

Open-Source Weather Stations and Forecast Usefulness across Agricultural Extension Services

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Abstract

The increasing frequency of extreme weather events necessitates hyper-local microclimate data to support adaptive decision-making in agricultural management. However, the high cost and proprietary nature of commercial automatic weather stations have historically limited their deployment in resource-constrained regions. This paper investigates the technical reliability and practical usefulness of low-cost, open-source weather stations integrated within agricultural extension services. Over a twelve-month period, a decentralized network of open-source monitoring systems was deployed alongside commercial standard reference stations across diverse agro-ecological zones. The study evaluated hardware durability, sensor calibration stability, data transmission consistency, and the subsequent utility of the generated localized forecasts for agricultural extension workers. The findings indicate that while open-source sensors for temperature and humidity demonstrate statistically acceptable error margins compared to commercial counterparts, precipitation and wind speed sensors require more frequent calibration and maintenance due to mechanical wear and environmental degradation. Furthermore, qualitative assessments from agricultural extension personnel revealed that integrating locally generated meteorological data significantly enhanced the timeliness and relevance of advisories related to irrigation scheduling, pest management, and crop harvesting. Despite minor reliability trade-offs, the open-source paradigm offers a scalable, economically viable alternative that can democratize access to critical climate information, thereby improving the resilience of smallholder farming communities.

Keywords: Open-Source Hardware; Agricultural Extension; Microclimate Monitoring; Forecast Reliability; Open-Source Weather Stations

1. Introduction

1.1 Background and Context

Global agricultural systems are currently facing unprecedented challenges driven by anthropogenic climate change, resulting in highly erratic weather patterns, altered precipitation cycles, and an increase in the frequency of localized extreme weather events. These environmental shifts pose significant threats to global food security, particularly in developing regions where smallholder farmers rely heavily on rain-fed agriculture and possess limited resources to buffer against climate shocks. In this context, accurate, timely, and hyper-local meteorological data has emerged as a critical requirement for modern agricultural management. Reliable weather information enables farmers to make informed decisions regarding optimal planting windows, precise irrigation scheduling, strategic application of fertilizers and pesticides, and the mitigation of post-harvest losses. However, the spatial resolution of national meteorological observation networks in many regions remains insufficient to capture the nuanced microclimate variations that directly impact agricultural productivity [1]. The traditional reliance on sparse, centrally managed weather stations often results in coarse-grained forecasts that lack the specificity required for effective, localized agricultural planning [2].

To bridge this data gap, agricultural extension services play a vital role. These services are tasked with translating complex scientific and meteorological data into actionable, practical advice for farming communities. Extension workers act as the critical intermediary between agricultural research institutions, national meteorological agencies, and the farmers on the ground [3]. Historically, extension services have been constrained by the lack of access to real-time, local weather data, forcing them to rely on generalized regional forecasts that may not accurately reflect the conditions of a specific village or farm [4]. The advent of commercial automatic weather stations offered a potential solution, providing high-frequency, automated environmental monitoring. However, the widespread deployment of these commercial systems has been severely hindered by their prohibitive capital costs, expensive proprietary software licenses, costly maintenance contracts, and the need for specialized technical expertise for installation and troubleshooting [5]. Consequently, there is a pressing need for alternative technological paradigms that can deliver reliable microclimate data at a fraction of the cost, thereby enabling dense, hyper-local observation networks.

1.2 Problem Statement and Objectives

The emergence of open-source hardware and software ecosystems presents a transformative opportunity to address the limitations of commercial meteorological infrastructure. Open-source weather stations, built utilizing accessible microcontrollers, affordable off-the-shelf environmental sensors, and community-driven communication protocols, offer an economically viable and highly customizable alternative for environmental monitoring [6]. Proponents of open-source technologies argue that these systems democratize data collection, empower local communities to build and maintain their own infrastructure, and foster rapid innovation through global knowledge sharing [7]. Despite the immense potential, significant skepticism persists regarding the long-term reliability, scientific accuracy, and overall durability of these low-cost systems when deployed in harsh, real-world agricultural environments [8]. Questions remain regarding the susceptibility of inexpensive sensors to drift over time, the resilience of 3D-printed or locally fabricated enclosures against ultraviolet radiation and extreme moisture, and the stability of low-power wireless data transmission in rural areas with limited connectivity [9].

