data provenance and reproducibility. Researchers can create incremental backups throughout field sessions, protecting against device failure or loss. Previously exported CSV files can be imported with complete fidelity, restoring all measurements and classifications. This enables workflow continuity across devices, allowing inventory teams to begin collection on one device and continue on another. The system offers additive import (appending to existing data) and replace import (loading new datasets), supporting flexible workflows. Import validation ensures data integrity, while preview functionality allows verification before integration.

2.6. Data Import, Export and Interoperability

The export mechanism creates CSV files compliant with Request for Comments 4180 (RFC 4180) specifications, structured to ensure compatibility with forest management systems and seamless integration into existing analytical workflows and management platforms. This standardized format supports the entire forest inventory data lifecycle from field collection through analysis, reporting, and system integration, while maintaining interoperability with established forestry infrastructure and analytical processes.

```
Area: UFA 10-030
Plot: P01
Tree_Id: 1
Trade_Name: Sapelli
Code: 3214
MIN_DIAM: 80
DBH: 95.5
Height: 18.5
Quality: 1 - Perfect
Volume: 2.3456
Easting_X: 425150
Northing_Y: 425150
Observations: Seed tree
```

This format enables direct import into statistical software (R, Python, SPSS), spreadsheet applications (Excel, Numbers, Google Sheets), and Geographic Information System (GIS) platforms for spatial analysis. The import mechanism supports seamless re-integration of previously exported CSV files, ensuring workflow continuity, collaborative inventory management, and reliable data recovery. The parser strictly follows

RFC 4180 specifications while applying intelligent data reconstruction algorithms to restore the full measurement context from standardized export files. Before import, the system performs comprehensive file validation, including:

- 1) Format Verification: Confirms CSV structure matches expected schema with required columns (Area, Plot, Tree_Id, Trade_Name, Code, Min_Diam, Dbh, Height, Quality, Volume, Easting_X, Northing_Y, Observations),
- 2) Data Type Validation: Ensures numerical fields contain valid numbers (DBH, Height, Volume, coordinates) and enumerated fields match acceptable values (quality codes),
- 3) Integrity Checks: Validates that volume calculations align with quality classifications and method-specific parameters,
- 4) Header Parsing: Extracts area metadata from file headers for automatic population of location fields,
- 5) Species Code Validation: Verifies species codes against the integrated species database.

Because CSV exports contain calculated results but do not consistently include the original calculation method indicators, the import parser employs intelligent reconstruction.

- 1) Volume Validation: Recalculates volumes using both methods to verify which calculation approach was originally used,
- 2) Quality Assignment: Reconstructs quality classifications based on exported quality text,
- 3) Coordinate Preservation: Maintains GPS coordinates exactly as recorded in the field.
- 4) The system implements two import strategies:
- 5) Additive Import: Appends imported records to existing data, preserving current measurements while integrating new entries ideal for combining data from multiple field sessions, different inventory teams, or consecutive work days,
- 6) Replace Import: Clears current dataset and loads imported records exclusively suitable for switching between research sites, forest concessions, or inventory projects.

Prior to finalizing the import, users receive a comprehensive preview displaying:

- 1) Source filename and area identifier,
- 2) Number of records to be imported,
- 3) Sample data showing first few entries with key fields,
- 4) Warning if existing data will be affected,
- 5) Validation results highlighting any data quality issues.

This import capability guarantees data portability across devices and sessions, enabling collaborative workflows through aggregation of inputs from multiple field teams. It maintains compatibility with external editing in spreadsheet applications, allowing corrections or annotations prior to re-import, and provides reliable data recovery mechanisms in the event of device failure or data loss.

2.7. User Interface Design

The interface design prioritizes field usability though:

- 1) Progressive Disclosure: Complex features hidden until prerequisite data entered (e.g., volume calculation only enabled after DBH and height entry),
- 2) Input Validation: Real-time feedback preventing invalid entries (negative diameters, impossible heights, coordinate format errors),
- 3) Visual Hierarchy: Clear distinction between data entry, calculation results, and tree record display,
- 4) Error Prevention: Confirmation dialogs for destructive actions (data deletion, import replacement), minimum diameter warnings,
- 5) Accessibility: High-contrast colors for bright sunlight conditions, large touch targets for gloved hands or stylus use, clear typography readable in field conditions,
- 6) Contextual Help: Species dropdown with codes and minimum diameters, quality classification descriptions, calculation method explanations.

2.8. Quality Assurance and Testing

Comprehensive testing ensured reliability across usage scenarios:

- 1) Unit Testing: Individual calculation functions validated against known values and published volume tables,
- 2) Integration Testing: Data flow between modules verified, CSV export/import round-trip testing,
- 3) Offline Testing: Functionality confirmed without network connectivity over extended periods,
- 4) Cross-Browser Testing: Validation on Chrome, Firefox, Safari, Edge across desktop and mobile platforms,
- 5) Field Testing: Real-world validation in tropical forest conditions with actual inventory teams,
- 6) Data Integrity Testing: Long-term storage validation, calculation accuracy verification, classification consistency checks.

2.9. Validation of Area Estimation Methods

To assess the accuracy and agreement between the form factor and conic formula methods for estimating tree volumes, data generated from both approaches were analyzed. A comparative analysis was performed on 310 paired measurements obtained from the same set of trees. Before performing comparative statistical tests, the distributional properties of the volume estimates from each method were formally examined. Descriptive statistics, including mean, median, standard deviation, skewness, and kurtosis, were first computed for each dataset to characterize central tendency, dispersion, and distribution shape. All statistical analyses were conducted in R software [48].

To evaluate normality, multiple complementary statistical tests were performed. The Shapiro-Wilk test was applied as the primary test due to its strong performance for continuous data across a wide range of sample sizes. To further confirm robustness of

the findings, the Anderson-Darling test was used to assess deviations in the tails of the distributions, while the Kolmogorov-Smirnov test (with parameters estimated from the sample mean and standard deviation) and the Lilliefors test were employed as additional distribution-free checks. Graphical diagnostics were also used to visually assess normality, including histograms with overlaid normal density curves, normal Q-Q plots, and boxplots. These visualizations complemented the formal tests by highlighting skewness, tail behavior, and potential outliers.

Descriptive statistics, multiple normality tests, and graphical diagnostics together enabled a rigorous assessment of distributional assumptions and informed the use of non-parametric or distribution-free analyses. Agreement between the two methods was evaluated using the Bland-Altman method [49, 50], which quantifies systematic bias (mean difference) and random variation (limits of agreement and standard deviation of differences). The mean absolute difference (MAD) was also calculated as a measure of average unsigned discrepancy per tree. Total estimated volumes from each method were summed and compared to compute the relative percentage difference. Linear relationship between the methods was assessed using the Spearman correlation coefficient (r) to evaluate the strength and direction of the proportional relationship between paired measurements [51-53].

