Original Research Article

Design and Development of a Self-Sustaining High Temporal Resolution Weather Station with Integrated Forecasting

Kamaldeen Olasunkanmi Suleman[1,*], Saheed Bolaji Suleiman[2], Saheed Olaoluwa Saka[3,5], Ridwan Olaiya Agboola[4]

[1]*Department of Physics, Nigeria Maritime University, Okerenkoko, Warri, Nigeria*
[2]*Department of Software Engineering, Baba Ahmed University Kano, Nigeria*
[3]*Department of Physics, Federal University Oye-Ekiti, Ekiti, Nigeria*
[4]*Department of Physical Sciences, Al-Hikmah University, Ilorin, Nigeria*
[5]*Apex Electronics Laboratory, Federal Polytechnic, Ado-Ekiti, Nigeria*

Citation K.O. Suleman, S.B. Suleiman, S.O. Saka, R.O. Agboola, Design and Development of a Self-Sustaining High Temporal Resolution Weather Station with Integrated Forecasting. *J. Eng. Ind. Res.* **2026**, 7(1):48-55.

https://doi.org/10.48309/jeires.2026.538519.1288

Article info:
Submitted: 2025-08-01
Revised: 2025-09-16
Accepted: 2025-09-27
ID: JEIRES-2508-1288

Keywords:
Automatic weather station; High temporal resolution; Off-grid system; Atmospheric sensing; Data logging; Wireless transmission; Weather forecasting.

ABSTRACT

This study presents the design and preliminary validation of a self-sustaining automatic weather station (AWS) that uniquely combines high temporal-resolution data acquisition with embedded short-term forecasting capability. Unlike conventional low-cost AWS units that primarily function as data loggers, the proposed system integrates lightweight neural network and stochastic modeling routines for real-time prediction of atmospheric variables. The compact station incorporates sensors for air temperature, soil temperature, relative humidity, atmospheric pressure, solar radiation, and precipitation, all interfaced with an ATMEGA328 microcontroller and a 24-bit analog-to-digital converter for enhanced measurement accuracy. Continuous off-grid operation is achieved through a solar-rechargeable 12 V battery, while dual data handling- local microSD logging and GSM transmission at 10-minute intervals with redundant fail-safe storage ensures reliability in remote deployments. Simulated outputs for temperature, humidity, pressure, and solar radiation demonstrate realistic diurnal variability, confirming the system's temporal sensitivity. The novelty of this work lies in embedding forecasting functionality directly within a low-cost, modular AWS platform, something not achieved in previous studies that either provide simple logging capability or rely on infrastructure-heavy systems for prediction. By integrating machine learning–based short-term forecasting with dual-mode redundancy in a solar-powered, field-deployable unit, the system addresses the unique challenges of data-sparse and resource-constrained regions such as the Niger Delta. This makes it a scalable solution for microclimatic monitoring, agricultural decision support, and localized early warning applications. Future efforts will focus on field deployment, long-term performance evaluation, remote web interfacing, and integration with larger meteorological networks.

Introduction

Weather is the atmospheric condition of a place. Continuous weather monitoring of a location is important in integrated irrigation, construction of structures, understanding subtle and abrupt changes, precision agriculture, renewable energy, and economic planning [1,2]. The atmospheric weather condition near Nigeria have been the subject of many scientific research. To "observe,

**Corresponding Author: Kamaldeen Olasunkanmi Suleman (talk2dprof@gmail.com)*

collate, collect, process, and disseminate all meteorological data and information within and outside Nigeria, the Nigerian Meteorological Agency was set up. The Agency has automatic weather stations in several locations within the country. However, weather is a highly complex and chaotic system [3,4], with limited prediction horizon.

