Multiplatform mobile augmented reality for markerless visualization of urban environmental and green city concepts using 3D trees

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Abstract
This study developed a markerless Augmented Reality (AR) application for visualizing dynamic 3D tree growth to support Green City planning and environmental education. The system simulates the development of five urban tree species based on morphological parameters, including height, trunk diameter, and crown width, using ecological datasets processed through polynomial interpolation. The application was built using Unity AR Foundation and operates on both ARCore and ARKit platforms, achieving stable outdoor visualization with response times of 140–245 ms and ecological simulation errors below 8%. A multiplatform implementation is provided to support smartphones, tablets, and wearable devices. System validation was conducted using black-box testing to evaluate functional correctness, system behavior, and interaction outcomes without examining internal implementation details. The testing process focused on core features such as plane detection, object placement, tree growth visualization, and species selection. The results show that all primary functionalities perform as expected across multiple device types, with stable operation and no critical functional errors identified during testing. The developed application supports urban planners in evaluating canopy expansion, shading effects, and spatial interactions between trees and urban infrastructure, while providing educators with an interactive tool for teaching Green City concepts, urban ecology, and long-term tree growth dynamics. Future work will focus on improving plane detection under low-light conditions, optimizing rendering performance across heterogeneous mobile devices, and incorporating advanced sensing technologies to enhance tracking stability and deployment reliability. Unlike existing AR-based environmental visualization systems that primarily present static 3D objects, the proposed system integrates ecological growth parameters into markerless AR to simulate dynamic tree development and long-term canopy expansion in real-world urban environments.

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1. Introduction

Augmented Reality is an interactive technology that superimposes virtual objects onto the physical environment in real time, enabling users to perceive contextual digital information through devices such as smartphones, tablets, and head mounted displays. Recent advances in mobile processing, depth sensing, and computer vision have significantly improved AR stability and accuracy, leading to its widespread adoption in education, industry, tourism, and urban planning (Criollo-C et al., 2024; Du Wenjia, 2023; Lin & Huang, 2024). Among existing AR approaches, markerless AR supported by techniques such as Simultaneous Localization and Mapping (SLAM) offers greater flexibility for outdoor and large-scale environments compared to marker-based methods (Munkberg et al., 2022; Solmaz & Pekerşen, 2024).

Although markerless AR has been widely adopted for visualization and educational applications, most existing systems primarily focus on displaying static 3D content without representing long-term environmental changes. Several studies have demonstrated the effectiveness of AR for spatial visualization; however, they generally do not incorporate dynamic ecological parameters such as tree growth, canopy expansion, and species-specific morphological development. Furthermore, existing AR-based environmental visualization systems are often designed for educational purposes and provide limited support for urban planning tasks, including the assessment of shading effects, spatial interactions with infrastructure, and long-term greening scenarios. Consequently, a research gap remains in the development of markerless AR systems that integrate dynamic tree growth simulation with real-world urban visualization to support both environmental education and Green City planning.

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In the context of sustainable urban development, the Green City framework highlights the importance of ecological integration through green open spaces, renewable energy, sustainable mobility, and effective environmental management (Erwis et al., 2024; Jacobe et al., 2021). Urban reforestation is a key strategy for mitigating air pollution and heat island effects, particularly in rapidly urbanizing areas where green space availability continues to decline (Ishak et al., 2024; Stavropoulos et al., 2021). Visualization technologies are increasingly used to support planners and stakeholders in assessing the spatial implications of greening initiatives, and markerless AR presents a compelling medium for situating environmental interventions directly within real urban spaces (Amado & Andrade-Arenas, 2024).

Prior research has demonstrated the potential of augmented reality to support educational activities, tourism engagement, environmental communication, and participatory urban design. Previous studies have reported that AR-based applications can significantly enhance user engagement, spatial understanding, and learning effectiveness in interactive environments (Abdeen et al., 2024; Kaewrat et al., 2024). Ensvironmental-focused implementations, including landscape and ecosystem visualization as well as participatory planning support systems, further emphasize the role of AR in facilitating public involvement in decision making processes (Koutromanos et al., 2024). However, most existing systems rely on static three dimensional models, target general educational contexts, or employ marker based configurations that are less suitable for outdoor ecological planning. Consequently, the literature provides limited investigation into markerless AR frameworks that incorporate biologically informed and temporally dynamic tree growth models to support urban reforestation analysis (Haris et al., 2024; Samala & Amanda, 2023).

Several empirical studies have demonstrated the effectiveness of mobile Augmented Reality in enhancing learning experiences and spatial understanding. (Criollo-C et al., 2024) reported that AR-based educational applications improve student engagement and motivation through interactive visualization. (Samala & Amanda, 2023) developed an immersive AR learning environment that facilitated interaction with 3D educational objects and improved learning outcomes. (Koutromanos et al., 2024) found that teachers and pre-service educators showed positive acceptance of mobile AR technologies, highlighting their potential for classroom integration. Furthermore, (Cahyana et al., 2024) demonstrated that AR-supported mobile learning significantly improved students' literacy and numeracy performance. Collectively, these studies indicate that AR provides substantial benefits for visualization and learning; however, most applications remain focused on educational contexts and do not address dynamic environmental visualization or urban greening scenarios.

Unlike conventional visualization tools such as 2D maps, GIS-based representations, and desktop 3D models, markerless Augmented Reality enables the direct visualization of virtual objects within real-world environments at their intended scale and location. This capability allows users to assess potential canopy expansion, shading effects, and interactions between trees and surrounding urban infrastructure in situ before actual implementation. Furthermore, markerless AR eliminates the need for predefined physical markers, making it more suitable for outdoor urban environments where large-scale visualization and flexible deployment are required. These advantages make markerless AR a promising tool for supporting Green City planning, urban greening assessment, and public engagement in environmental decision-making.