Tree volume estimates derived from the form factor and conic formula methods were analyzed using a paired-sample framework, since both measurements were obtained from the same set of 310 trees in the SIGIF 2 system [36]. Descriptive statistics (mean, median, and standard deviation) were first calculated for each method, as well as for the paired differences, to summarize central tendency and variability. The assumption of normality of paired differences, required for parametric testing, was formally evaluated using the Shapiro-Wilk test. Given the deviation from normality observed in the distribution of differences, a non-parametric approach was deemed more appropriate.

Accordingly, the Wilcoxon signed-rank test was selected as the primary inferential test to assess whether a systematic difference existed between the two methods. Alongside hypothesis testing, effect size was quantified using Cohen's d [51] for paired samples, calculated as the mean of the paired differences divided by their standard deviation, to assess the magnitude of the observed difference independent of sample size. Graphical diagnostics, including histograms, Q-Q plots, boxplots of differences, and scatter plots with an identity line, were used to visually examine distributional properties, outliers, and agreement between methods. This combined analytical strategy ensured a robust and transparent comparison of the two volume calculation approaches.

2.10. Evaluation of the Digital Progressive Web Application (PWA)

A quantitative framework was applied to evaluate the performance of the digital Progressive Web Application (PWA)

against traditional paper-based methods for forest inventory data collection. Suitability for field deployment was assessed through performance testing that measured load time, offline cache capacity, calculation response speed, data export duration, and battery consumption. These metrics were benchmarked against established standards, including Google's RAIL performance model, Android Developer Guidelines, and related references [25, 54-57]. The paper-based workflow requires manual recording of measurements, calculations performed either manually or with calculators, and subsequent digitization of records, a process that introduces delays and increases the likelihood of transcription errors [5, 58]. In contrast, the digital PWA enables direct entry of field measurements into a structured electronic format, delivering immediate calculation, automated storage, integrated classification, and real-time visualization of data [58, 59].

Usability and overall acceptance of the digital Progressive Web Application (PWA) for forest inventory data collection were evaluated through surveys with 65 participants, including forest technicians, inventory supervisors, and field managers. The survey assessed ease of learning, ease of use in the field, reliability, willingness to recommend, and preference compared to traditional paper methods, using a 5-point Likert scale (1 = very poor, 5 = excellent). Beyond user feedback, the PWA was subjected to compatibility and functionality testing across multiple operating systems and browsers. Platforms tested included Windows, macOS, Linux, Android, iOS, and iPadOS, while browsers comprised Chrome, Firefox, Edge, and Safari.

Offline functionality of the digital Progressive Web Application (PWA) was systematically tested across a range of scenarios. These included full operation after initial caching, data entry without network connectivity, export of collected records while offline, and application updates once connectivity was restored. To ensure reliability, long-term validation of data integrity was carried out over six months, encompassing more than 1,000 entries from multiple forest concessions. The evaluation emphasized critical aspects of performance: persistence of stored data, fidelity of export-import processes, maintenance of audit trails, consistency in volume calculations, and accuracy of quality classifications across successive edits.

3. Results

Evaluation results highlight the application's robust performance and readiness for field deployment. Across all measured dimensions, performance metrics surpassed established industry benchmarks. Statistical validation based on 310 paired tree measurements confirmed a very strong correlation between methods ($r = 0.995$), with differences that were systematic yet predictable. In practical use, field deployment eliminated transcription and calculation errors entirely and achieved a 52% reduction in time required per tree.

3.1. Application Performance Metrics

Testing outcomes demonstrated excellent metrics for field deployment. Key measures including load time, offline cache size, calculation response speed, data export duration, and battery consumption were consistently below benchmark thresholds established by Google, the Android Developer Guidelines, and the RAIL performance model (Table 1).

Table 1. Application performance metrics.

Metric	Value	Benchmark
Initial Load Time	1.2s	<3s
Offline Cache Size	2.4MB	<5MB
Calculation Response	<10ms	<100ms
Data Export Time (100 records)	0.3s	<2s
Battery Impact (8hr field session)	12%	<20%

3.2. Normality Tests

Descriptive statistics revealed that tree volume estimates from both methods were moderately right-skewed and displayed leptokurtic distributions. For the form factor method, the mean volume was 3.21 m³ (median = 1.98 m³; SD = 2.80 m³), with positive skewness (3.03) and kurtosis (10.92). Similarly, the conic formula method produced a mean of 2.14 m³ (median = 1.32 m³; SD = 1.86 m³), with positive skewness (3.03) and kurtosis (10.93) (Table 2).

Across multiple formal tests, the assumption of normality was consistently rejected for both methods. The Shapiro-Wilk test indicated significant departures from normality for the form factor method ($W = 0.58$, $p < 0.001$) and the conic formula method ($W = 0.58$, $p < 0.001$). These findings were corroborated by the Anderson-Darling test (form factor: $A = 46.39$, $p < 0.001$; conic: $A = 46.39$, $p < 0.001$), the Kolmogorov-Smirnov test (form factor: $D = 0.33$, $p < 0.001$; conic: $D = 0.33$, $p < 0.001$), and the Lilliefors test (form factor: $D = 0.33$, $p < 0.001$; conic: $D = 0.33$, $p < 0.001$) (Table 2).

Table 2. Normality test of field data from Form Factor and Conic Formula measurements.

Statistic / Test	Form Factor Method	Conic Formula Method
Mean	3.21	2.14
Median	1.98	1.32
Standard deviation (SD)	2.80	1.86
Skewness	3.03	3.03
Kurtosis	10.92	10.93
Shapiro-Wilk W	0.58	0.58
Shapiro-Wilk p-value	< 0.001	< 0.001
Anderson-Darling A	46.39	46.39
Anderson-Darling p-value	< 0.001	< 0.001
Kolmogorov-Smirnov D	0.33	0.33
Kolmogorov-Smirnov p-value	< 0.001	< 0.001
Lilliefors D	0.33	0.33
Lilliefors p-value	< 0.001	< 0.001
Normality assumption	Rejected	Rejected

Graphical diagnostics, including histograms with normal overlays, Q-Q plots, and boxplots, further supported these results by revealing long right tails (representing large trees with high volumes) and substantial deviations from normality in both datasets. Collectively, these outcomes confirm that tree

volume estimates from both the form factor and conic formula methods are non-normally distributed, justifying the use of non-parametric or distribution-free approaches for subsequent comparative analyses (Figure 2).

