Autonomous Edge Computing Station for Precision Soil and Climate Monitoring in Remote and Low-Connectivity Environments

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Abstract.

Cloud-dependent precision-agriculture platforms impose continuous internet connectivity and recurring subscription costs that make them inaccessible to smallholder farmers in remote tropical regions. This paper presents SAGA (Soberania e Autonomia para Gestão Agrícola — Sovereignty and Autonomy for Agricultural Management), an autonomous edge computing station designed to run entirely without network infrastructure. The station is built around an ESP32-S3 microcontroller (ESP-IDF/FreeRTOS) connected via an RS485/Modbus RTU bus to three probes monitoring seven soil and microclimate parameters: soil temperature, volumetric moisture and electrical conductivity (EC), air temperature, relative humidity, vapour-pressure deficit (VPD), and illuminance. A 10 W photovoltaic panel paired with a LiFePO4 4S battery bank (5.5 Ah, 70.4 Wh), MPPT controller, and deep-sleep scheduling ensures complete energy autonomy. The offline-first architecture keeps irrigation control and data logging running even during complete connectivity loss, with all sensor records stored locally under full user control. LoRa (915 MHz, star topology, 5–10 km range) is targeted as a TRL-6 upgrade for multi-plot monitoring without recurring costs. The current prototype (bill-of-materials approximately BRL 1,489 per node) is validated at Technology Readiness Level 5. A field trial of the lite variant logged 8,143 records over 28 days at 5-minute intervals, capturing air temperatures from 17.5 to 33.7°C, relative humidity from 37.0 to 83.1%, and vapour-pressure deficit from 0.59 to 2.99 kPa. Due to local environmental fluctuations, 0.7% of the soil temperature readings fell outside physical limits, demonstrating the necessity of local anomaly filtering prior to any data storage or control actions. This filtering is processed on-device without remote cloud reliance. A proprietary PCBA under development targets BRL 750 per node — roughly 10% of the nearest commercially available alternative (Epsilon EPS, publicly listed at BRL 7,350) — and a five-year total cost of ownership 10.9× lower than a subscription-based alternative, thereby democratizing precision farming tools for smallholder farming communities.

Keywords. Precision agriculture, edge computing, LoRa, soil monitoring, offline-first IoT, low-connectivity environments

Introduction

Wireless sensor networks for precision agriculture rely on cloud-based telemetry, imposing continuous 4G/5G connectivity, monthly subscription fees, and centralised data storage — constraints often incompatible with the infrastructure available to family farms in tropical developing regions (Wolfert et al., 2017). In Brazil, persistent water deficits affecting agricultural production across cerrado and semi-arid biomes make efficient, sensor-driven irrigation a national priority (ANA, 2023). Representative commercial precision-agriculture stations available in Brazil — priced between BRL 7,350 and BRL 28,240 per node — widen the affordability gap further through upfront capital cost and recurring subscription charges. Edge computing — processing data locally at or near the source without cloud involvement (Shi et al., 2016) — offers a direct architectural response. This paper describes the SAGA edge node: an autonomous, infrastructure-independent station combining industrial RS485/Modbus soil-and-climate sensors, photovoltaic energy autonomy, a built-in Wi-Fi access point for field-side dashboards, and LoRa multi-plot communication for precision monitoring where connectivity is unreliable or absent.

Materials and methods

The SAGA node is built around an ESP32-S3 (Waveshare RS485 module) running ESP-IDF/FreeRTOS firmware. The RS485/Modbus RTU bus connects a 3-in-1 soil probe for temperature, volumetric moisture, and electrical conductivity (Waveshare TH-EC), a SHT30 air-temperature-and-humidity probe (Waveshare SJ75), and a BH1750 light sensor (GY-30), collectively monitoring seven agro-meteorological parameters (Fig. 1). Energy autonomy uses a 5.5 Ah (70.4 Wh) $LiFePO_4$ 4S pack (4 × 26800 cells, DALY 20 A BMS), a 10 W mono-crystalline panel, a 5 A MPPT controller, and FreeRTOS deep-sleep scheduling; an INA226 module logs real-time energy telemetry. All electronics sit in an IP68-rated ABS enclosure (160 × 120 × 100 mm) with SP16 cable glands.