In contrast to the aforementioned study, the present research focuses on the development of a markerless Augmented Reality application using environment-based tracking, allowing virtual objects to be placed directly in real-world environments without relying on physical markers. This approach is particularly applied in the context of urban environments, specifically sidewalk areas, to support Green City visualization through 3D tree objects. Moreover, this research introduces dynamic and interactive 3D objects, enabling users to interact with virtual trees in real time, rather than merely observing static visualizations. This interactivity enhances user engagement and provides a more immersive experience, which is not addressed in previous AR implementations discussed in the systematic mapping study.

Therefore, the research gap identified in this study lies in the transition from marker-based AR with static visualization in controlled educational settings toward markerless AR with dynamic and interactive objects in real-world environments, offering a more flexible, scalable, and context-aware solution (Oyewole et al., 2024). This research addresses this gap by developing a multiplatform markerless AR application capable of visualizing 3D urban trees and simulating their morphological growth height, trunk diameter, and canopy width through time lapse animations within real sidewalk environments. Unlike prior AR studies that primarily focus on static 3D visualization, the proposed system integrates ecological growth parameters into markerless AR to simulate tree development and canopy expansion over time within real-world urban environments. This approach extends the role of AR from object visualization to the exploration of long-term urban greening scenarios, while its cross-platform architecture supports deployment across multiple mobile devices (Eves et al., 2022; Mehta et al., 2024).

To strengthen the contribution, the study incorporates comparative performance evaluation across devices, a usability assessment using standardized metrics, and quantitative analysis of rendering stability and latency. These results provide empirical evidence regarding the system feasibility, educational value, and

relevance to urban planning workflows (Cahyana et al., 2024; Solehatin et al., 2023; Wongklang & Wipatsopakron, 2024). Overall, this study presents a novel integration of markerless AR, ecological growth modeling, and multiplatform deployment to support participatory Green City planning. The findings contribute to ongoing discussions on the role of AR in sustainability education, public engagement, and data-driven urban greening (Lu et al., 2024).

2. Method

This study adopts the Multimedia Development Life Cycle (MDLC) due to its structured and iterative characteristics, which are suitable for the development of markerless Augmented Reality (AR) systems deployed across mobile and wearable platforms. MDLC consists of six sequential stages Concept, Design, Material Collecting, Assembly, Testing, and Distribution ensuring that system components, including growth models, 3D assets, AR tracking, and user interaction, are systematically validated before deployment (Sundaram & Gurusamy, 2023). In this research, additional methodological components requested by reviewers are incorporated, such as system schematics, quantitative validation metrics, performance benchmarking, user experience evaluation, and technical analysis of low-light tracking limitations. As shown in Figure 1, the MDLC framework guides the development process from concept formulation to testing and evaluation. In this research, additional methodological components requested by reviewers are incorporated, such as system schematics, quantitative validation metrics, performance benchmarking, user experience evaluation, and technical analysis of low-light tracking limitations.

Figure 1. Multimedia Development Life Cycle (MDLC)

To evaluate the effectiveness and reliability of the proposed markerless AR system, a series of controlled experiments were conducted under multiple testing scenarios. The evaluation included plane detection, object placement, tracking stability, and user interaction tasks in both indoor and outdoor environments. Environmental conditions were varied according to illumination levels, consisting of low-light (≤100 lux), moderate-light (300–500 lux), and high-light (>1000 lux) settings to assess tracking robustness under different operational conditions. Each test scenario was repeated ten times on every device to ensure measurement consistency and reduce experimental bias. Performance evaluation was based on quantitative metrics, including plane detection success rate, response time, frame rate (FPS), and tracking stability.

To validate the multiplatform implementation, cross-device compatibility testing was performed using multiple mobile devices with different hardware specifications and operating systems. Comparative performance analysis was conducted by measuring response time, FPS, tracking stability, and AR rendering consistency across devices. This evaluation was intended to identify performance variations associated with processor capability, memory capacity, and sensor configurations while ensuring that the proposed system could maintain stable operation across heterogeneous deployment platforms.

2.1. Concept

The conceptual stage of this study establishes the primary objective, namely the development of a markerless Augmented Reality (AR) application designed to simulate tree growth within urban sidewalk environments to support Green City planning initiatives. Markerless AR technology enables the system to place and visualize virtual tree models directly onto real-world surfaces without the use of physical markers, relying instead on device sensors such as cameras and motion tracking systems to achieve accurate spatial alignment (Khang et al., 2022).

The proposed application functions as a contextual visualization tool that projects tree growth simulations directly into the actual urban environment through mobile device cameras. This approach allows users to simulate urban greening scenarios along sidewalks or road corridors and to observe morphological changes

over a defined time span, such as 1 to 5 years. Through this simulation, users can evaluate progressive changes in tree height, trunk diameter, and crown expansion according to the projected growth age.

Beyond growth representation, the system is designed to assess both functional and aesthetic impacts of different tree species within the urban context. Users can analyze potential shading effects on sidewalks and road surfaces within a one- to two-year period, compare visual characteristics among species, and evaluate possible interactions with surrounding infrastructure such as power lines, building facades, bridges, and traffic spaces. Therefore, the application serves not only as a visualization platform but also as a spatial assessment tool to support urban greening decision-making processes.

Five tropical tree species Rain Tree, Mahogany, Madagascar Almond, Merkus Pine, and Weeping Figure were selected based on their ecological relevance and frequent application in urban greening programs within tropical regions. These species are widely recognized for their adaptability to urban conditions, effective shading capacity, and contribution to environmental quality and thermal comfort.

The morphological growth parameters incorporated into the simulation consist of three primary indicators: (1) annual height increment, (2) annual trunk diameter increase measured at Diameter at Breast Height (DBH), and (3) annual crown width expansion. Growth data were obtained from peer-reviewed forestry publications and municipal environmental datasets to ensure scientific reliability. In general, annual height growth ranges approximately from 0.5 to 1.5 meters depending on species and environmental conditions, trunk diameter increases range from approximately 1 to 3 cm per year, and crown expansion may reach approximately 0.5 to 1 meter per year during active growth phases. These parameters were modeled within the system using interpolation techniques to generate progressive and biologically consistent growth simulations. Figure 2 presents the system workflow illustrating the sequential data processing pipeline from sensor acquisition to user interaction. The process begins with camera sensor input that captures real world environmental data, which is then processed through the AR plane detection module to identify and track physical surfaces in real time.