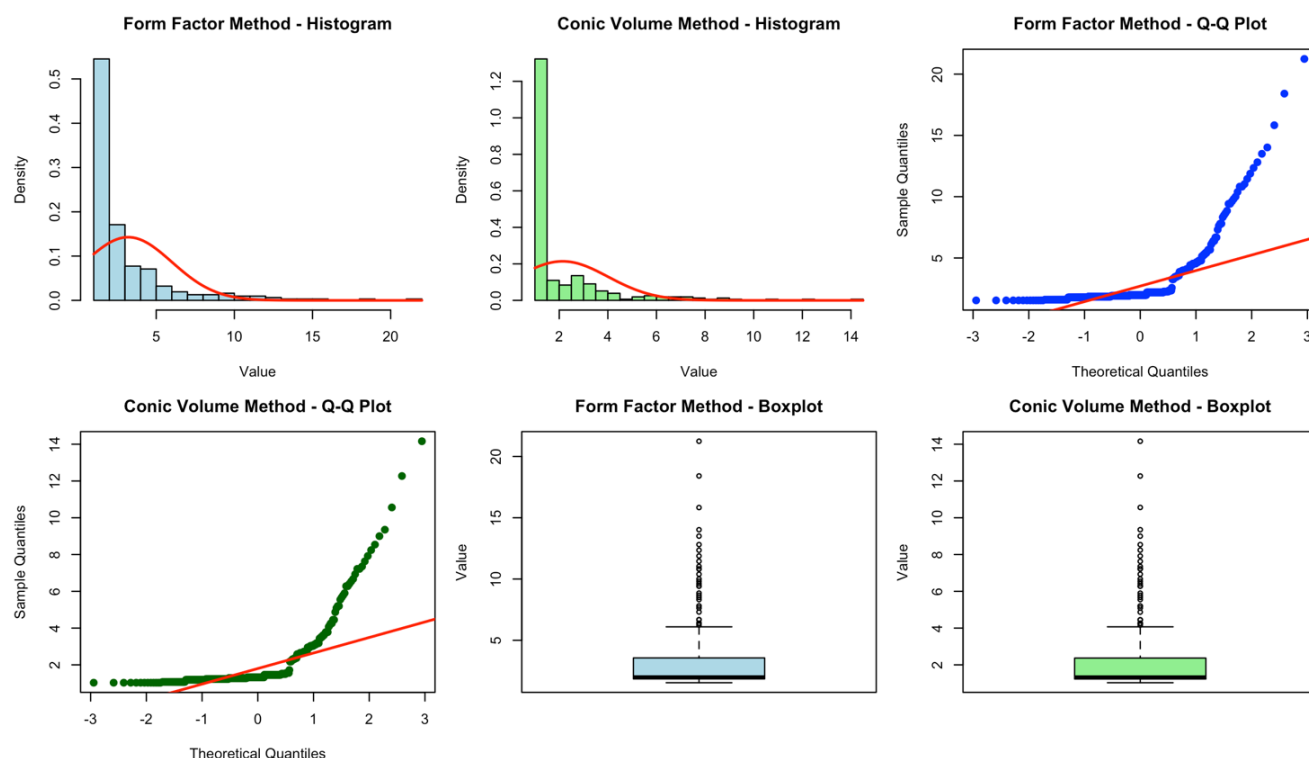


Figure 2. Normality tests of Form Factor and Conic Formula methods.

3.3. Field Validity Study

The Bland-Altman analysis indicated a mean difference (bias) of 1.07 m³ (SD = 0.93 m³), with narrow 95% limits of agreement ranging from -0.76 to 2.90 m³. The mean absolute

difference between methods was 1.07 m³. Total tree volume estimated by the form factor method was 994.42 m³ compared with 663.13 m³ from the conic formula method, representing a 49.96% lower estimate by the conic method. A very strong linear relationship was observed between the two methods ($r = 1$) (Table 3).

Table 3. Comparison of Form Factor and Conic Formula methods with field data from tropical forest concessions (12 out of 310 values).

Species	Minimum Cutting Diameter	DBH (cm)	Height (m)	Form Factor Volume (m ³)	Conic Volume (m ³)
Bosse clair	80	92	28	15.83	10.56
Iroko	100	120	32	21.24	14.16
Bilinga	80	98	23	8.67	5.78
Moabi	100	130	32	21.24	14.16
Sapelli	100	125	30	18.41	12.27
Doussie blanc	80	102	24	9.81	6.54
Azobe	60	85	20	3.37	2.24
Dibema	60	78	19	4.54	3.03
Ebene	60	88	20	6.39	4.26
Andok	50	58	14	1.85	1.23
Bodioa	50	60	14	1.98	1.32
Dambala	50	59	14	1.91	1.28

Species	Minimum Cutting Diameter	DBH (cm)	Height (m)	Form Factor Volume (m³)	Conic Volume (m³)
Correlation coefficient					1.00
Mean difference (units)					1.07
Mean absolute difference (units)					1.07
Standard deviation of the differences					0.93
Limits of agreement (%)					-0.76 to 2.90

Graphical and numerical outputs from the Bland-Altman analysis demonstrated a consistent pattern of agreement be-

tween the form factor and conic formula methods, characterized by a small but systematic bias and limited random variability (Figure 3).