Fig. 1 RS485/Modbus RTU industrial sensors integrated in the SAGA node: 3-in-1 soil probe (temperature, moisture, EC) and SHT30 air probe (TRL-5 bench configuration)

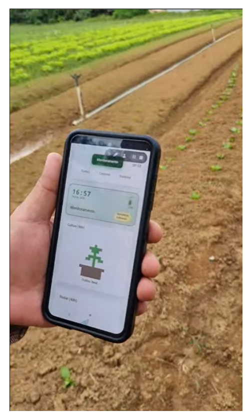

Fig. 2 SAGA supervisory interface: traffic-light status (Normal/Attention/Critical) for all seven monitored parameters, enabling at-a-glance field diagnosis without internet connectivity

Decision logic runs entirely on-device: per-parameter tolerance thresholds trigger relay-controlled irrigation outputs without any external connection. A simplified deployment (lite variant) omits the Android application and operates in stand-alone data-logging mode, enabling cost-efficient long-duration field monitoring. An Android application communicates via BLE/Wi-Fi for real-time dashboard readout, contextual agronomic guidance, and threshold configuration. LoRa (915 MHz, star topology, 5–10 km range per gateway) is the TRL-6 upgrade target, enabling multi-plot deployments over a single gateway without recurring network costs.

Results and discussion

The integrated prototype — ESP-IDF/FreeRTOS firmware, RS485/Modbus sensor bus, photovoltaic energy subsystem, and Android application — was verified at TRL 5 on the BioEngLab bench at UnB Gama, with all seven parameters reading stably and the irrigation relay responding to tolerance triggers without internet connectivity. A field trial of the lite variant logged 8,143 records over 28 days at 5-minute intervals, capturing air temperatures from 17.5 to 33.7°C (mean 29.1°C), relative humidity from 37.0 to 83.1% (mean 53.3%), vapour-pressure deficit from 0.59 to 2.99 kPa (mean 1.90 kPa), and peak luminosity of 54,612 lux. The mean VPD of 1.90 kPa, with peak values approaching 3.0 kPa, indicates recurrent atmospheric water-demand stress associated with increased crop transpiration under tropical Cerrado conditions. This is precisely the scenario in which autonomous, sensor-triggered irrigation can provide agronomic, environmental, and economic benefits. Among 8,102 valid soil-temperature readings, 54 (0.7%) fell outside expected physical limits — confirming the need for on-device filtering before upstream transmission, a task handled locally without remote infrastructure. Assembled bill-of-materials cost stands at BRL 1,489 per node (Andrade, 2025). The subscription-free approach eliminates all recurring expenditure: BRL 0/month against BRL 89/month for a cloud-connected alternative (subscription plus rural data plan), and projected five-year total cost of ownership of BRL 750 (PCBA target) against BRL 8,140 for the subscription-based alternative (which includes BRL 2,800 for equipment purchase plus monthly service and cellular data fees) — a 10.9× advantage. For comparison, commercially available alternatives are publicly listed at BRL 7,350 (Epsilon EPS) and BRL 28,240 (Metos iMETOS); these publicly available list prices (consulted in 2025) are cited solely as an economic-accessibility reference, and no assessment of the quality or performance of these technologies is made or implied. Field validation at TRL 6 is planned at FAL/UnB and Embrapa Hortaliças, targeting water-use reduction above 20% versus timer-based irrigation (Brewster et al., 2017).

Conclusions

The SAGA edge computing station shows that precision soil and climate monitoring is achievable in remote, low-connectivity environments without centralised cloud infrastructure or recurring costs. The offline-first architecture, industrial RS485/Modbus sensor bus, energy-autonomous photovoltaic supply, and local data ownership address three structural barriers — connectivity dependency, prohibitive total cost of ownership, and loss of data sovereignty — that block precision agriculture adoption on resource-limited farms. The immediate next steps are TRL-6 field validation at FAL/UnB and Embrapa Hortaliças and completing the sub-BRL 750 proprietary PCBA with integrated LoRa. Independent recognition came from Brazil's 1st National Invention Contest (MDA; Embrapa; Anater, 2026), where the project placed among the selected finalists, reinforcing its relevance to family farming.

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Transparency on generative AI (CNPq policy)

In compliance with CNPq policy on generative AI: a large language model (Cursor) supported English-language editing and ISPAG formatting checks only. All hardware specifications, BOM data, firmware architecture, cost analysis, and agronomic interpretation derive from SAGA project documentation and BioEngLab records (Andrade, 2025); all authors accept full responsibility for the final text.

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