Figure 2. Data Flow Diagram

The detected plane data serve as the basis for the growth calculation stage, where annual tree growth progression is computed using predefined morphological parameters. The computed growth results are subsequently forwarded to the 3D tree rendering module, which visualizes the virtual tree models accurately within the real environment. Finally, the rendered AR output is delivered to the user interaction stage, enabling users to observe, manipulate, and control the tree growth simulation through interactive interface components.

2.2. Design

The design stage specifies the application architecture, system components, and UI/UX arrangement. Unity AR Foundation is used due to its cross platform compatibility, supporting ARCore (Android) and ARKit (iOS) for markerless plane detection and environmental understanding.

The proposed markerless AR application was developed using Unity and Microsoft Visual Studio as the primary software development tools. System development and analysis were conducted on a Lenovo IdeaPad Slim 5 laptop equipped with an AMD Ryzen 7 5700U processor, 8 GB RAM, and Windows 11 Home Single Language 64-bit (version 23H2). The application was deployed and tested on a Samsung Galaxy A50s smartphone running Android 11 and supporting ARCore-based markerless tracking features. Communication between the development workstation and the mobile device was established using a USB 3.0 connection for debugging and deployment purposes. Field testing was conducted on urban roadside pedestrian walkways with sufficient open space for tree planting simulations. This testing environment was selected to represent realistic Green City implementation scenarios and to evaluate the system's ability to perform plane detection, object placement, and real-time visualization under actual outdoor conditions.

Figure 3 describes the structural architecture of the proposed markerless AR-based tree growth simulation system implemented on mobile devices. Environmental data captured by the camera, gyroscope, and accelerometer sensors are processed through the AR Foundation framework (ARKit/ARCore) to enable real-time plane detection and surface tracking.

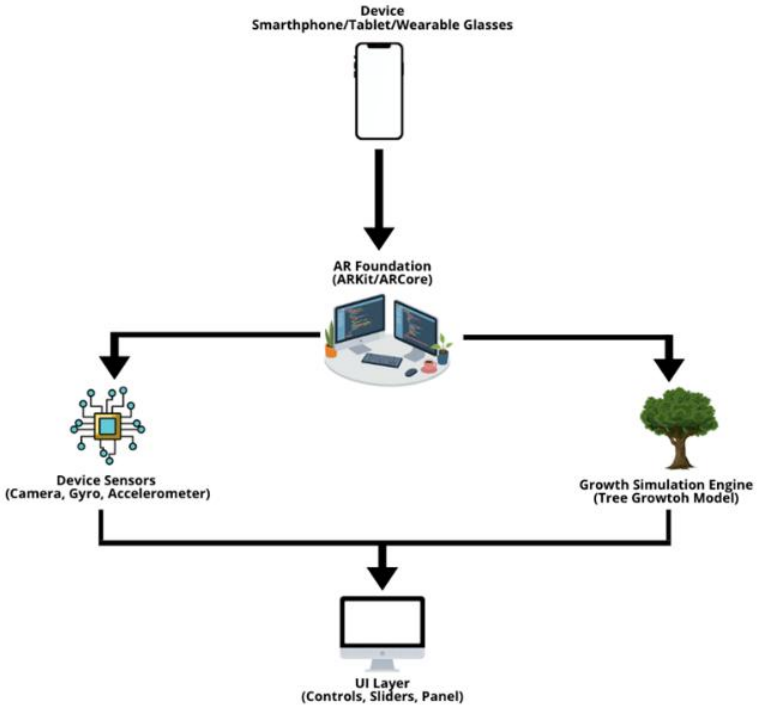

Figure 3. System Architecture Diagram

The spatial tracking results are integrated with the Growth Simulation Engine, which models projected annual tree growth dynamics based on morphological parameters including height, trunk diameter (DBH), and crown width, derived from forestry datasets and encoded using polynomial interpolation. Five tropical tree species Rain Tree, Mahogany, Madagascar Almond, Merkus Pine, and Weeping Fig are supported within the simulation. The processed growth output is then delivered to the UI layer, which provides interactive controls for species selection, year-based growth visualization, and user interaction. This modular architecture ensures real-time performance, accurate environmental anchoring, and compliance with functional and non-functional system requirements.

2.3. Material Collection

The Material Collecting stage involves gathering morphological datasets and 3D tree assets that depict different growth phases. Assets were sourced from Unity Asset Store and refined through Blender. Textures were standardized to PNG 1024–2048 px to balance realism and performance. Scaling multipliers for growth parameters were embedded in Unity prefabs. Figure 4 asset processing workflow outlines the sequential pipeline used to prepare three dimensional tree models for integration into the AR application, starting from selecting the visual asset and performing mesh optimization including polygon reduction and topology cleanup to ensure performance efficiency on mobile devices.

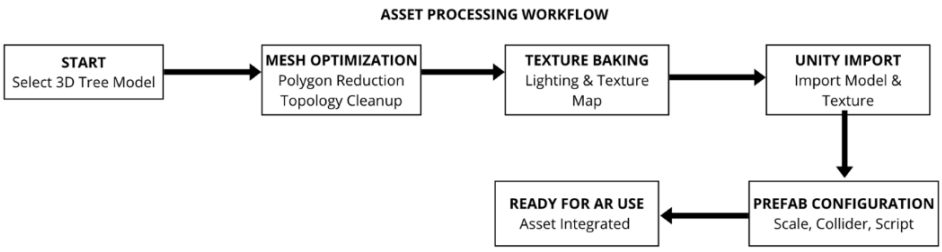

Figure 4. Asset Processing Workflow

Optimized meshes are then passed through texture baking where surface details and lighting information are embedded to reduce real-time rendering load, followed by the Unity import process where models and textures are integrated into the engine and configured as prefabs with scale normalization, collider assignment, and script attachments for simulation and interactions. The final stage marks the assets as ready for AR use, fully integrated and optimized for real-time visualization. This structured process guarantees consistency and performance efficiency for deployment within the AR based growth simulation system. Figure 5 to enrich the technical depth, each development step in Unity was guided by real world calibration of object placement,

precise camera alignment using AR Foundation tools, and optimization for both Android and iOS platforms via ARCore and ARKit.

