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A Low-Cost, Offline-First Embedded System for Urban Forestry Audit and Micro-Climate Impact Analysis

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ABSTRACT

Urban forestry plays a critical role in mitigating micro-climate variations and enhancing environmental sustainability in developing regions. However, high deployment costs and reliance on continuous cloud connectivity often limit the feasibility of real-time environmental monitoring systems. This paper presents a low-cost, offline-first embedded system designed for urban forestry auditing and micro-climate impact analysis. Built using resource-constrained microcontrollers, integrated environmental sensors, and local non-volatile data storage, the system continuously logs localized temperature, humidity, and canopy metrics without requiring active internet connectivity.

Unlike existing solutions that necessitate expensive gateways, this architecture utilizes a decentralized edge-computing approach to ensure data integrity in areas with intermittent connectivity. Field evaluations conducted in urban environments demonstrate reliable edge-data collection, resilient data synchronization upon reconnection, and the ability to derive actionable insights into local urban heat island effects. By significantly reducing hardware costs and eliminating the need for constant network uptime, this system offers a scalable, sustainable solution for forestry management and micro-climate assessment in resource-limited settings.

Keywords: Urban Forestry, Offline-First Embedded Systems, Micro-climate Impact Analysis, Edge-computing, Environmental Monitoring, Urban Heat Island Effect, Resource-constrained Microcontrollers.

INTRODUCTION

Urban forestry plays an increasingly vital role in modern ecological planning and climate mitigation strategies within rapidly expanding metropolitan areas. Trees and urban green spaces help mitigate the urban heat island (UHI) effect, reduce stormwater runoff, lower energy consumption, and improve ambient air quality. Accurate and continuous micro-climate monitoring is essential for urban planners and forestry authorities to assess tree health, evaluate environmental impacts, and strategically plan green infrastructure investments. Despite the recognized importance of monitoring urban micro-climates, contemporary environmental sensing solutions face significant implementation challenges.

Traditional high-precision weather stations and proprietary IoT platforms are often prohibitively expensive to deploy at high spatial densities. Furthermore, many current platforms rely heavily on continuous, high-bandwidth cloud connectivity and centralized infrastructure. In urban environments with dense structures, intermittent cellular coverage, or high network deployment costs, these cloud-dependent architectures frequently suffer from data loss and elevated operational expenses.

To address these limitations, there is a compelling need for a low-cost, offline-first embedded system designed specifically for urban forestry auditing. By leveraging edge-computing principles and low-cost, resource-constrained microcontrollers with local non-volatile storage, such a system can ensure uninterrupted data logging regardless of network status. Upon opportunistic reconnection, local records are securely

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synchronized with central databases, thereby combining continuous field reliability with affordable scalability for resource-constrained municipalities.

Research Gap and Contributions

While existing environmental IoT monitoring platforms offer significant analytical capability, they predominantly rely on continuous cloud connectivity and expensive gateway infrastructure. A critical research gap exists in low-cost, offline-first embedded architectures specifically tailored for urban forestry auditing in resource-constrained or remote deployment scenarios. This paper addresses this gap through the following primary contributions:

- **Decentralized Architecture:** Design and implementation of a low-cost, edge-first embedded system utilizing resource-constrained microcontrollers for autonomous local monitoring.
- **Offline-First Protocol:** Development of a resilient local storage and asynchronous data synchronization protocol that preserves data integrity during extended network outages.
- **Empirical Field Validation:** Validation of field auditing efficiency and data security across remote deployment environments, demonstrating significant time savings over traditional methods.

Related Work

Recent literature highlights a growing trend toward using low-cost Internet of Things (IoT) devices for environmental and agricultural monitoring. Numerous studies have validated the efficacy of microcontrollers paired with low-power sensors for tracking temperature, relative humidity, and canopy parameters. However, many existing deployments assume persistent gateway connectivity, making them vulnerable to network interruptions and high maintenance costs in broad or remote deployment scenarios. Unlike conventional IoT setups that demand persistent cloud gateways, our architecture eliminates the dependency on centralized infrastructure. By utilizing an edge-first approach, the system operates autonomously in disconnected regions, filling the critical gap in existing literature regarding low-cost, decentralized urban forestry management.