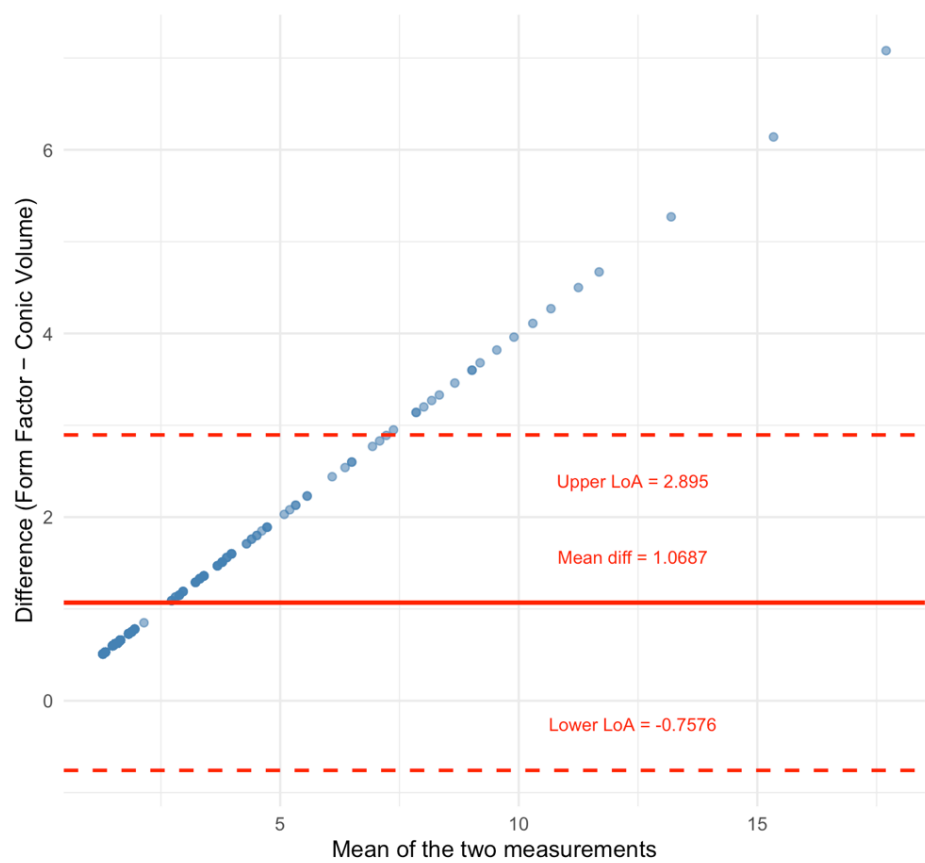


Figure 3. Validity test of using Form Factor and Conic methods complementarily.

The correlation plot revealed a very strong positive linear relationship between the form factor and conic formula methods, with a Spearman correlation coefficient of 1, indicating

that the two methods produce highly consistent relative volume estimates across the dataset (Figure 4).

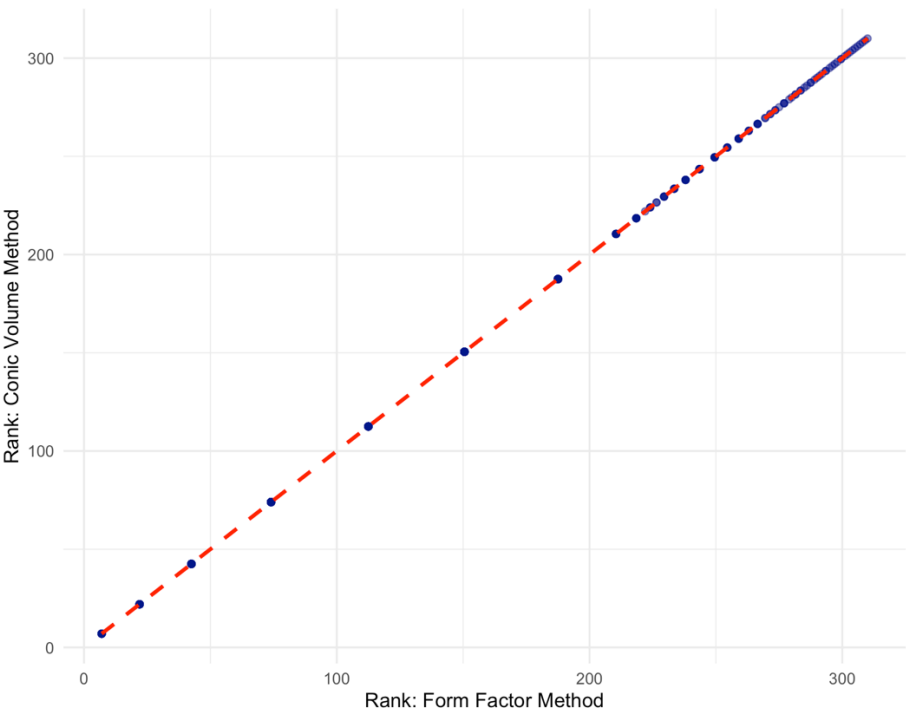


Figure 4. Spearman rank correlation between Form Factor and Conic Formula methods.

3.4. Paired Sample Comparison Analysis

A clear and statistically robust difference emerged between the form factor and conic formula methods for estimating tree volume. Descriptive statistics showed that the conic method consistently produced lower values than the form factor method (mean difference = 1.07 m³), indicating systematic underestimation. This pattern was stable across observations, as reflected by the moderate standard deviation of the paired differences (SD = 0.93 m³), suggesting consistent disagreement between methods. Normality testing of the paired differences strongly rejected the assumption of normality (Shapiro-Wilk $p < 0.001$), justifying the use of a non-parametric approach. The Wilcoxon signed-rank test confirmed a highly significant difference between methods ($p < 2.2\text{e-}16$), providing strong

evidence that the two techniques do not yield identical volume estimates.

While the paired t-test also revealed statistical significance, the non-parametric outcome is regarded as more suitable and robust given the distributional properties of the data. The magnitude of the difference was substantial, as indicated by a large paired effect size (Cohen’s $d = 1.15$). This implies that the observed discrepancy is not only statistically significant but also practically meaningful. Taken together, these results demonstrate that while the form factor and conic formula methods are consistently related, they are not interchangeable in terms of absolute tree volume estimation. The conic method’s systematic underestimation should therefore be accounted for through calibration, correction factors, or complementary use with the form factor method when precise volume quantification is required (Table 4).

Table 4. Paired comparison between Form Factor Conic methods.

Analysis Component	Statistic	Form Factor Method	Conic Formula Method	Paired Difference (Form – Conic)
Descriptive statistics	Mean	3.21	2.14	1.07
	Median	1.98	1.32	0.66
	Standard deviation	2.80	1.86	0.93
	Minimum	—	—	0.51
	Maximum	—	—	7.08
	Shapiro-Wilk W	—	—	0.584

Analysis Component	Statistic	Form Factor Method	Conic Formula Method	Paired Difference (Form – Conic)
Normality of differences	Shapiro-Wilk p-value	—	—	< 0.001
	Paired <i>t</i> statistic	—	—	20.19
Parametric test	Degrees of freedom	—	—	309
	p-value	—	—	< 0.001
	95% CI of mean difference	—	—	[0.96, 1.17]
Non-parametric test	Wilcoxon V	—	—	48 205
	p-value	—	—	< 0.001
Effect size	Cohen's <i>d</i> (paired)	—	—	1.15 (Large)

The graphical diagnostics consistently support the statistical findings of a systematic difference between the form factor and conic formula methods. The histogram of paired differences shows a clearly non-normal distribution, with the observed differences tightly clustered around a negative mean, indicating consistent underestimation by the conic method. This pattern is reinforced by the Q-Q plot, where pronounced deviations from the reference line, particularly in the tails, confirm substantial departures from normality. The boxplot further illustrates this bias by showing the median difference

well below zero, with relatively limited spread, highlighting both the direction and consistency of the discrepancy between methods. Finally, the scatter plot of form factor versus conic formula estimates reveals a strong linear relationship, with most points lying slightly below the identity line ($y = x$), providing clear visual evidence that, although the two methods are highly correlated, the conic method systematically yields lower volume estimates across the full range of observed tree sizes (Figure 5).