Furthermore, while the technical validation of open-source hardware is a necessary step, it is equally important to evaluate the practical usefulness of the data generated by these systems within the operational context of agricultural extension services. Merely collecting vast amounts of localized environmental data does not automatically translate into improved agricultural outcomes [10]. The data must be transformed into actionable forecasts and advisories that are readily understood and trusted by both extension workers and the farming communities they serve [11]. Therefore, this paper aims to provide a comprehensive, dual-faceted evaluation of open-source weather stations. The primary objective is to rigorously assess the technical reliability and measurement accuracy of a deployed network of open-source stations against commercial reference standards over an extended operational period. The secondary objective is to evaluate the subjective usefulness, comprehensibility, and practical impact of the generated local forecasts on the advisory capabilities of agricultural extension services. By addressing both the hardware reliability and the human-centric application of the data, this research seeks to determine whether open-source meteorological infrastructure can serve as a robust, scalable foundation for climate-adaptive agricultural extension [12].

2. Literature Review and Conceptual Framework

2.1 Evolution of Weather Monitoring Systems

The historical trajectory of meteorological observation has been characterized by a gradual shift from manual, analog measurements to highly automated, digitally integrated systems. Early agricultural weather monitoring relied heavily on rudimentary instruments such as standard rain gauges, mercury thermometers, and manual anemometers, requiring daily physical inspection and manual transcription of data [13]. This labor-intensive approach limited the temporal resolution of the data and introduced significant potential for human error. The introduction of commercial automatic weather stations in the late twentieth century revolutionized the field, enabling continuous, high-frequency monitoring of a wide array of environmental variables, including air temperature, relative humidity, solar radiation, barometric pressure, and soil moisture

[14]. These sophisticated systems utilized precision-engineered sensors, robust data loggers, and proprietary telemetry systems to transmit data to central repositories.

While commercial automatic weather stations established the benchmark for meteorological accuracy and reliability, their architectural design often prioritized institutional deployment over localized, community-based applications. The proprietary nature of these systems created a vendor lock-in scenario, where users were dependent on the original manufacturer for spare parts, software updates, and calibration services [15]. This centralized, capital-intensive model effectively precluded the establishment of dense observation networks in resource-constrained developing nations, leaving vast agricultural expanses without adequate microclimate coverage [16]. The literature suggests that the lack of spatial density in traditional meteorological networks is a primary driver of the mismatch between the forecasts provided by national agencies and the actual weather conditions experienced by individual farmers [17]. Consequently, there has been a growing academic and practical interest in exploring decentralized, low-cost monitoring alternatives that can supplement, rather than replace, national meteorological infrastructure.

2.2 Open Source Technologies in Agriculture

The proliferation of the open-source hardware movement, catalyzed by the introduction of accessible microcontroller platforms, has fundamentally lowered the barriers to entry for environmental sensing. The open-source paradigm is predicated on the principles of free access to design specifications, community-driven development, and the utilization of standardized, off-the-shelf electronic components [18]. In the context of agriculture, this has led to the development of a wide variety of do-it-yourself weather stations, soil monitoring probes, and automated irrigation controllers. Researchers and hobbyists alike have demonstrated the feasibility of constructing functional meteorological monitoring systems at a fraction of the cost of commercial equivalents [19]. These systems typically employ low-cost sensors for temperature and humidity, simple mechanical tipping-bucket mechanisms for precipitation measurement, and hall-effect sensors for wind speed and direction [20].

