Scalable Offline Infrastructure for Agriculture 4.0: A Linux-Gateway Architecture for Edge Connectivity and Data Sovereignty

Celio Soares de Souza[1], Marcelino M. de Andrade[2]
[1]UNESP – São Paulo State University, Brazil; [2]University of Brasília (UnB/FGA), Brazil

A paper from the Proceedings of the
17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture
13-15 July 2026
Porto Alegre, Brazil

Abstract.

Brazilian agribusiness accounts for approximately 25% of national GDP, yet Agriculture 4.0 tools are not adopted uniformly. Large properties can support cloud platforms and dedicated connectivity; smaller farms often operate with intermittent mobile coverage and cannot absorb recurring software fees. Simulation studies cite productivity gains of up to 25% and ROI between 18% and 35%, but these estimates assume continuous uplink—conditions that fail across much of rural Brazil where 4G/5G service is weak or absent. This paper presents a work-in-progress offline architecture: autonomous SAGA monitoring stations designed to be linked to a Raspberry Pi Linux gateway on a private field subnet. The edge node uses an ESP32-S3 controller, RS485/Modbus probes, and a 10 W solar/LiFePO4 supply. The two subsystems are specified and bench-tested separately but have not yet been field-deployed as an integrated system. Planned local interfaces use MQTT for telemetry and actuator commands and HTTP REST for configuration and record retrieval, without cloud relay. Gateway-side aggregation on Raspberry Pi OS Lite is defined, with field integration planned for TRL-6 evaluation. Field validation to date covers only a TRL-5 SAGA lite unit in stand-alone mode. Over 28 days it logged 8,143 samples at 5-minute intervals for seven parameters—soil temperature, moisture, EC, air temperature, relative humidity, VPD, and illuminance. Anomaly filtering rejected 0.7% of soil temperature readings. All records were stored on-device. Observed ranges were air temperature 17.5–33.7 °C (mean 29.1 °C), humidity 37.0–83.1% (mean 53.3%), VPD 0.59–2.99 kPa (mean 1.90 kPa), and peak illuminance 54,612 lux. Operating expenditure was BRL 0/month compared with about BRL 89/month for a representative cloud subscription plus rural data plan. Prototype hardware cost ≈ BRL 1,489 per node, with an industrial target of ≈ BRL 750. Coupling SAGA firmware to the Raspberry Pi broker and REST services, along with testing LoRa 915 MHz multi-node links, is planned and authorized for TRL-6 field evaluation at FAL/UnB and Embrapa Hortaliças.

Keywords: Edge Computing Architecture, Offline Infrastructure, Farm Connectivity, Data Sovereignty, Smallholder Technology Adoption

Introduction

Agriculture accounts for roughly one quarter of Brazil's GDP, but digital monitoring tools are still unevenly adopted. Family farms in remote areas often lose connectivity for hours or days, which limits the usefulness of cloud dashboards (Andrade, 2025; Brewster et al., 2017; Wolfert et al., 2017).

Because uplink outages are common at rural test sites, sensor data are logged and processed on the SAGA node before any gateway upload. Reported ROI for digital tools ranges from 18% to 35%, but only if logging continues through outages (Rejeb et al., 2022; Shi et al., 2016).

We present an architecture—not yet integrated in the field—that pairs SAGA (Sovereignty and Autonomy for Agricultural Management) stations with a Raspberry Pi gateway for local aggregation over a private subnet (Fig. 1). TRL-5 results below refer to the SAGA node alone; gateway-side software and multi-node tests are TRL-6 work.

Materials and Methods

Each field node is a SAGA autonomous edge station built around an ESP32-S3 microcontroller running ESP-IDF/FreeRTOS firmware. An RS485/Modbus RTU bus connects three industrial probes monitoring seven agro-meteorological parameters: soil temperature, volumetric moisture, electrical conductivity (EC), air temperature, relative humidity, vapour-pressure deficit (VPD), and illuminance. A 10 W photovoltaic panel with a $LiFePO_4$ battery bank (5.5 Ah, 70.4 Wh) and MPPT controller supplies field power. Threshold logic (Normal, Attention, Critical), anomaly filtering, and relay-driven irrigation run on the node, with status shown on a local traffic-light interface (Fig. 2). At TRL 5, units log CSV data locally over Wi-Fi/BLE at configurable intervals. In the target deployment, these nodes connect to a Raspberry Pi running Raspberry Pi OS Lite for subnet routing, local storage, and monitoring services without internet uplink. LoRa 915 MHz multi-plot links are planned for TRL 6.