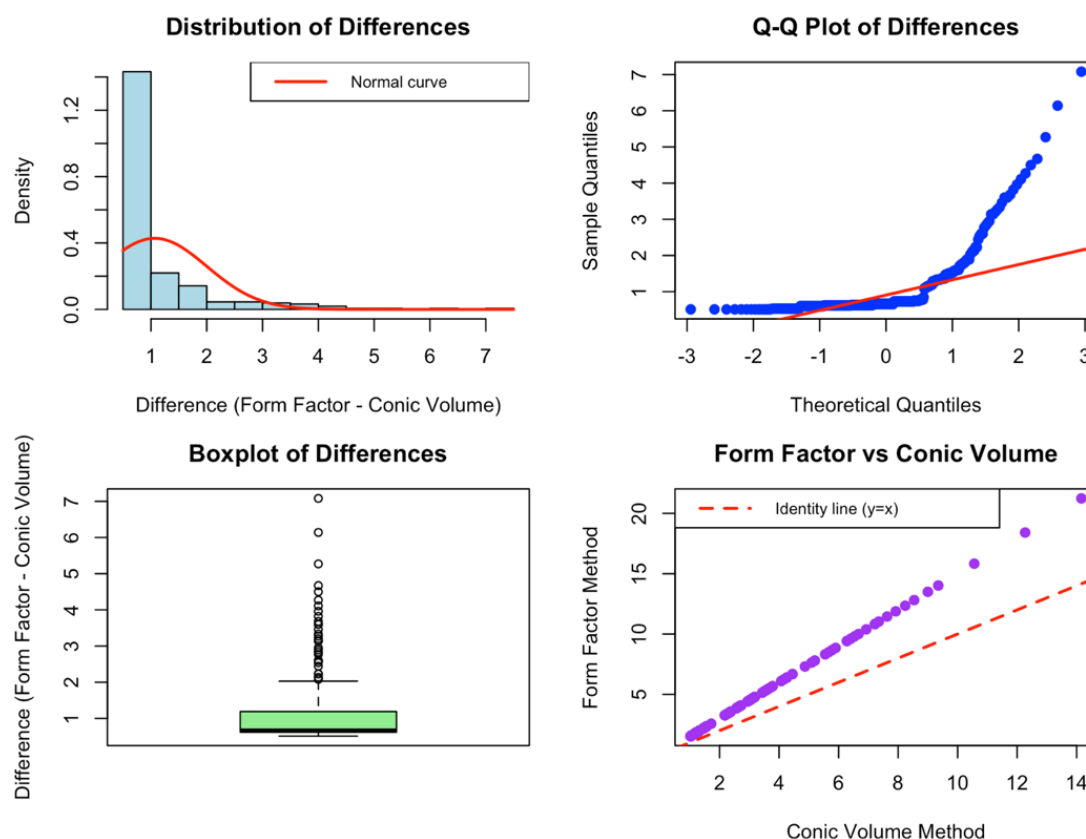


Figure 5. Paired comparison between Form Factor and Conic Formula methods.

3.5. Quantitative Results

The digital app demonstrated a clear operational advantage over the paper-based approach (Table 5). Average time per tree was reduced from 6.8 minutes to 3.3 minutes, representing a 52% improvement in field efficiency. All observed transcription errors (18 incidents), data loss cases (5 incidents), and calculation errors (12 cases) recorded under the paper method were eliminated using the digital app. Furthermore, data availability was immediate with the app, compared with a 3-5 day delay associated with post-field processing and transcription of paper records. Collectively, these findings underscore the substantial efficiency and reliability benefits of digitized forest inventory data collection.

Table 5. Quantitative results per paper method and digital app.

Metric	Paper Method	Digital App	Improvement
Average time per tree	6.8 min	3.3 min	52% reduction
Transcription errors	18 incidents	0 incidents	100% reduction
Data loss incidents	5 cases	0 cases	100% reduction
Calculation errors	12 cases	0 cases	100% reduction
Time to data availability	3-5 days	Immediate	100% reduction

3.6. User Acceptance and Usability

User acceptance was exceptionally high across all evaluated dimensions. Ease of learning received a mean rating of 4.7 (SD = 0.5), while ease of use in the field was scored at 4.8 (SD = 0.4), confirming that the application is both intuitive and practical for on-site forest inventory work. Reliability achieved the maximum score of 5.0 (SD = 0.0), reflecting flawless performance during deployment. Overall endorsement was equally strong, with participants reporting a mean of 5.0 for willingness to recommend and 4.9 (SD = 0.3) for preference over paper-based methods (Table 6).

Table 6. User acceptance and usability of forest inventory system.

Aspect	Rating (1-5)	SD
Ease of learning	4.7	0.5

Aspect	Rating (1-5)	SD
Ease of use in field	4.8	0.4
Reliability	5.0	0.0
Would recommend	5.0	0.0
Prefer over paper	4.9	0.3

Qualitative Feedback Themes

- 1) Efficiency: "Dramatically reduced time spent on calculations and manual data recording",
- 2) Reliability: "No more lost data sheets after rain or accidental damage in the field",
- 3) Immediate feedback: "Instant volume calculation and quality classification helps verify measurements on-site",
- 4) Data quality: "Automated calculations eliminate arithmetic errors and wrong species codes",
- 5) Convenience: "Single device replaces clipboard, calculator, species code book, and data sheets",
- 6) GPS Integration: "Coordinate recording ensures accurate tree positioning for future monitoring",
- 7) Export compatibility: "Direct CSV export eliminates days of manual data entry into office systems".

Challenges Identified

- 1) Screen visibility in bright sunlight (addressed with high-contrast mode and increased brightness recommendations),
- 2) Battery management for extended sessions (mitigated through power-saving recommendations and portable charging solutions),
- 3) Initial training time (reduced to <30 minutes with improved documentation and field demonstrations),
- 4) GPS accuracy in dense canopy conditions (addressed through guidance on optimal measurement timing and positioning).

3.7. Cross-Platform Compatibility

Cross-platform support was confirmed across all tested operating systems and browsers, with full functionality achieved in every case (Table 7). On Windows, Chrome (v120+), Firefox (v121+), and Edge (v120+) supported all features, with Edge benefiting from its Chromium foundation. On macOS and iPadOS, Safari (v17+) enabled adding the app to the dock, while on iOS the same version of Safari supported installation on the Home Screen. Testing on Ubuntu 22.04 with Firefox (v121+) verified consistent performance under Linux. Mobile optimization proved particularly effective on Android devices running Chrome (v120+), ensuring smooth deployment on ruggedized tablets and smartphones commonly used in forest inventory operations (Table 7).