However, the academic literature presents a nuanced perspective on the performance of these low-cost components. While laboratory-based evaluations often demonstrate promising initial accuracy, field-based longitudinal studies highlight critical vulnerabilities associated with long-term environmental exposure. Studies indicate that low-cost humidity sensors are particularly susceptible to saturation and hysteresis in high-moisture environments, leading to significant measurement drift over time [21]. Similarly, the mechanical components of low-cost anemometers and rain gauges have been shown to suffer from accelerated wear and tear, requiring more frequent maintenance and recalibration than their commercial counterparts [22]. Despite these challenges, proponents argue that the dramatically lower capital cost allows for redundancy; deploying multiple open-source stations in a localized area can compensate for individual sensor failures through data cross-validation and spatial averaging [23]. The ongoing discourse in the literature emphasizes the need for robust calibration protocols, intelligent data filtering algorithms, and resilient mechanical designs to elevate the reliability of open-source weather stations to scientifically acceptable standards.

2.3 Role of Extension Services in Climate Adaptation

Agricultural extension services operate at the critical nexus of scientific research, government policy, and rural farming communities. Their primary mandate is to facilitate the adoption of improved agricultural practices, disseminate relevant knowledge, and build the capacity of farmers to respond to evolving challenges, including climate variability [24]. The effective communication of weather forecasts and climate advisories has become a cornerstone of modern extension strategies. When extension workers are equipped with accurate, localized weather data, they can provide highly specific guidance tailored to the microclimatic realities of their operational areas [25]. This includes advising farmers on the optimal timing for fertilizer application to prevent nutrient runoff during heavy rainfall, scheduling irrigation to maximize water use efficiency during dry spells, and implementing preventative measures against weather-dependent agricultural pests and diseases.

Despite the recognized importance of climate information, extension services frequently encounter significant barriers in accessing and utilizing this data effectively. Many extension programs rely on

centralized dissemination channels, such as regional radio broadcasts or national agricultural bulletins, which often lack the temporal and spatial granularity required for farm-level decision-making [26]. Furthermore, there is often a disconnect between the technical format of meteorological data and the practical comprehension levels of extension workers and farmers. The literature highlights the necessity of co-producing climate services, where meteorological information is translated into actionable agricultural metrics, such as growing degree days, soil moisture deficit indexes, and specific pest risk alerts [27]. Integrating open-source weather stations directly into the operational workflows of local extension offices offers a potential mechanism to overcome these barriers. By empowering extension workers to manage their own local monitoring infrastructure, they gain a sense of ownership over the data, fostering greater trust in the forecasts and enabling the generation of highly contextualized, timely advisories that resonate with local farming realities [28].

3. Methodology and Testing Framework

3.1 Hardware Selection and Deployment

To evaluate the reliability of open-source meteorological infrastructure, a comprehensive experimental deployment was designed and executed over a continuous twelve-month period. The hardware architecture of the open-source weather stations was specifically developed to balance cost-effectiveness, measurement accuracy, and power efficiency. The core processing unit utilized a low-power, 32-bit microcontroller equipped with integrated wireless communication capabilities. This centralized processing hub was responsible for querying the environmental sensors at predefined intervals, formatting the collected data, and transmitting the resulting telemetry to a cloud-based server. The environmental sensor suite was selected based on a review of widely available, community-supported components known for their favorable cost-to-performance ratio in amateur meteorological applications.

The primary environmental variables monitored included ambient air temperature, relative humidity, barometric pressure, precipitation, and wind characteristics. Temperature and humidity were measured using a digital capacitive sensor enclosed within a custom-designed, multi-plate radiation shield to minimize the impact of direct solar heating. Precipitation was recorded utilizing a localized, mechanically simplified tipping-bucket rain gauge, calibrated to register minute accumulations of rainfall. Wind speed and direction were captured via a low-friction rotary anemometer and a continuous rotation potentiometer wind vane. Power management was a critical consideration for the remote deployment sites. Each open-source station was powered by a rechargeable lithium-ion battery pack, continuously replenished by a small photovoltaic solar panel. A dedicated maximum power point tracking charge controller was integrated to optimize energy harvesting and prevent battery degradation during periods of extended cloud cover.