Node-to-gateway exchange is specified with MQTT for telemetry and commands and HTTP REST for queries and dashboard configuration, both restricted to the private subnet. These interfaces are defined but not yet validated in a field-integrated deployment. Because the gateway was not connected during the trial, a 28-day test used a SAGA lite unit in stand-alone mode at 5-minute intervals, yielding 8,143 records across all seven parameters. A reference cloud bundle was priced at about BRL 89/month including subscription and rural data. The gateway stack specifies an Eclipse Mosquitto broker on the Raspberry Pi, per-client authentication on the local subnet, and no cloud forwarding; REST endpoints are intended for read-only dashboard queries and threshold configuration. This 28-day dataset is the same one reported at the node level by Andrade and Toledo (2026); the present paper analyses it from the gateway and network-integration perspective.

Fig. 1 Proposed architecture (not yet field-integrated): SAGA nodes, Raspberry Pi gateway, local MQTT/HTTP REST, and private IP / LoRa 915 MHz subnet (TRL-6 planned).

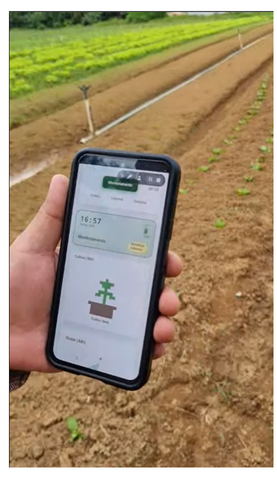

Fig. 2 SAGA local interface (TRL-5, stand-alone node): traffic-light status (Normal/Attention/Critical) for seven parameters, usable without internet access.

Results and Discussion

The 28-day trial produced 8,143 records at 5-minute intervals across all seven parameters, including soil temperature, volumetric moisture, and EC alongside the atmospheric and light variables. Air temperature ranged 17.5–33.7 °C (mean 29.1 °C), relative humidity 37.0–83.1% (mean 53.3%), VPD 0.59–2.99 kPa (mean 1.90 kPa), and peak illuminance reached 54,612 lux. Anomaly filtering flagged 0.7% of soil temperature readings before storage.

Only the standalone SAGA node has been validated so far (TRL 5): offline logging, local HMI, and irrigation relay logic. The Raspberry Pi gateway, MQTT broker, REST endpoints, and LoRa 915 MHz link are defined on paper and in bench tests, not yet as one integrated field system. Multi-site integration is planned at FAL/UnB and Embrapa Hortaliças (MDA; Embrapa; Anater, 2026). For TRL-6, integration success is defined as at least 99% local packet delivery over the LoRa subnet plus stable dashboard access without internet uplink.

Local storage eliminated recurring platform fees: operating cost was BRL 0.00/month versus ≈ BRL 89/month for a reference cloud bundle (subscription plus rural data). The prototype bill of materials is ≈ BRL 1,489 per node, with a target of ≈ BRL 750 at industrial PCBA volumes.

Conclusions

We describe a partial implementation: TRL-5 field data support the SAGA node, while Raspberry Pi gateway services and live MQTT/REST links remain to be validated. Next work includes coupling nodes to the gateway on the private subnet and TRL-6 trials at FAL/UnB and Embrapa Hortaliças.

Generative AI transparency (CNPq). In compliance with CNPq policy on generative artificial intelligence, a large language model (Cursor) assisted English-language editing and ICPA 2026 template formatting only. Hardware specifications, bill-of-materials values, firmware and gateway architecture descriptions, cost comparisons, field-trial statistics, and agronomic interpretation come from SAGA/greenSe project documentation and BioEngLab records (Andrade, 2025). All authors accept full responsibility for the content of the final manuscript.

References

Andrade, M. (2025). greenSe: IoT ecosystem for offline precision agriculture. https://greense.com.br [accessed Jun. 2026].

Andrade, M. M. de, & Toledo, R. (2026). Autonomous edge computing station for precision soil and climate monitoring in remote and low-connectivity environments. In Proceedings of the 17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture and Brazilian Congress on Precision and Digital Agriculture.

Brewster, C., Roussaki, I., Kalatzis, N., Doolin, K., & Ellis, K. (2017). IoT in agriculture: Designing a Europe-wide large-scale pilot. IEEE Communications Magazine, 55(9), 26–33. https://doi.org/10.1109/MCOM.2017.1600528

MDA; Embrapa; Anater. (2026). 1st National Invention Contest for Family Farming -- Preliminary Results. Brasilia: MDA/Embrapa, Mar. 2026.

Rejeb, A., Keogh, J. G., & Leseure, M. (2022). Internet of Things in smart farming: A review. Smart Agricultural Technology, 3, 100023. https://doi.org/10.1016/j.atech.2022.100023

Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. IEEE Internet of Things Journal, 3(5), 637–646. https://doi.org/10.1109/JIOT.2016.2579198

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming – A review. Agricultural Systems, 153, 69–80.