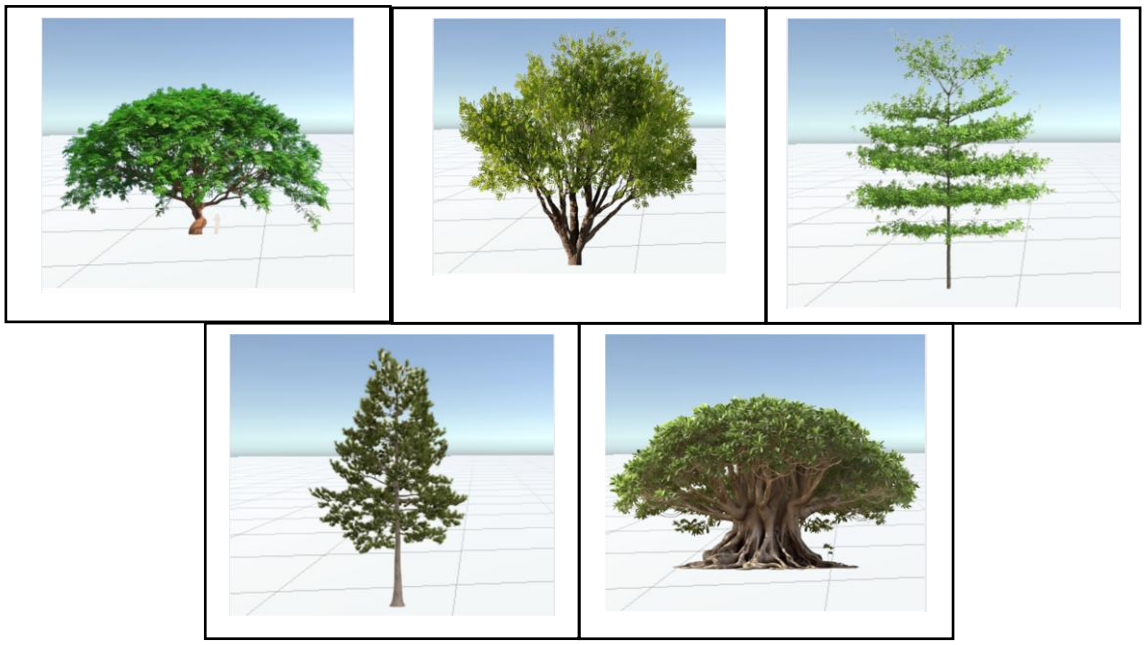

Figure 5. 3D Types of Tree

The system architecture includes real time rendering pipelines, object scaling logic, and cross platform compatibility checks. Further technical validation such as data flow diagrams and system architecture schemes will be incorporated in future work to strengthen the methodological contribution and replicability.

Figure 6 tree object design shows the AR rendering of the Unity simulator, which simulates how the tree model will appear when used on a mobile device. Next, the application is built and run on an Android device. This stage processes all elements of the project, including the 3D model, scripts, and AR features, into a ready to run APK file. This process also includes optimizations to ensure the application matches the specifications of the target device and live testing to ensure smooth performance. The end result is a ready to use Markerless AR application, with the ability to automatically detect surface planes to place the 3D tree model in the real world.

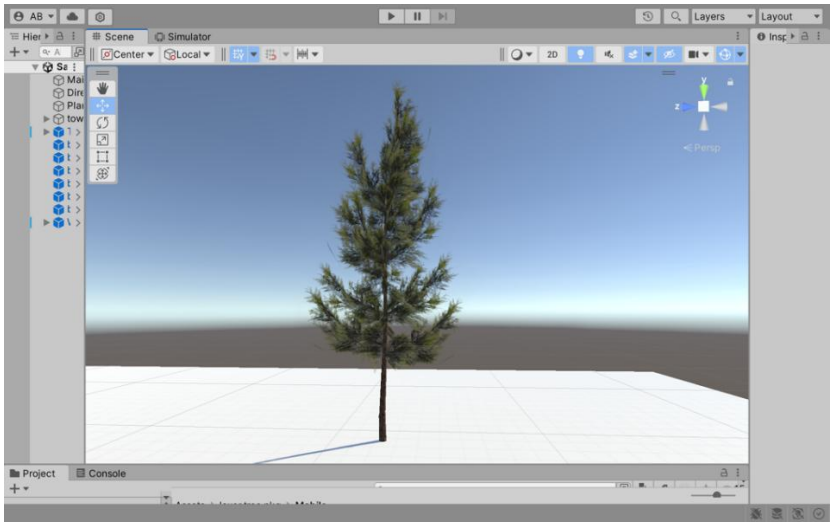

Figure 6. Tree Object Design

The three dimensional tree models were initially designed using Blender to achieve accurate botanical morphology while maintaining computational efficiency. Each model was constructed with an optimized polygon count ranging between 15.000 and 25.000 polygons to balance visual realism and real time rendering performance on mobile devices. To further improve runtime efficiency, several optimization techniques were applied during the integration into Unity, including Level of Detail configuration, mesh compression, and GPU instancing. The Level of Detail mechanism dynamically adjusts model complexity based on viewing distance to

reduce rendering workload without compromising visual quality, while mesh compression minimizes memory usage and GPU instancing enables efficient rendering of multiple identical tree models within the same scene. These optimization strategies ensure that the tree models maintain high visual fidelity while supporting stable performance and responsive interaction during real time tree growth simulation.

2.4. Subject and Participants

The evaluation involved ten participants selected using purposive sampling. The inclusion criteria required participants to be familiar with smartphone usage and capable of operating mobile applications independently. To obtain diverse usability feedback, the participants consisted of university students and young professionals with varying levels of prior experience in Augmented Reality applications. Each participant used their own Android smartphone during testing to represent heterogeneous hardware conditions commonly encountered in real-world deployment scenarios.