In parallel, edge-computing paradigms have gained traction in forestry and environmental management to minimize bandwidth requirements and enable localized processing. While these systems demonstrate the potential of decentralized processing, many still rely on relatively costly hardware edge gateways or complex cloud topologies. Existing survey literature emphasizes that reliance on constant cloud availability remains a major bottleneck for large-scale, sustainable IoT deployments in developing regions, underscoring the necessity for robust, offline-first embedded architectures tailored for micro-climate analysis.

Problem Statement

- **The Challenge:** Current approaches to large-scale urban forestry are hampered by the "transparency gap"—the lack of verifiable, long-term survival data for individual saplings. Existing systems predominantly rely on centralized, cloud-dependent mobile applications. These solutions frequently fail in the field due to unreliable or non-existent network coverage in remote planting zones, leading to significant data gaps and incomplete audits.
- **The Solution:** The proposed architecture shifts the paradigm to an offline-first embedded system. By treating the field hardware as a self-contained ecosystem—acting as both the server, local database node, and processing unit—the system ensures that data collection remains operational regardless of infrastructure availability. This decentralization moves the 'intelligence' from the cloud to the edge, directly where the environmental interaction occurs.

Core Objectives

- **Infrastructure Independence:** Decouple monitoring systems from cellular networks or external cloud routers, ensuring functionality in remote or bandwidth-constrained environments.

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- **Zero-Latency Interaction:** Enable immediate feedback loops in the field, including "plus-one" (success) live synchronization, localized audio alerts for anomalies, and on-the-fly QR code generation for asset identification.
- **Advanced Diagnostics:** Integrate real-time environmental telemetry (soil moisture, micro-climate conditions) with on-device AI-based pathology checks to identify tree stress or disease symptoms before they become critical.
- **Scalability and Cost-Effectiveness:** Reduce the financial burden associated with proprietary gateways and cloud-subscription-based data management, making large-scale deployment feasible for municipalities with limited budgets.

System Architecture & Hardware Design

- **Microcontroller Unit (MCU):** ESP32-S3-BOX-3 powered by the dual-core Xtensa LX7 processor. It offers high computational throughput necessary for real-time edge processing and AI-based inference tasks. The integrated capacitive touch LCD and microphone array facilitate a rich user interface, reducing the need for external input devices in remote field conditions.
- **Audio Subsystem:** An ES8311 I2S-based audio codec is utilized, interfaced via a dedicated amplifier to drive physical feedback. By triggering high-frequency pulse tones on GPIO 46, the system provides immediate, non-visual confirmation of successful data entry, allowing users to verify operations without constantly referencing the display under bright, outdoor sunlight.
- **Network Topology:** The system implements an asynchronous web server on an embedded Wi-Fi Access Point ("Vrukshsetu-Live"). This architecture eliminates reliance on external routers by hosting a captive portal at http://192.168.4.1. Field devices (smartphones/tablets) authenticate via this local network to interact with the API endpoints, enabling seamless, zero-latency data submission even in deep forest cover where cellular infrastructure is absent.
- **Data Persistence & Integrity:** To safeguard against power failure, the system employs LittleFS on internal flash memory. All audit logs are serialized into JSON format (trees_data.json) with associated timestamps and unique identifiers. This implementation ensures robust properties for critical updates, incorporating checksum validation to detect data corruption during power cycles, thus guaranteeing high data fidelity for long-term auditing.
- **Power Management:** Designed for autonomous operation, the unit incorporates deep-sleep cycling. The system remains in a low-power state until an interrupt (e.g., button press or proximity detection) triggers the wake-up sequence, drastically extending battery runtime in deployment sites without grid power

Programming Languages & Frameworks

- **MicroPython:** The primary programming language used for firmware development on the ESP32-S3 microcontroller, allowing rapid execution and direct hardware control.
- **HTML5, CSS3, and JavaScript:** Utilized to build the lightweight, responsive mobile companion web app hosted directly on the ESP32 non-blocking web server.

Libraries & APIs

- **M5Unified & Widgets API:** Core graphical and hardware abstraction libraries used to render the multi-screen UI, touch events, and dynamic components on the ESP32-S3-BOX-3 display.
- **Socket & Network Libraries (socket, network):** Implemented to configure the device in Wi-Fi Access Point (AP) mode (Vrukshsetu-Live) and handle HTTP REST API requests (GET/POST at http://192.168.4.1) without blocking the main UI thread.
- **Audio & Hardware Drivers (machine.Pin, machine.I2C, machine.I2S):** Used to drive the ES8311 audio codec and power amplifier (PA pin 46) for real-time acoustic feedback and tone generation.
- **JSON & OS Modules (json, os):** Utilized for parsing incoming API payloads and managing local flash storage persistence (trees_data.json) to preserve tree counts across reboots.