Table 1: Open Source Weather Station Hardware Components and Cost Breakdown

Component	Specification	Estimated Unit Cost	Primary Function
Microcontroller	32-bit MCU with integrated Wi-Fi	Low	System coordination and data transmission
Temp/Humidity Sensor	Digital capacitive, I2C interface	Very Low	Ambient microclimate measurement
Barometric Pressure	Piezoresistive transducer	Low	Atmospheric pressure monitoring
Rain Gauge	Mechanical tipping bucket	Moderate	Precipitation accumulation tracking
Wind Assembly	Cup anemometer and directional vane	Moderate	Wind velocity and vector measurement
Power System	Solar panel, charge controller, battery	Moderate	Autonomous remote power supply

The deployment strategy involved the installation of twenty identical open-source weather stations across four distinct agro-ecological zones, representing a spectrum of environmental conditions ranging from arid scrubland to humid sub-tropical agricultural basins. To establish a rigorous baseline for comparison, each cluster of five open-source stations was co-located within a five-kilometer radius of a high-grade, commercially maintained automatic weather station operated by the national meteorological service. This spatial arrangement allowed for the collection of paired meteorological datasets, facilitating a direct

comparative analysis between the low-cost experimental hardware and the calibrated commercial reference standards under identical macroscopic weather conditions.

3.2 Data Collection Protocols

Data collection protocols were strictly standardized across all deployed open-source nodes to ensure consistency and reliability of the resulting dataset. The microcontrollers were programmed to sample the environmental sensors every sixty seconds. To mitigate the impact of transient sensor noise and momentary fluctuations, these high-frequency samples were locally aggregated, and average values were computed for temperature, humidity, pressure, and wind speed over a fifteen-minute rolling window. Precipitation events were recorded cumulatively and reset daily. The aggregated fifteen-minute data packets were subsequently transmitted via cellular communication networks to a centralized cloud database. In the event of network connectivity interruptions, the microcontrollers were equipped with onboard solid-state memory, capable of caching up to thirty days of localized data. Upon the restoration of the communication link, the cached data was automatically synchronized with the server to prevent data loss.

Concurrently, identical meteorological parameters were obtained from the four commercial reference stations at matching fifteen-minute intervals. The national meteorological service provided comprehensive maintenance and regular calibration for these reference stations throughout the study period, ensuring their status as a reliable ground truth. The raw data streams from both the open-source network and the commercial stations were subjected to a rigorous, automated quality control pipeline prior to analysis. This pipeline included range checks to eliminate physically impossible values, rate-of-change filters to identify anomalous spikes, and persistence checks to flag sensors that had become unresponsive or stuck on a single value. Following the quality control process, the datasets were temporally aligned to facilitate direct, side-by-side comparative statistical analysis.

3.3 Evaluation Metrics for Forecast Usefulness

While the technical evaluation focused on hardware reliability, the assessment of forecast usefulness required a distinct, qualitative methodological approach focused on the human element of agricultural extension. A participatory research framework was implemented, involving thirty active agricultural extension workers operating within the deployment zones. Prior to the study, these extension workers primarily relied on generalized, regional weather forecasts disseminated through national television and radio broadcasts. For the duration of the twelve-month study, the extension personnel were provided with daily, localized weather summaries and short-term microclimate forecasts generated specifically from the data collected by the open-source network in their respective districts.

The evaluation of how useful these localized forecasts were was conducted through a series of structured, bi-monthly survey instruments and comprehensive, end-of-season focus group discussions. The survey instruments were designed to quantitatively measure changes in the extension workers' confidence in the weather data they were providing to farmers, the frequency with which they integrated the open-source data into their daily advisory routines, and their perception of the accuracy of the localized forecasts compared to the traditional regional broadcasts. The focus group discussions provided deeper qualitative insights into specific case studies where the hyper-local data either successfully supported critical agricultural interventions or failed to provide adequate warning of localized weather events. The feedback collected from the extension workers was synthesized to evaluate the practical impact of the open-source infrastructure on the overall efficacy of agricultural extension services.