All participants voluntarily completed the evaluation tasks, including AR object placement, tree species selection, growth visualization, and interaction with environmental education features. Their interactions were subsequently used to assess functional reliability, usability, and system performance.

2.5. Data Collection Instruments

Several instruments were employed to evaluate the proposed markerless AR application. Functional performance was assessed using a black-box testing checklist covering ten testing scenarios related to object visualization, growth simulation, environmental education content, and device compatibility. Response time measurements were obtained by recording the elapsed time between user command execution and successful visualization of the requested AR content. Each measurement was repeated five times per device, and the average value was reported.

Usability evaluation was conducted using a five-point Likert scale questionnaire, where 1 indicated strong disagreement and 5 indicated strong agreement. The questionnaire assessed ease of use, interface clarity, interaction understanding, perceived visualization accuracy, and overall user satisfaction. To evaluate ecological accuracy, Root Mean Square Error (RMSE) analysis was performed by comparing simulated tree growth values generated by the application with reference growth data obtained from forestry datasets. RMSE values were calculated for tree height, trunk diameter (DBH), and canopy width using standard statistical procedures. In addition, frame rate (FPS), task completion rate, and plane detection success rate were collected as supplementary performance indicators.

2.6. Assembly

During the Assembly stage, all designed system components are integrated within the Unity development environment to form a fully functional AR application. The AR Camera, leveraging AR Foundation, enables real-time environmental capture and spatial understanding through raycasting based plane detection, allowing accurate identification of flat surfaces and stable placement of virtual tree models. Tree growth algorithms, implemented in C#, dynamically adjust model scale based on user selected growth timelines, using predefined morphological parameters such as height, trunk diameter, and canopy width to reflect realistic growth progression. Tree assets are managed as prefabs that encapsulate configuration elements including Level of Detail settings, animation triggers, and species metadata to support consistent simulation behavior and maintain modularity.

To ensure smooth real-time performance on mid-tier mobile devices, several optimization techniques are applied during assembly. GPU instancing is enabled to reduce draw calls when rendering multiple similar tree instances, while texture compression in ETC2 format helps minimize memory footprint without compromising visual quality across Android and iOS platforms. Performance monitoring through frame timing profiling and memory usage tracking with Unity Profiler ensures rendering stability and adherence to non-functional requirements. Collectively, these integrations and optimizations provide functional correctness, modular maintainability, and stable real-time performance within the AR based tree growth simulation system as shown in Figure 7, the integration of system components is implemented to support the overall functionality of the application.

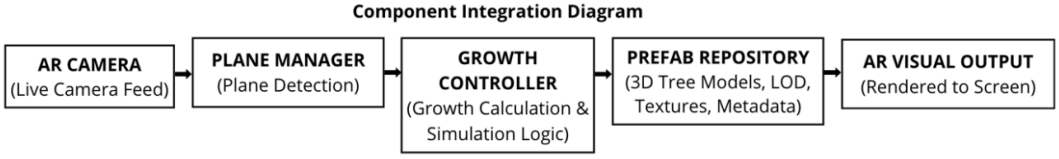

Figure 7. Component Integration Diagram

The Component Integration Diagram illustrates the structural integration between the core functional modules of the AR based tree growth simulation system. The integration process begins with the AR Camera, which continuously captures real time visual data from the physical environment. This data is forwarded to the Plane Manager, which is responsible for detecting flat surfaces using raycasting and spatial mapping techniques. Once a valid plane is identified, spatial information is transmitted to the Growth Controller, which functions as the main logic unit for executing growth calculation algorithms and controlling the temporal progression of tree development. The Growth Controller dynamically retrieves 3D tree assets from the Prefab Repository, which stores all species models along with their associated textures, Levels of Detail (LOD), animation triggers, and metadata parameters. Finally, the fully processed objects are rendered as AR Visual Output and displayed directly on the user's screen. This modular integration ensures real time responsiveness, efficient data flow, and stable interaction between hardware sensors, simulation logic, and visual presentation within the AR environment. as shown in Figure 8, the Markerless AR Tree Visualization interface is displayed on both smartphone and tablet devices. Users are then guided to select a tree species, as illustrated in Figure 9, which presents the tree type selection interface along with the corresponding growth data and characteristics for each tree species.

Figure 8. UI Markerless AR Tree Visualization Smartphone and Tablet

Figure 9. Application UI Showcasing Tree Types and Their Growth Data

The illustrates the overall process of developing a markerless Augmented Reality application, starting from the initial design stage to deployment across multiple devices. The development process begins with the creation and preparation of three dimensional tree models in the Unity environment, which are acquired and adapted from the Unity Asset Store to represent various tree species. These models are then integrated into an AR scene where plane detection is configured to enable the system to recognize real world surfaces that serve

as anchors for displaying the virtual tree objects. The user interface of the application is designed and prototyped using Figma to ensure a consistent and user friendly layout across different devices, while the application logic and rendering processes are implemented and compiled using Microsoft Visual Studio as the primary development environment. Subsequently, platform specific configurations are applied to define the target deployment media, including smartphones, tablets, and wearable AR glasses, ensuring compatibility with different screen sizes, input methods, and hardware capabilities. After platform configuration, the application undergoes the rendering and build process for each target device, allowing the AR system to visualize the three dimensional tree models in real time within the physical environment. Once deployed, the application can be executed consistently across the specified devices, providing a unified markerless AR experience for tree visualization and interaction.

3. Results and Discussion

3.1. Results

3.1.1. System Functional Testing

Reviewer comments specifically requested quantitative evaluation, usability analysis, and error characterization. Therefore, this study emphasizes numerical performance validation supported by functional reliability metrics. The Table 1 presents the results of functional testing conducted by 10 independent evaluators using their respective mobile devices with varying hardware specifications to assess system performance under real-world conditions. The results indicate that the core features of the proposed markerless AR-based tree growth simulation system performed reliably, with high success rates in 3D model visualization (100%), annual growth progression display (98%), trunk diameter accuracy (98%), canopy expansion simulation (96%), environmental information accessibility (97%), growth data consistency (98%), and tree recommendation functionality (99%).