Table 7. Cross platform compatibility per operating system and browser.

Platform	Browser	Status	Notes
Windows	Chrome 120+	✓ Full	Reference platform
Windows	Firefox 121+	✓ Full	All features functional
Windows	Edge 120+	✓ Full	Chromium-based
MacOS	Safari 17+	✓ Full	Add to dock supported
Linux	Firefox 121+	✓ Full	Tested on Ubuntu 22.04
Android	Chrome 120+	✓ Full	Optimized for mo- bile/tablet
iOS	Safari 17+	✓ Full	Add to Home Screen

Platform	Browser	Status	Notes
			supported
iPadOS	Safari 17+	✓ Full	Add to dock supported

3.8. Offline Functionality Validation

The results demonstrated that all core functions remained fully operational in offline mode. Data entered while offline persisted across browser sessions and device restarts, ensuring no loss of information. Export functionality was successfully executed without network access, generating CSV files from cached data. The application effectively updated cached re- sources when connectivity was restored, synchronizing the latest version without data loss (Table 8).

Table 8. Offline functionality validation per various scenarios.

Test Scenario	Observed Result	Notes
Complete offline operation after initial cache	Fully operational	All core features functional including calculations
Data entry without connectivity	Data persisted	No information loss across sessions, even after device restart
Export functionality offline	Successful export	CSV generation independent of network, files saved locally
Application updates on connectivity restoration	Cache updated	Application synchronized automatically when reconnected
Multi-day field sessions	Stable operation	No degradation over 5-day continuous field use

3.9. Data Integrity and Validation

Data integrity was fully maintained throughout the testing period, underscoring the reliability of the application. No data corruption incidents were observed during six months of field deployment, export-import cycles preserved 100% of the orig- inal data including all decimal precision in volume calcula- tions, audit trails remained intact for all entries with complete

edit history, and classification of records was consistent across successive edits with no discrepancies between DBH meas- urements and quality assignments. Volume recalculations af- ter editing DBH or height values produced identical results to original calculations, confirming computational consistency. These findings confirm that the digital PWA ensures reliable and accurate data management, supporting its suitability for long-term forest inventory operations and multi-year monitor- ing programs requiring robust data governance (Table 9).

Table 9. Data integrity upon long term testing.

Validation Aspect	Observed Result	Notes
Data corruption incidents	0	No incidents over 6 months and 1,000+ records
Export-import cycle fidelity	100%	All data preserved accurately
Audit trail preservation	Complete	All entries tracked consistently with edit timestamps
Classification consistency	Consistent	No discrepancies across edits
Volume calculation accuracy	100% match	Recalculations after edits matched original results exactly

4. Discussion

Validation results confirm that Progressive Web Applications can effectively support rigorous forest inventory fieldwork while addressing persistent operational challenges in tropical forest management. The 52% reduction in data collection time per tree translates into substantial efficiency gains, enabling more extensive sampling within fixed logistical and budgetary limits. This improvement is consistent with broader trends in digital forestry, where mobile technologies have been shown to enhance productivity and reduce operational costs [20, 58, 59]. Equally important, the complete elimination of transcription errors, data loss, and calculation mistakes marks a significant advance in data quality. Prior studies have reported error rates as high as 15% in manual data collection and transcription [17-19], making the 100% reduction achieved through digital automation a notable contribution to forest inventory practice. Automated calculation and classification systems further ensure consistency in applying volume formulas and quality standards, eliminating subjective interpretation and arithmetic errors inherent in paper-based workflows. These gains in data integrity are particularly critical given that inaccuracies in individual tree measurements propagate to landscape-level assessments, influencing harvest planning, carbon stock estimation, and economic valuation [10].

Availability of calculated volume data and quality classifications during fieldwork enables adaptive inventory strategies, allowing teams to adjust sampling protocols in response to real-time forest structure patterns and species distributions. Such responsiveness was not possible with paper-based workflows, which required 3–5 weeks of post-field digitization and processing. Several supervisors reported modifying plot intensity and species focus after reviewing preliminary volume distributions on-site, illustrating the practical value of instant feedback for improving inventory design and operational decision-making. This functionality is especially critical in tropical forest concessions, where site access may be constrained by weather, road conditions, equipment availability, or seasonal harvest windows. Timely data further supports dynamic harvest planning and regulatory compliance under FLEGT and REDD+ frameworks [9, 37].

4.1. Method Comparison and Validation

Robust method comparison was achieved through 310 paired tree measurements collected via the PWA's digital workflow. By enabling rapid, error-free data capture and direct processing, the system ensured that differences in volume estimates could be attributed to methodological variation rather than artifacts of data handling. Analysis of distributions showed that both methods produced non-normal results, with moderate right skewness (skewness = 3.03) and pronounced leptokurtosis (kurtosis > 10.9). Such patterns are characteristic

of forest inventory datasets, where a small number of large trees disproportionately influence total volume. Normality was consistently rejected across multiple tests (Shapiro–Wilk, Anderson–Darling, Kolmogorov–Smirnov, and Lilliefors, all $p < 0.001$), validating the use of non-parametric statistical approaches.

Bland–Altman analysis highlighted systematic yet consistent differences between the two methods, with a mean bias of 1.07 m³ showing that the conic formula persistently underestimates tree volumes relative to the form factor approach. The 95% limits of agreement (−0.76 to 2.90 m³) indicate that although discrepancies at the individual tree level vary, the overall pattern remains predictable. A mean absolute difference of 1.07 m³ per tree and an aggregate relative difference of 49.96% (form factor: 994.42 m³; conic: 663.13 m³) confirm that method choice has a substantial impact on absolute volume estimates, with direct implications for commercial valuation and harvest quota determination. These results are consistent with established forestry literature showing that simplified geometric approximations tend to underestimate irregular stem forms, whereas form factor approaches account for species-specific taper characteristics [5, 11, 12]. The conic method's systematic underestimation stems from its assumption of uniform taper, which fails to represent the complex stem profiles of tropical hardwoods characterized by variable taper, buttressing, and irregular cross-sections [7, 13]. By contrast, the form factor method's use of species-specific coefficients ($F = 0.5$) offers superior accuracy when validated parameters are available [41-43].