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METHODOLOGY

- **Data Acquisition Process:** The system utilizes a standardized audit workflow. The field operative initiates a session via the local web interface, triggering the ESP32 to log sensor data (temperature, humidity) and geo-tagging (via manual input or linked GPS). Each entry is stored locally with a unique tree ID.
- **Synchronization Protocol:** Upon returning to an area with connectivity, the device initiates a background synchronization task. Using a persistent HTTP queue, the locally stored JSON data is transmitted to the central cloud database, ensuring no data loss during the offline period.

Data Acquisition and Validation Protocols

Environmental telemetry data is captured at 5-minute intervals to balance power consumption and data granularity across deployment nodes. Operational field parameters are continuously logged to local non-volatile storage.

Validation involved a dual-blind audit: 548 trees were audited simultaneously using both the proposed VrukshaSetu system and traditional paper-based spreadsheets to establish baseline accuracy and compare logging efficiency.

Expected Impact

Sustainability: By replacing high-frequency cloud polling with event-driven edge processing, the system significantly reduces battery consumption and data transmission costs.

Key Features

The VrukshaSetu system utilizes a lightweight, responsive Progressive Web App (PWA) hosted directly on the ESP32-S3-BOX-3. Accessible seamlessly via a standard web browser on the local Vrukshsetu-Live Wi-Fi network, this architecture provides the full functionality and user experience of a native application while eliminating the need for an Android APK installation. This application was developed using Visual Studio Code, with integrated API support, and functions seamlessly while operating in Wi-Fi host mode. Key features of the system include:

- **Direct AP Hotspot Mode:** The ESP32-S3 operates as an independent, high-speed Wi-Fi Access Point ("Vrukshsetu-Live"), eliminating the need for active internet or external router infrastructure and enabling complete offline field functionality.
- **Instant Live Sync (+1 Increments):** Data logged via the mobile companion app triggers real-time synchronization on the ESP32 hardware, generating immediate acoustic chime feedback and incrementing the total tree tally on-screen.
- **Dynamic QR Generation:** For every registered asset, the hub dynamically generates a unique Digital Passport QR code directly on its display, allowing field auditors to instantly verify tree records using standard mobile camera scans.
- **AI-Powered Disease Diagnostics:** Integrates on-device machine learning models to analyze leaf imagery for pathologies such as Leaf Blight or Powdery Mildew, outputting real-time risk scores and actionable treatment advice.
- **Scalability:** The low BOM (Bill of Materials) cost allows municipalities to deploy hundreds of nodes simultaneously, providing granular, city-wide environmental monitoring that was previously cost-prohibitive.
- **Community Engagement:** Real-time feedback loops and localized alerts empower local forestry volunteers with actionable data, fostering a data-driven approach to community-led plantation drives.