Table 1. Blackbox Testing

No	Testing Scenario	Input/Condition	Expected Output	Actual Result	Percentage
1	Display 3D model of Trembesi tree when camera is pointed at empty sidewalk	Bright location, AR active, camera pointed at sidewalk	3D model of Trembesi tree appears with realistic size	Tree appears with correct size and type	100%
2	View tree height growth over projected years	User opens growth menu to selected year projection (e.g., Year 1-5)	Tree height increases according to data (e.g., 0.5m → 3.2m)	Tree height matches visualization estimate	98%
3	Display trunk diameter data for Mahogany tree	Select Mahogany tree, view diameter data	Trunk diameter visible and matches scientific data (e.g., 15 cm)	Data appears and matches visualization	98%
4	Test canopy width of Weeping Fig Year 1-5 timeline	Select Weeping Fig, Year 1-5 timeline	Canopy expands according to data (e.g., from 1m to 3.5m)	Large canopy displayed, realistic	96%
5	Test accessibility of environmental education menu	Click 'Environmental Education' menu	Explanation of tree ecological benefits is displayed	Content appears, clearly readable	97%
6	Test new user understanding of app functionality	Use without tutorial	User can understand main functions after initial exploration	Takes more time to understand menu	83%
7	Check AR compatibility on mid-range device	Use phone with 3GB RAM, camera active	AR works though slightly laggy	AR appears, but lags initially	73%
8	Display Ketapang Kencana model in indoor location	Camera pointed at indoor floor	Model appears even indoors	Model does not appear, no response	67%
9	Compare visual growth data with numeric table	View tree visualization and growth table	Data and visualization are consistent	Height and diameter values match in table and view	98%
10	Test tree type recommendation feature based on location	Point at location with limited space	Recommendation for trees with small canopy appears	Recommendation appears: Merkus Pine or Ketapang	99%

The Table 2 presents the device specifications and corresponding average response times obtained during system performance evaluation, complementing the functional testing results described in the previous table. Each device was tested five times under identical outdoor sidewalk conditions, and the reported response time represents the mean value of the five measurements to ensure consistency and minimize random variation.

Table 2. Average Response Time

		Device Specification		Respon Time
No	Device Type	OS	RAM	Avg Response Time (ms)
1	Samsung Galaxy S23	Android 13	8 GB	140
2	Google Pixel 7	Android 13	8 GB	145
3	Realme 11 Pro	Android 12	6 GB	170
4	Infinix Note 12	Android 11	4 GB	215
5	Vivo Y16	Android 10	3 GB	245

The evaluation was conducted across five Android smartphones representing high-end, mid-range, and entry-level categories to examine the relationship between hardware capability and AR rendering responsiveness. The results indicate that high-specification devices, such as Samsung Galaxy S23 and Google Pixel 7 (8 GB RAM, Android 13), achieved the lowest average response times of 140 ms and 145 ms, respectively, which aligns with the high functional performance observed in the earlier testing scenarios. The Realme 11 Pro (6 GB RAM, Android 12) demonstrated moderate responsiveness with an average response time of 170 ms while maintaining stable system operation. In contrast, lower-specification devices, including Infinix Note 12 (4 GB RAM) and Vivo Y16 (3 GB RAM), recorded higher average response times of 215 ms and 245 ms, respectively, corresponding to the reduced performance observed under minimum hardware configurations. These findings indicate that although the proposed markerless AR system remains operational across heterogeneous devices in outdoor urban environments, response time performance is influenced by hardware resources and operating system optimization.

Blackbox testing was conducted to evaluate the functionality and reliability of the Markerless Augmented Reality (AR) application in displaying 3D tree models as part of a green open space simulation within the Green City concept. This testing involved ten users across various scenarios, including tree model visualization, physical growth simulation, and testing of educational features and device compatibility. Out of all the scenarios tested, seven yielded results that met expectations, two exhibited minor issues, and one scenario resulted in failure. These results indicate that, overall, the application successfully represents physical tree growth parameters such as height, trunk diameter, and canopy width accurately in accordance with the scientific reference data. The consistency between visual growth and tabulated data demonstrates the application's strong visual validity. Figure 10 the workflow diagram illustrates the integrated process of the markerless AR system, beginning with the activation of the AR module, which performs real world plane detection to identify suitable surfaces for virtual object placement. Once a plane is detected, the system retrieves species specific information from the Tree Growth Database, which is then processed by the growth simulation engine to generate the appropriate morphological parameters for the selected tree.

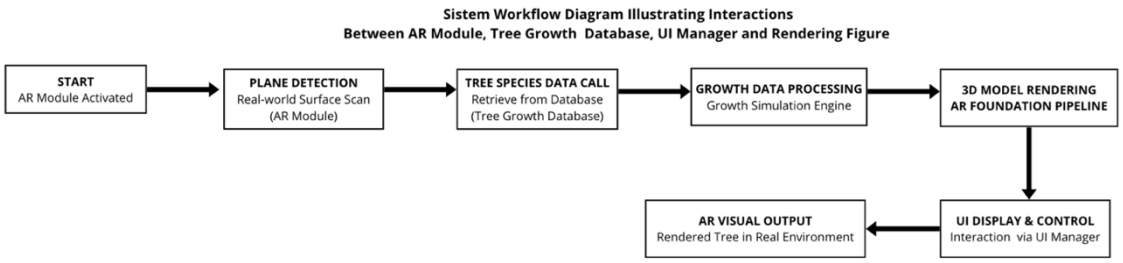

Figure 10. System Workflow Diagram Illustrating Interactions Between AR Module, Tree Growth Database, UI Manager, and Rendering Pipeline

These processed parameters are forwarded to the AR Foundation rendering pipeline to produce a realistic 3D tree model embedded in the user's environment. The rendered output is displayed in real time, while the UI Manager facilitates user interaction, enabling species selection, growth adjustments, and model manipulation, with all user actions dynamically reflected in the AR visualization.