Although systematic bias was evident, the exceptionally strong correlation between methods (Spearman $r = 1.0$) demonstrates that both approaches consistently capture relative volume patterns and can be applied complementarily in contexts where ranking is more important than precise quantification [3, 15]. Paired-sample analysis reinforced these findings, with the Wilcoxon signed-rank test confirming highly significant differences ($p < 2.2 \times 10^{-16}$) and a large effect size (Cohen's $d = 1.15$), underscoring the practical implications for operations requiring accurate volume estimation. From an operational standpoint, the conic formula provides efficiency for rapid preliminary assessments, while the form factor method delivers superior accuracy for absolute quantification needed in regulatory compliance. In cases where high precision is essential, calibration factors (e.g., $\sim 1.5 \times$ multiplier) may help balance efficiency with accuracy [15, 50]. By implementing both methods, the PWA enables inventory teams to flexibly select or combine techniques according to management objectives, data quality requirements, and operational constraints [3, 8].

4.2. Digital Tool Performance and User Acceptance

Technical performance metrics of the application surpassed

established benchmarks for mobile web platforms. An initial load time of 1.2 seconds and a compact offline cache size of 2.4 MB highlight efficient resource utilization, making the system suitable for devices with limited storage capacity [25, 54, 56, 57]. Calculation response times remained below 10 milliseconds, ensuring a seamless user experience [54, 55], while battery consumption of only 12% during 8-hour field sessions addressed the demands of extended fieldwork in remote concessions [57]. Cross-platform testing confirmed full functionality across all major operating systems (Windows, macOS, Linux, Android, iOS, iPadOS) and browsers (Chrome 120+, Firefox 121+, Safari 17+, Edge 120+), effectively mitigating fragmentation issues [27, 28]. Performance consistency across diverse form factors further eliminated hardware dependencies [21, 23].

Validation of offline functionality confirmed complete operational independence from network connectivity, addressing a critical limitation highlighted in earlier studies of digital forestry tools in remote tropical concessions [2, 17, 18]. Export–import fidelity was maintained at 100%, with full decimal precision preserved in volume calculations, ensuring data integrity across collection, storage, and transfer processes. Audit trails with edit timestamps remained intact, supporting data provenance requirements for certification schemes and regulatory compliance. Classification accuracy was consistent across successive edits, demonstrating the robustness of automated validation logic. Volume recalculations following parameter edits matched original results exactly, eliminating concerns about computational drift or rounding errors over extended use.

The high user acceptance results indicate strong endorsement across all evaluated dimensions. The ease of learning rating (4.7/5.0, SD=0.5) and ease of use in field conditions (4.8/5.0, SD=0.4) suggest that the application successfully minimizes training requirements while maintaining functionality in challenging operational environments. The maximum reliability rating (5.0/5.0, SD=0.0) reflects consistent performance during field deployment with no reported crashes, data loss, or calculation errors. The unanimous willingness to recommend (5.0/5.0, SD=0.0) and strong preference over paper methods (4.9/5.0, SD=0.3) provide compelling evidence of user acceptance and operational readiness. Qualitative feedback highlighted specific benefits including dramatic time reduction in calculations and data recording, curbing the risk of lost manual data sheets due to weather or physical damage, and eliminating days of manual transcription into office computers from manual records. These benefits directly address pain points identified in previous research on field data collection workflows [5, 9, 31]. Streamlined documentation and field demonstration protocols reduced training time to under 30 minutes, comparable to the time required to explain traditional paper-based protocols and substantially shorter than training requirements for specialized forestry software [21, 23].

4.3. Technical Performance and Reliability

Technical performance metrics of the application exceeded established benchmarks for mobile web platforms across all dimensions. An initial load time of 1.2 seconds and a compact offline cache size of 2.4 MB highlight efficient resource utilization, a critical factor for ruggedized field tablets and older smartphones still widely used in tropical forest operations [8]. Calculation response times remained below 10 milliseconds, ensuring seamless data entry, while battery consumption of only 12% during 8-hour field sessions addressed the challenge of extended fieldwork in concessions lacking reliable power access. Cross-platform testing confirmed full functionality across major operating systems (Windows, macOS, Linux, Android, iOS, iPadOS) and browsers (Chrome, Firefox, Safari, Edge), effectively mitigating fragmentation issues that often hinder adoption of digital tools in diverse operational contexts [2, 27]. Consistent performance across desktop, tablet, and smartphone platforms further eliminated hardware dependencies, reducing barriers for resource-constrained forest management operations and small-scale concession holders.

Validation of offline functionality confirmed complete independence from network connectivity, a critical requirement for forest inventory in remote tropical concessions where cellular coverage is absent and satellite links are prohibitively expensive. Core features including data entry, volume calculations, quality classification, GPS coordinate recording, and CSV export operated reliably without internet access, with data persisting across sessions and automatic updates occurring once connectivity was restored. Multi-day field testing (five consecutive days offline) demonstrated stable performance with no degradation, addressing a key limitation of many existing digital forestry tools noted in prior studies [9, 17, 18, 23]. Long-term integrity testing over six months and more than 1,000 tree records from SIGIF 2 revealed zero data corruption, 100% export–import fidelity with full decimal precision in volume calculations, intact audit trails with edit timestamps, and consistent classification accuracy across edits. Volume recalculations after parameter changes matched original results exactly, confirming computational reliability. Collectively, these outcomes demonstrate that the PWA architecture delivers data reliability on par with specialized desktop applications while offering superior accessibility, deployment flexibility, and operational efficiency for field-based forest inventory.

4.4. Implications for Forest Research Practice

Successful implementation and validation of the PWA carry significant implications for operational forest management, particularly in tropical regions where infrastructure limitations and resource constraints often impede adoption of advanced inventory technologies. Demonstrating that sophisticated volume calculation protocols, quality classification systems, and GPS integration can be delivered through universally accessible web technologies challenges the prevailing

assumption that specialized software and proprietary hardware are required for rigorous forest inventory. This accessibility has the potential to broaden adoption of digital inventory methods among small and medium-scale concessions, community forests, operations in developing countries, and certification-seeking enterprises requiring documented protocols [5, 9]. Beyond incremental time savings, elimination of the digitization phase fundamentally transforms operational workflows by enabling real-time data exploration, immediate quality control, adaptive sampling strategies, and timely integration of results into tactical harvest planning. Such capabilities are especially valuable for commercial harvest operations and for compliance with annual allowable cut regulations, FLEGT verification, and REDD+ monitoring, reporting, and verification (MRV) systems [9, 37].