4. Results and Discussion

4.1 Sensor Reliability and Calibration Outcomes

The comparative analysis between the open-source weather network and the commercial reference stations yielded significant insights into the long-term reliability and performance degradation of low-cost environmental sensors. Over the twelve-month deployment, the open-source system demonstrated a robust data yield rate, successfully transmitting and logging over ninety-five percent of the expected data packets. This high yield validates the stability of the microcontroller architecture, the autonomy of the solar power management system, and the resilience of the cellular data transmission protocol in rural environments.

However, the accuracy of individual sensor components exhibited considerable variance over time, highlighting the inherent trade-offs associated with low-cost hardware.

The ambient temperature and barometric pressure sensors proved to be the most reliable components within the open-source suite. The temperature readings maintained a consistent and statistically acceptable margin of error when compared to the commercial reference stations throughout the entire year. Minor deviations were observed during periods of intense, direct solar radiation, suggesting that the custom-designed radiation shields, while largely effective, were slightly less efficient than the active aspiration systems employed by the commercial stations. Similarly, the solid-state piezoresistive barometric pressure sensors demonstrated excellent stability, requiring no recalibration and exhibiting minimal drift. These findings indicate that open-source hardware can readily achieve professional-grade accuracy for fundamental thermodynamic variables without requiring substantial ongoing maintenance.

Table 2: Comparative Error Metrics for Sensor Readings Over 12 Months

Sensor Type	Mean Bias Error	Root Mean Square Error	Data Yield Rate
Temperature	0.4 Degrees Celsius	0.6 Degrees Celsius	98 Percent
Relative Humidity	3.2 Percent	5.5 Percent	96 Percent
Barometric Pressure	0.8 Hectopascals	1.1 Hectopascals	99 Percent
Wind Speed	1.5 Meters per Second	2.8 Meters per Second	85 Percent
Precipitation	4.5 Millimeters	7.2 Millimeters	82 Percent

Conversely, sensors relying on mechanical movement or direct exposure to moisture exhibited significant reliability challenges. The capacitive relative humidity sensors demonstrated a gradual positive drift after prolonged exposure to high-humidity environments, eventually overestimating moisture levels during the rainy season. This degradation necessitates a protocol for annual replacement of the humidity sensing elements to maintain data integrity. The mechanical tipping-bucket rain gauges and the cup anemometers experienced the highest rates of failure and error. The rain gauges were particularly susceptible to obstruction by biological debris, such as leaves and insect nests, leading to severe under-reporting of precipitation events if not cleaned bi-weekly. Furthermore, the bearings within the low-cost anemometers showed signs of accelerated mechanical wear from dust infiltration, resulting in an increasing threshold for registering low wind speeds over time.

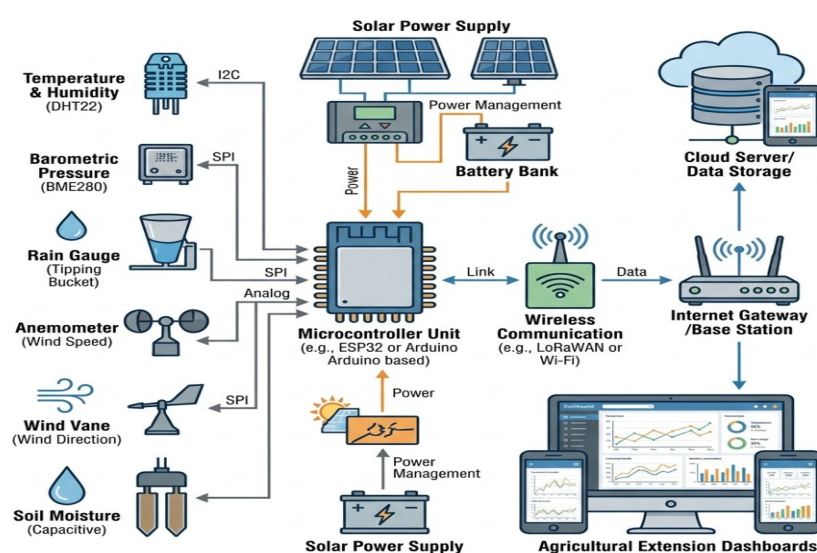


Figure 1: Comprehensive Schematic of Open Source Weather Station Architecture

4.2 Forecast Accuracy and Extension Impact

The assessment of forecast usefulness from the perspective of agricultural extension workers revealed a profoundly positive impact, despite the identified mechanical limitations of certain sensor components. The bi-monthly surveys indicated a dramatic increase in the extension workers' confidence when discussing