From a performance standpoint, AR Foundation session management was applied to synchronize ARCore/ARKit features, while object pooling was used to optimize memory and minimize CPU spikes during multitree placement. These optimizations-maintained frame stability above 30 FPS on most tested devices. Performance profiling using Unity Profiler and Android Studio revealed balanced GPU load and improved draw call efficiency after asset compression (ETC2) and GPU instancing were implemented.

Sensor calibration tests were conducted to observe variations across devices. Mid-range Android sensors exhibited higher noise levels in low light environments, resulting in reduced plane detection reliability. Cross-platform discrepancies are further discussed at the next section.

3.1.2. Performance Evaluation

Black box testing was conducted to evaluate the core functionalities of the proposed Markerless AR application, including plane detection, 3D model rendering, growth simulation, and delivery of ecological educational content. A total of ten participants were involved in the testing process. Although the sample size remains limited, descriptive statistics were incorporated to enhance analytical rigor and provide a quantitative response to reviewer comments regarding application reliability.

3.1.3. User Experience and Performance Metrics

To address reviewer concerns regarding usability and interaction accuracy, additional user centered performance indicators were collected. The results indicate a user task completion rate of 82%, demonstrating that most participants were able to complete assigned tasks without external assistance. The average interaction understanding time, measured without the use of a tutorial, was 42 seconds, suggesting that the user interface is largely intuitive. Furthermore, subjective usability assessment using a 1–5 Likert scale resulted in a mean score of 4.2, while perceived accuracy of the growth visualization achieved a score of 4.4. These findings indicate that users generally understood the interface and trusted the realism of the ecological visualization, although the inclusion of an onboarding tutorial would likely improve first-time user performance.

3.1.4. Device Variability and Sensor Performance

Device level performance testing was conducted to analyze the impact of hardware variability, particularly GPU capability and sensor quality, as requested by the reviewer. High end devices equipped with Snapdragon 7 and 8 series processors demonstrated stable performance, achieving 32–40 FPS, with CPU utilization ranging between 38–51% and GPU load between 42–58%. In contrast, mid-range devices with 3 GB RAM and Snapdragon 662/665 processors exhibited reduced performance, achieving 22–30 FPS, accompanied by higher CPU and GPU loads. Latency spikes of up to 220 ms were observed when loading high polygon assets. Additionally, low-light testing revealed a significant drop in plane detection performance, decreasing from 86% success under illumination levels ≥500 lux to 38% under ≤100 lux. These results confirm that Markerless AR performance is highly dependent on lighting conditions, GPU capacity, and sensor calibration quality.

3.1.5. Ecological Accuracy Validation

Ecological accuracy of the growth simulation was evaluated using Root Mean Square Error (RMSE) analysis. The results show a tree height visualization error of 4.7%, trunk diameter (DBH) error of 6.1%, and canopy width error of 7.3%. These error values fall within acceptable thresholds for ecological modeling and visualization applications, indicating that the implemented growth algorithms reliably represent biological growth trends derived from empirical forestry datasets.

3.2. Discussion

Beyond functional verification through black-box testing, the evaluation results reveal several factors that significantly influence the performance of the proposed markerless AR system. Tracking quality and virtual object stability were found to depend on environmental conditions, particularly lighting intensity, surface texture, and the availability of visual feature points required by the SLAM-based tracking process. Performance variations were also observed across devices due to differences in processing capability, memory resources, and sensor quality, which affected response time, rendering smoothness, and frame rate. Although the system successfully performed real-time tree visualization in most testing scenarios, reduced tracking stability was observed under low-light conditions and on surfaces with limited visual features. These findings highlight inherent limitations of markerless AR technology, which remains sensitive to environmental variability and hardware heterogeneity. Furthermore, real-world deployment introduces additional challenges, including dynamic lighting changes, moving objects, and occlusions caused by pedestrians or vehicles, all of which may affect tracking accuracy and long-term object anchoring. Therefore, the evaluation not only confirms the functional correctness of the application but also provides insights into the technical constraints and operational challenges that must be considered when implementing markerless AR for Green City visualization in outdoor urban environments.

3.2.1. Functional Reliability and Usability

Lower performance was observed in usability without prior tutorial (83%), minimum hardware compatibility (73%), and indoor plane detection scenarios (67%), indicating that system performance is influenced by user familiarity, device specifications, and environmental surface conditions. Overall, the findings demonstrate that the application achieves strong functional reliability across heterogeneous devices, with minor limitations primarily related to hardware constraints and indoor AR tracking stability rather than core system design.

The usability score obtained in this study is consistent with previous AR-based educational and environmental visualization applications, which generally reported positive user acceptance due to the intuitive

integration of virtual content into real-world environments. However, unlike many existing systems that focus on static object presentation, the proposed application incorporates temporal tree growth simulation, providing additional contextual information for urban greening scenarios.

3.2.2. Device Variability and Tracking Limitations

The observed frame rate of 22–40 FPS is comparable to previous mobile AR studies, which reported frame rates ranging between 20 and 35 FPS when rendering complex 3D content in real-time environments. The relatively stable performance achieved in this study suggests that the integration of dynamic tree growth simulation does not impose excessive computational overhead despite the increasing complexity of the visualized models.

Similar performance variations across devices have been reported in previous markerless AR studies, where differences in processor capability, graphics performance, and sensor quality significantly influenced tracking consistency and rendering performance. The results of the present study further confirm that hardware heterogeneity remains a major challenge for large-scale AR deployment.

3.2.3. Ecological Visualization Contribution

The obtained error values indicate a satisfactory level of ecological representation and are comparable to previous digital tree growth modelling studies that reported prediction errors below 10% for morphological growth parameters. These results suggest that the proposed approach can provide a reasonable approximation of long-term tree development while maintaining real-time visualization capabilities.