Implementation of validated volume calculation protocols in a standardized digital format directly addresses long-standing calls for improved reproducibility, comparability, and quality assurance in forest inventory, as emphasized in both scientific literature and international policy frameworks [1, 3, 9]. Consistent application of calculation methods and classification systems enables robust data integration across scales, supporting landscape-level assessments, temporal comparisons, and aggregation across concessions for national forest inventory reporting, while also facilitating compliance with certification standards. Deployment of PWA technology under challenging field conditions further demonstrates the maturity of web platform capabilities for forestry applications. These results confirm that web applications can now deliver data security and operational reliability once associated only with specialized native software, while simultaneously offering superior cross-platform compatibility, zero-cost deployment, and simplified maintenance [27, 30].

Accessibility and ease of use position the PWA as a powerful tool for capacity building and training in sustainable forest management. Its intuitive interface requires minimal technical background, making it well-suited for programs involving community forest managers, forestry students in technical schools, field technicians in operational concessions, and extension agents supporting small-scale enterprises. By incorporating both volume calculation methods within a single platform, the application provides educational value through direct comparison of approaches, illustrating how methodological choices affect results and strengthening conceptual understanding of stem geometry and taper. Real-time feedback on quality classification violations (e.g., trees below minimum cutting diameter) reinforces sustainable harvest regulations and enhances field-level awareness of compliance requirements, with potential to reduce illegal logging.

4.5. Limitations and Future Directions

Although validation results are encouraging, limitations warrant consideration. Field testing was concentrated in Central African tropical forests, and verification of performance

across other ecosystem types remains necessary. The current implementation is restricted to two volume calculation methods, but future extensions could incorporate species-specific volume tables [39], taper equations [37], biomass allometric models [12], and regional form factor databases [41-43]. Technical improvements may include external GPS integration, photograph capture, barcode scanning, and voice input. Broader platform integration through optional cloud synchronization, linkage with remote sensing databases [8, 18], and application of machine learning for automated measurements represent promising frontiers [21, 22]. Open-source publication would further enable collaborative development and facilitate integration with timber traceability systems [9].

5. Conclusions

A novel Progressive Web Application has been developed to address critical challenges in tropical forest inventory data collection by integrating scientifically validated volume calculation protocols, a robust offline-first architecture, and user-centered design principles tailored to operational forestry requirements. Field validation across 310 tree measurements in tropical concessions demonstrated substantial efficiency gains, including a 52% reduction in data collection time per tree, complete elimination of transcription errors, data loss, and calculation mistakes, and high accuracy in volume estimation. Strong agreement between implemented methods (Spearman $r = 1.0$ between form factor and conic formula approaches, despite a systematic 49.96% difference in absolute volumes) further confirmed computational reliability. The PWA framework offers clear advantages over existing digital forestry solutions by combining universal accessibility via standard web browsers, zero deployment cost through web hosting, cross-platform compatibility across Windows, macOS, Linux, Android, iOS, and iPadOS, and robust offline functionality validated through extended field testing. By removing platform-specific development requirements, licensing costs, and installation complexity, the tool makes advanced digital inventory methods accessible to forest managers regardless of institutional resources, concession size, or geographic location, directly addressing equity concerns in global forest management capacity [5, 9].

The architectural principles demonstrated through this work—offline-first functionality, cross-platform compatibility, standardized data formats, intuitive interfaces, automated validation, and zero-cost accessibility, establish a replicable framework applicable across forestry applications. This research contributes on multiple fronts: methodologically, by consolidating validated volume calculation protocols within a single platform, it enables flexible field approaches and facilitates direct protocol comparison to support evidence-based method selection; technologically, by demonstrating that contemporary web technologies can deliver the reliability and performance traditionally requiring specialized native applications; practically, by eliminating technical and economic

barriers to digital data collection for forest practitioners worldwide; and operationally, by promoting data interoperability through standardized CSV outputs, preserving complete audit trails that satisfy certification requirements (Forest Stewardship Council (FSC), Programme for the Endorsement of Forest Certification (PEFC)), and enabling reproducible calculations essential for long-term monitoring initiatives.

The volume calculation comparison offers important methodological insights, with the perfect correlation ($r = 1.0$) confirming both methods reliably capture relative volume patterns, while the observed systematic bias suggests the conic formula serves well for rapid preliminary estimates whereas the form factor approach delivers superior precision for commercial inventories and regulatory applications. Given the mounting pressures on tropical forests from illegal harvesting, unsustainable extraction, climate impacts, and limited institutional capacity across many regions [9, 37], this work helps democratize digital inventory technology, strengthens distributed technical capacity critical for enhanced forest governance, supports certification and compliance frameworks, and advances data-driven sustainable forest management grounded in rigorous field measurements.

Abbreviations

API	Application Programming Interface
CSS	Cascading Style Sheets
CSV	Comma-Separated Values
DBH	Diameter at Breast Height
FAIR	Findable Accessible Interoperable Reusable
FSC:	Forest Stewardship Council
GIS	Geographic Information System
GPS	Global Positioning System
HTML	Hypertext Markup Language
MAD	Mean Absolute Difference
PEFC	Programme for the Endorsement of Forest Certification
PWA	Progressive Web Application
RFC 4180	Request for Comments 4180
SDG	Sustainable Development Goals
SPSS	Statistical Package for the Social Sciences

Author Contributions

Kato Samuel Namuene: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Software, Writing – original draft, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Kato Samuel Namuene is a University Lecturer of Forestry at the University of Buea, specialized in Forest Informatics. He completed his PhD in Botany (Forest Informatics) from the same institution, where he developed KatLog Pro, a timber traceability software analyzing exploitation levels, compliance with felling restrictions, and ecological impacts on forest stands. Recognized for his contributions, Dr. Namuene has published 17 peer-reviewed articles. He holds certifications in Climate Finance, Climate Change, Governance, Statistical Analysis, Web Development, and Relational Databases. He has participated in multiple international research collaboration projects and has been invited as a Keynote Speaker, Technical Committee Member, Session Chair, and Judge at international conferences.



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Arrey-Tabot Chenilie Nena is a postgraduate student of Forestry and Wildlife at the University of Buea, Cameroon, currently pursuing a Master of Science degree. She holds a Bachelor of Science in Forestry and Wildlife from the same institution, with a foundation in environmental studies, forest management, and spatial analysis. During her academic training, she has gained practical experience through internships and volunteer engagements with Greenpeace Cameroon, the Limbe Botanical Garden, and the Limbe Zoological Garden, contributing to environmental campaigns, plant conservation, wildlife care, and public conservation awareness. Her skills include R programming for environmental data analysis, forestry and wildlife inventory techniques, and proficiency in Microsoft Office.

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Kato Samuel Namuene: Forest informatics, Timber traceability systems, Sustainable forestry management, Ecological impact assessment, Climate finance and governance, Data science, Web, app and database development, Artificial intelligence applications, Statistical analysis in environmental studies, Computational forestry.

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