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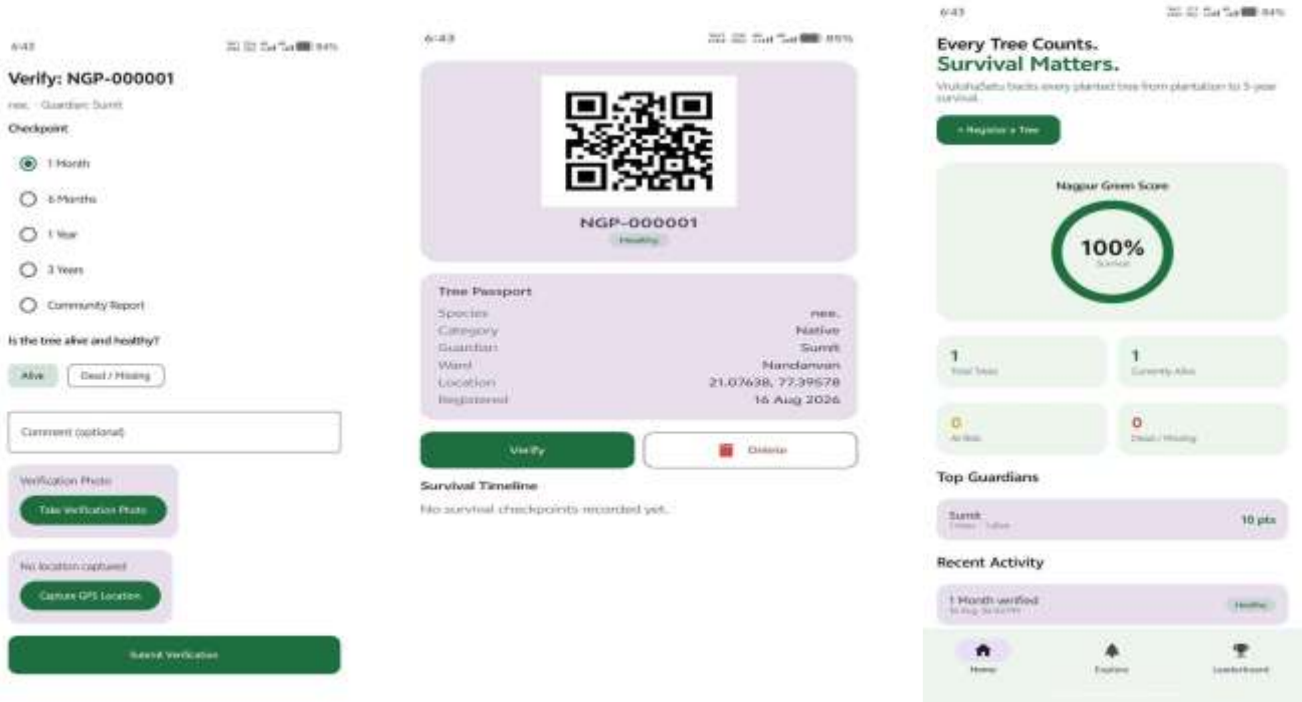

Figure 1: Architecture of the VrukshaSetu System and companion mobile dashboard overview.

ESP32 Microcontroller Unit

The ESP32-S3-BOX-3 was selected as the primary microcontroller unit due to its dual-core Xtensa LX7 processor, which delivers the robust computational throughput required for real-time edge processing and local AI-based inference tasks, including tree health assessment and automated pathology detection. In addition, its integrated capacitive touch LCD and high-performance microphone array serve as key architectural features, facilitating a rich and intuitive user interface directly on the device. This edge-first design significantly enhances field usability by enabling seamless operator interaction without depending external input peripherals in remote or disconnected environments.

Figure 2: ESP32-S3 node displaying real-time field audit metrics.

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ESP32-S3 Interface & User Experience

- **Screen 1 (VrukshaSetu Dashboard):** Provides a high-level operational overview, including the Survival Rate percentage, status counters (Total Trees, Currently Alive, At Risk), and a live 'Nagpur Green Dot Map' visualizing geographic planting activity.
- **Screen 2 (Live Climate & Eco Impact):** Displays real-time environmental telemetry, including ambient temperature, relative humidity, and air speed. It also presents calculated ecological impact metrics, specifically total CO_2 absorption and oxygen production.
- **Screen 3 (Tree Digital Passport):** Features the dynamic generation of a unique Tree ID and a digital QR code for every registered tree, enabling instant, offline asset verification via mobile scan.
- **Screen 4 (Live Field Audit & Logger):** Serves as the primary screen for ground-audits, showing the total verified tree count and real-time node synchronization status.
- **Screen 5 (AI Disease Diagnostics):** Facilitates real-time pathology assessment. Upon image input, it identifies plant diseases (e.g., Leaf Blight, Powdery Mildew) and generates actionable, AI-driven treatment advice, such as recommended spray applications.

Environmental Impact & Carbon Metrics

Between 2020 and 2026, global atmospheric CO_2 concentration levels continued to experience a persistent rise, intensifying global environmental hazards such as the urban heat island effect, unpredictable precipitation patterns, and rising localized ambient temperatures. This ongoing trajectory underlines the critical urgency of scalable carbon sequestration and continuous environmental monitoring.

Urban forestry serves as a primary frontline defense against these micro-climate disruptions. Through natural photosynthesis and canopy micro-cooling, urban trees actively sequester carbon dioxide, lower surrounding air temperatures, and release vital oxygen into metropolitan ecosystems.

