Development and Validation of a Low-Cost IoT-Based Weather Station Using LoRa Communication for Precision Agriculture

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Abstract.

Access to accurate local meteorological data remains a critical bottleneck for precision agriculture adoption among small and medium-scale Brazilian farmers. Commercial weather stations cost between R$ 15,000 and R$ 50,000, while public networks such as INMET operate with average inter-station spacing of 30 to 50 km. This study presents the development, field validation, and agronomic application of the Inova Precisão weather station, a low-cost IoT-based system assembled at R$ 890.00 (USD 150), representing a 95% cost reduction. The system uses ESP32-S3, DHT22, LoRa communication, and solar power. Validation over 31 days at EPAMIG ITAP produced daytime temperature MAE of 1.85 °C and humidity MAE of 9.72%. The station computes VPD, ET0, and ETc automatically and is deployed in a passion fruit trial with dual-confirmation irrigation.

Keywords. *IoT, LoRa, Microclimate Monitoring, Low-Cost Sensors, Evapotranspiration, Precision Agriculture, Passiflora edulis.*

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Introduction

Precision agriculture relies on spatially and temporally resolved environmental data. In tropical regions, local meteorological information is critical for irrigation scheduling, pest forecasting, and harvest planning (Allen et al., 1998). Inadequate meteorological data results in 20-40% water waste versus ET-based scheduling (Pereira et al., 2015).

Commercial stations cost R$ 15,000-50,000, while INMET networks have 30-50 km spacing, insufficient for field-scale microclimate variability (Sentelhas and Angelocci, 2009). Studies have documented 2-5 °C temperature differences between locations separated by less than 10 km (Marin et al., 2019).

ESP32 microcontrollers with LoRa communication enable data transmission over 10+ km without WiFi (Augustin et al., 2016). Recent studies demonstrated ESP32-based station feasibility with accuracy comparable to reference instruments (Da Silva et al., 2025; Saini et al., 2020). Beyond data collection, agronomic indices (ET0, ETc, VPD) translate raw readings into actionable recommendations (Allen et al., 1998).

- The objective was to develop, validate, and deploy a low-cost IoT weather station with LoRa, automated agronomic index computation, and a web dashboard for real-time decision support in smallholder precision agriculture.
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Materials and Methods

System Architecture

The station uses an ESP32-S3 microcontroller at R$ 890.00 total cost (USD 150), a 95% reduction vs commercial stations. Table 1 summarizes the hardware components.

Table 1 Hardware components and specifications

Component	Specification
Microcontroller	ESP32-S3 (Espressif Systems)
Temp./Humidity	DHT22 (Aosong Electronics)
Anemometer/Vane	Analog cup, 0-360°
Rain Gauge	Tipping-bucket, 0.26 mm/tip
ADC	ADS1115 16-bit (Texas Instruments)
Power	180 W solar + 12 V battery
Connectivity	LoRa (no WiFi needed)
Storage	MySQL via REST API

Data are sampled every 5 minutes, transmitted via LoRa to a gateway, then forwarded via REST API to MySQL. The web dashboard (PHP, Bootstrap 5, Chart.js) provides real-time visualization with automated agronomic alerts and WhatsApp notifications via CallMeBot API (25 messages/day free tier).

Fig. 1 Inova Precisão station at EPAMIG ITAP during 31-day validation alongside Davis Vantage Pro2

Agronomic Index Computation

The system continuously computes VPD (Tetens equation), ET0 by Hargreaves-Samani (1985) and FAO-56 Penman-Monteith (Allen et al., 1998), and ETc using phenology-based Kc coefficients. Table 2 details the indices and their agronomic applications.

Table 2 Agronomic indices computed by the system

Index	Method	Application
VPD	Tetens equation	Canopy stress alerts
ET0	Hargreaves-Samani; FAO-56 PM	Reference evapotranspiration
ETc	ET0 × Kc (phenology-based)	Crop-specific irrigation

Validation Protocol

Field validation: 31 days at EPAMIG ITAP (19°40'S, 44°53'W, 650 m) alongside Davis Vantage

Pro2. From 6,135 valid readings, 243 simultaneous pairs were extracted (±2.5 min tolerance). MAE and bias analysis stratified by daytime (08:00-17:00) and nighttime.