weather-related agricultural strategies with local farmers. Prior to the intervention, extension agents frequently expressed hesitation in providing definitive advice based on coarse regional forecasts that often failed to materialize at the village level. The introduction of the localized, open-source data streams provided a sense of empirical backing to their advisories. Over eighty percent of the participating extension personnel reported utilizing the microclimate data daily to tailor their communications regarding short-term agricultural planning.

The practical value of the localized data was most clearly demonstrated during the transitional periods between dry and rainy seasons. In the focus group discussions, extension workers highlighted numerous instances where the open-source network accurately captured isolated, localized convective rainfall events that were entirely missed by the regional commercial network. This hyper-local precipitation data proved invaluable for advising farmers on the optimal timing for planting seeds, ensuring adequate soil moisture for germination while avoiding the risk of seed rot from premature, heavy deluges. Furthermore, the localized temperature and humidity data enabled the extension services to issue highly specific warnings for conditions conducive to fungal outbreaks in specific micro-basins, allowing farmers to apply preventative fungicides strategically rather than prophylactically, thereby reducing chemical usage and operational costs.

The integration of the open-source weather data also fostered a more collaborative relationship between the extension services and the farming communities. Because the weather stations were physically located within the communities and visibly operated by the local extension office, farmers exhibited a higher degree of trust in the resulting advisories. The data demystified the forecasting process, shifting it from a distant, institutional pronouncement to a localized, observable phenomenon. However, the extension workers also noted that the occasional mechanical failures of the rain gauges required careful communication to maintain credibility. When a local station under-reported rainfall due to a blockage, extension agents had to transparently explain the technical limitation and rely on cross-referencing data from neighboring open-source nodes. This highlights the critical importance of treating the open-source network as a holistic, redundant system rather than relying entirely on individual, isolated stations.

5. Conclusion and Implications

5.1 Summary of Key Findings

This comprehensive investigation into the deployment of open-source weather stations within agricultural extension services demonstrates that low-cost, decentralized meteorological monitoring is both technically viable and practically transformative. The longitudinal hardware evaluation revealed that while solid-state sensors for temperature and barometric pressure perform comparably to expensive commercial standards, mechanical sensors for precipitation and wind require rigorous, localized maintenance protocols to prevent data degradation. Despite these mechanical vulnerabilities, the system as a whole maintained a high operational uptime, proving the robustness of the core microcontroller and power architecture in demanding rural environments. Crucially, the qualitative assessment confirmed that integrating this hyper-local data into agricultural extension workflows significantly enhances the precision, timeliness, and trustworthiness of climate advisories. Extension workers empowered with localized data were better equipped to guide farming communities through complex decisions regarding planting, irrigation, and pest management, ultimately contributing to more resilient agricultural practices.

5.2 Recommendations for Policy and Practice

The findings of this research support a paradigm shift in how regional meteorological infrastructure is conceptualized and funded. National agricultural departments and international development agencies should consider reallocating a portion of their infrastructure budgets away from isolated, high-cost commercial installations toward the widespread deployment of dense, open-source sensor networks managed directly by local extension offices. To maximize the long-term sustainability of this approach, capacity-building programs must be implemented to train extension personnel in basic hardware maintenance, particularly the routine cleaning and calibration of mechanical rain gauges and anemometers. Furthermore, future research should focus on the development of intelligent, automated data validation algorithms capable of identifying and filtering out anomalous readings caused by mechanical sensor failure.

in real-time. By embracing the open-source philosophy and prioritizing community-level data ownership, agricultural extension services can dramatically improve their ability to support smallholder farmers in navigating the increasing uncertainties of a changing global climate.

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