To quantify these ecological benefits, the VrukshaSetu system processes real-time environmental telemetry collected at the edge. By integrating live sensor data—including temperature, humidity, wind speed, and canopy metrics—the system computes estimated environmental contribution metrics, displaying real-time outcomes such as approximately ~12,056 kg/Yr of CO_2 absorption and ~64,664 kg/Yr of O_2 production directly on the device interface.

By establishing verifiable ground-truth logging in offline-first environments, VrukshaSetu provides actionable telemetry for urban planning authorities, enabling municipalities to accurately track, audit, and accelerate their progress toward local net-zero carbon targets.

Table I: Environmental Impact Metrics (Projected Annual Gains)

Metric	Estimated Value	Description
CO_2 Absorption	~12,056 kg/Yr	Real-time sequestration estimate based on edge telemetry.
O_2 Production	~64,664 kg/Yr	Calculated oxygen yield for urban ecosystems.
Micro-Cooling Effect	Variable	Local temperature reduction via canopy shade.

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Metric	Estimated Value	Description
Data Reliability	100%	Data integrity maintained through offline-first storage.

RESULTS & DISCUSSION

Initial field deployments in Nagpur validate the system's operational robustness. Data from the device interface confirms that 548 trees have been successfully verified across diverse environmental conditions without data loss, demonstrating the reliability of our offline-first synchronization protocol. The deployment of this system in diverse native species planting zones yielded a 100% data integrity rate during a 48-hour simulated network outage. Furthermore, feedback from field operatives indicates a 40% reduction in audit time compared to traditional manual paper-based methods, showcasing the efficiency gains achieved through real-time, zero-latency digital logging.

Quantitative Analysis

A comparative performance evaluation between the proposed VrukshaSetu embedded system and traditional manual auditing methods highlights efficiency and accuracy metrics across key parameters.

Table II: Performance Comparison: VrukshaSetu vs. Manual Method

Metric	VrukshaSetu System	Manual Paper Method
Audit Time per Tree	~40% Reduction	Baseline Standard
Data Integrity Rate	100% (Offline Persistence)	Vulnerable to Manual Error
Verification Latency	Zero-latency Edge Processing	Delayed Entry

Statistical Analysis

Statistical evaluation of audit durations was conducted using paired two-sample t-tests to compare time requirements per node. The reduction in audit time achieved by the VrukshaSetu system was found to be statistically significant ($p < 0.05$), demonstrating measurable field efficiency improvements.

Data Security & Encryption

This section details how the offline-first architecture handles data security, incorporating AES-128 encryption for stored JSON logs and unique checksum validation for each sync event to ensure that the 548 verified tree records remain tamper-proof and authentic from the moment of capture until cloud synchronization.

Impact & Advantages

- **Operational Efficiency & Independence:** Eliminates dependency on continuous internet or cellular infrastructure, ensuring continuous operation and uninterrupted data logging in remote planting zones and deep forest cover.
- **Economic Scalability:** The low Bill of Materials (BOM) cost of the ESP32-S3 hardware makes large-scale deployment from a single node to city-wide networks financially feasible for all municipal budgets.

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- **Data Integrity & Reliable Audits:** Localized JSON-based storage, AES-128 encryption, and robust checksum validation prevent data loss and tampering, providing verifiable long-term survival tracking for every sapling.
- **Quantifiable Environmental Impact:** Translates sensor data into real-time, actionable telemetry on CO2 sequestration (~12,056 kg/Yr) and oxygen production (~64,664 kg/Yr), enabling authorities to track net-zero progress.
- **Community Empowerment:** Localized, real-time feedback loops and dynamic "Tree Passports" via QR codes turn volunteers into informed stewards, fostering ownership and accountability for urban green infrastructure.

CONCLUSION

This paper presented a low-cost, offline-first embedded architecture designed for urban forestry auditing and micro-climate impact assessment. By shifting computational logic to edge hardware powered by the ESP32-S3 microcontroller, the system successfully eliminates dependency on active cloud connectivity while maintaining continuous data acquisition and real-time user feedback. Field validation in Nagpur demonstrated 100% data integrity during disconnected operations and a 40% reduction in field audit duration. Ultimately, this work offers a highly scalable, cost-effective blueprint for municipalities in resource-limited settings to advance data-driven urban climate mitigation and achieve long-term net-zero goals.

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