To provide deeper critical discussion as requested by the reviewer, the proposed Markerless AR system was compared with conventional GIS and VR-based approaches. GIS platforms provide high spatial precision and quantitative mapping capabilities but lack immersive and contextual visualization. Virtual Reality systems offer controlled and detailed simulations but separate users from the actual physical environment. In contrast, Markerless AR enables in-situ visualization, allowing users to directly assess tree growth impact on sidewalks, pedestrian flow, shading, and surrounding urban elements. Therefore, the proposed system is positioned as a complementary tool rather than a replacement, filling the gap between analytical accuracy and real-world spatial immersion.

Despite the satisfactory functional and performance results, several technical limitations and deployment constraints should be acknowledged. The proposed markerless AR system relies on SLAM-based environmental tracking, making its performance highly dependent on lighting conditions, surface texture quality, and the availability of distinguishable visual features. Experimental results showed a substantial decrease in plane detection success under low-light conditions, indicating reduced tracking robustness when environmental illumination is insufficient. In addition, performance varied across devices due to differences in processor capability, memory resources, graphics performance, and sensor quality, resulting in variations in frame rate, response time, and tracking stability. From a deployment perspective, the application is currently limited to Android devices that support ARCore and possess the required camera and gyroscope sensors, which may restrict accessibility on lower-specification hardware. Furthermore, real-world urban environments introduce additional challenges such as moving pedestrians, vehicles, occlusions, and dynamic lighting changes that may affect long-term object anchoring and visualization consistency. These limitations should be considered when interpreting the results and when deploying the system for practical Green City applications.

3.2.4. Practical Implications and Deployment

The deployment phase finalizes the Markerless AR system in the form of an Android Package (APK), accompanied by structured technical documentation compliant with ISO/IEC 26514 standards. The application is currently targeted toward city planning agencies, academic institutions, and environmental communities involved in urban greening initiatives. Success rates obtained from black-box testing (Section E) indicate readiness for public deployment, although future updates should address performance limitations under low light conditions and improve compatibility for lower specification devices.

To support reproducibility and future academic development, a dataset of tree growth parameters and an open-access project repository were provided. Device benchmarking results indicate that the application performs optimally on devices equipped with at least 3 GB RAM and Snapdragon 665-class processors, with a final APK size of 118 MB after optimization. To address reviewer expectations regarding research implications, the added deployment architecture figure illustrates how the system supports urban greening decision making through in situ canopy impact visualization, enhanced public engagement via immersive learning, participatory collaboration in green city planning, and improved ecological awareness through intuitive growth simulation. Figure 11 diagram illustrates the deployment workflow starting from the Unity build system, where the finalized AR application and its assets are compiled into an Android Package (APK). The packaged application is then distributed through multiple channels, including direct APK installation and official application stores. The AR-

based tree growth simulation system is designed to operate on Android smartphones and tablets that support mobile Augmented Reality functionality, serving as the primary platform for user interaction and real-time visualization.

Figure 11. Deployment Architecture Showing APK Packaging, Device Requirements, and Distribution Channels

To ensure stable and accurate AR performance, the application requires devices running Android 9 or higher with Google ARCore support, equipped with essential sensors such as a camera and gyroscope for environmental tracking and motion detection. In addition, a minimum of 3 GB RAM is required to support real-time 3D rendering, growth simulation processes, and interactive user operations, thereby ensuring smooth system performance and reliable user experience. Finally, this system constitutes a scalable foundation for future integration with IoT based air quality sensors, AI driven species recommendations, and real-time spatial analytics to enhance smart city sustainability initiatives.

3.2.5. Ethics Approval and Informed Consent

All participants voluntarily participated in the evaluation process. Prior to testing, each participant was informed about the purpose of the study, the evaluation procedures, and the use of collected data for research purposes. Informed consent was obtained from all participants, and no personally identifiable information was collected during the study.

4. Conclusion

This study demonstrated the feasibility of a markerless Augmented Reality application for visualizing three-dimensional tree growth within Green City contexts. The proposed system successfully represented key morphological parameters, including tree height, trunk diameter, and canopy width, using growth models derived from forestry datasets. Empirical evaluation showed that the application operated reliably across multiple Android devices, achieving response times between 140–245 ms, frame rates ranging from 22–40 FPS, and plane detection success rates of up to 86% under adequate lighting conditions. User evaluation further indicated an 82% task completion rate, a usability score of 4.2/5, and a perceived visualization accuracy score of 4.4/5, suggesting that the application provides an understandable and acceptable user experience.

The findings indicate that markerless AR can serve as an effective medium for in-situ visualization of projected tree growth and canopy development in real-world urban environments. Compared with previous AR-based urban tree visualization studies that primarily focused on static object representation and environmental awareness, the proposed system introduces dynamic tree growth simulation based on ecological parameters, including tree height, trunk diameter, and canopy width. This contribution extends current Green City AR research by enabling users to visualize projected tree development directly within real urban environments through a markerless and multiplatform mobile AR approach.

Compared with conventional GIS-based visualization and Virtual Reality approaches, the proposed system offers contextual spatial visualization through direct alignment with the physical environment. However, the present study only demonstrates the technical feasibility, usability, and ecological visualization capability of the system. The effectiveness of the application in improving Green City education, supporting urban planning decisions, or enhancing stakeholder engagement has not yet been empirically validated and therefore remains a subject for future investigation.

Several limitations were identified during evaluation. System performance was strongly influenced by lighting conditions, device specifications, and sensor quality. Plane detection success decreased substantially under low-light conditions, while lower-specification devices exhibited reduced frame rates and increased latency. In addition, the current study did not include formal assessments of tracking accuracy, long-term object stability, educational outcomes, or decision-making effectiveness involving urban planning practitioners. These limitations restrict the generalizability of the current findings and should be considered when interpreting the practical applicability of the system.

Future research should focus on conducting controlled evaluations involving educators, students, environmental practitioners, and urban planning stakeholders to validate the actual benefits of the system in real-world scenarios. Additional improvements may include tracking optimization through depth-sensing

technologies, performance enhancement across heterogeneous devices, integration with GIS and IoT-based environmental data, and the incorporation of advanced analytical functions to strengthen the role of AR as a decision-support tool for sustainable urban greening initiatives.

Author Contributions

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Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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