Agronomic Field Application

Deployed with passion fruit (Passiflora edulis Sims) at a smallholder property 5 km from validation site. Four plants (~2 m, trellis-trained) under drip irrigation. The dual-confirmation protocol integrates ETc scheduling with capacitive soil moisture feedback to correct ET overestimation under wet antecedent conditions.

Results and Discussion

Temperature Validation

Daytime MAE was 1.85 °C (deviation: -1.6 to +1.1 °C), consistent with ESP32 systems validated against INMET (MAE 1.34 °C; Da Silva et al., 2025). This falls within the acceptable threshold for ET0 estimation via Hargreaves-Samani, which has ~15% inherent uncertainty (Hargreaves and Samani, 1985). A 1.85 °C error translates to ~0.3-0.5 mm/day ET0 uncertainty, smaller than most field irrigation system precision. Table 3 presents complete validation results.

Table 3 Validation results (31 days, n=243 pairs)

Parameter	MAE	Bias	Dev. Range	n
Temp. (daytime)	1.85 °C	+0.62 °C	-1.6 to +1.1 °C	243
Temp. (nighttime)	~6.0 °C	-5.8 °C	-6.0 to -2.1 °C	243
Temp. (24h)	3.42 °C	-1.9 °C	-6.0 to +1.1 °C	243
Rel. Humidity	9.72%	-7.3%	-15.2 to +3.1%	243

Humidity and Nighttime Performance

Humidity MAE of 9.72% is attributable to the DHT22 saturation ceiling above 90% RH, concentrated outside the agronomically relevant range (40-85% RH). The elevated nighttime temperature bias of approximately 6 °C reflects radiative cooling of the unshielded sensor under clear-sky conditions, a known phenomenon mitigated in professional stations by ventilated Stevenson-type radiation shields (WMO, 2018). This shielding was not included in the current prototype to maintain cost targets. Both limitations are addressed in the next hardware revision by replacing the DHT22 with the SHT30 (±0.2 °C, ±2% RH) at under R$ 1,200 total.

Spatial Variability and Agronomic Application

The 5 km deployment produced measurable divergence: 1-3 °C temperature and 5-15% RH humidity differences between sites, confirming inadequacy of 30-50 km public networks. The dual-confirmation irrigation protocol (ETc + soil moisture) corrected ET overestimation after rainfall, preventing unnecessary irrigation. Table 4 summarizes observed divergence.

Table 4 Microclimate divergence at 5 km separation

Parameter	Typical Divergence	Agronomic Impact
Daytime Temp.	1 to 3 °C	ET0 diff. of 0.5-1.5 mm/day
Rel. Humidity	5 to 15% RH	VPD shift affecting irrigation triggers

Cost Analysis

Table 5 Comparison with commercial alternatives

Feature	Inova Precisão	Commercial
Cost	< R$ 1,000 (USD 150)	R$ 15,000-50,000
Connectivity	LoRa (no recurring cost)	WiFi/Cellular (monthly)
Power	Solar autonomous	Solar or grid
Agro. indices	VPD, ET0 (2 methods), ETc	Varies
Dashboard	Open web + WhatsApp alerts	Proprietary
Maintenance	Modular, user-serviceable	Manufacturer-dependent

The 95% cost reduction with LoRa (no recurring data costs) positions the system as viable for smallholders previously lacking local meteorological monitoring.

Conclusions

The Inova Precisão station demonstrated technical reliability and economic viability. Daytime MAE of 1.85 °C is within acceptable range for ET0-based irrigation. The system produced 6,135 valid records on solar power alone, confirming operational robustness. The 5 km deployment revealed measurable microclimate divergence (1-3 °C, 5-15% RH), reinforcing the need for distributed low-cost networks. LoRa connectivity, automated VPD/ET0/ETc computation, and dual-confirmation irrigation constitute a replicable framework for field-scale crop management. The SHT30 revision will close remaining accuracy gaps at minimal cost increment.

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