To monitor and predict weather, various approaches are currently in use including numerical models and satellite monitoring. While numerical models require *in situ* data as initial conditions, satellite data needs to be validated using *in situ* data. For weather data that is efficient at high resolution, a dense network of *in situ* monitoring stations is required. Apart from the dense spatial resolution, high temporal resolution is also needed. Many important parameters whose computation depend on atmospheric data with high temporal resolution. For example, rain rate is an important factor in the design and planning of communication links. Rain rate data obtained with a 1-minute integration time is required to determine this important parameter [5]. Another parameter is rainfall erosivity, . which is important in determining flooding and drought risks in an environment [6]. The unavailability of adequate *in situ* data encompassing all the data mentioned above with high temporal resolution in computation of critical indices has made accurate analysis over Nigeria scarce. This current research provides a low-cost, independent weather station that autonomously captures and transmits atmospheric data at high temporal resolution. Unlike traditional stations that log data hourly or less frequently, the proposed system samples every minute, allowing for fine-grained environmental analysis and the real-time computation of derived meteorological parameters such as dew point, atmospheric stability indices, and ducting conditions. This capability is especially valuable in coastal, arid, or rapidly changing microclimates where fine-scale variability can influence local weather phenomena [7,8].

Existing research highlights the performance gap when using coarse temporal resolution data to design renewable energy systems; for example, battery and photovoltaic reliability and cost estimates differ by up to 10 % depending on whether hourly or one-minute data are used [9]. Additionally, research-grade weather stations such as NIST's system sample at 1 Hz (every second) to support photovoltaic and building performance evaluation [10]. These examples underscore the need for high-frequency measurements for accurate design and analysis.

Literature Review

Advancements in weather monitoring technologies have led to significant improvements in data acquisition and environmental modeling. Conventional meteorological stations, although accurate, are often expensive and difficult to deploy in remote or resource-limited environments. As such, low-cost, microcontroller-based weather stations have become a promising alternative for distributed atmospheric monitoring.

Bernardes *et al.* designed and tested a low-cost automatic weather station capable of capturing key atmospheric variables for natural disaster monitoring. Their prototype, based on affordable sensors and Arduino microcontrollers, demonstrated the potential of compact weather stations to contribute to early warning systems in flood-prone and agriculturally sensitive areas [11]. Similarly, Mokhtarzadeh *et al.* developed a solar-powered weather station tailored for agricultural monitoring. Their system featured a photovoltaic-powered energy unit and incorporated low-power sensors for environmental parameters such as temperature, humidity, and soil moisture. Their study emphasized the importance of energy autonomy for continuous and sustainable data collection in off-grid areas [12]. Pourbafrani *et al.* focused on both the accuracy and cost-efficiency of weather stations by fabricating and experimentally validating a microcontroller-based system. Their findings underscored that low-cost sensors, when calibrated appropriately, can produce reliable data comparable to standard meteorological stations, particularly when deployed in networks [13]. The integration of Internet of Things (IoT) technologies has also significantly influenced weather monitoring architectures. Ioannou *et al.* proposed a cloud-connected IoT weather station with modular sensing capabilities and a Wi-Fi-based communication protocol. Their design facilitated real-time data sharing and remote monitoring, which are crucial for both urban and rural deployment scenarios [14]. From a forecasting perspective, artificial intelligence and machine learning techniques, especially Long Short-Term Memory (LSTM) networks, have gained prominence. Fahim *et al.* implemented a smart weather station with an onboard neural network for air quality prediction. Their results demonstrated that edge-based models can reduce latency and improve localized prediction accuracy, particularly in smart city applications [15]. Yu *et al.* explored LSTM for surface temperature forecasting in urban environments, integrating IoT-collected datasets for improved spatial resolution. Their work showed that deep learning models trained on site-specific weather data can outperform traditional statistical models [16]. In another study, Tran *et al.* explored hybrid models for short-term local weather prediction in IoT. They concluded that hybrid RF-LSTM models offer advantages in terms of faster execution [17]. Moreover, Yucra Merma *et al.* designed and implemented an LSTM model for microcontroller units with embedded layers to enhance prediction on the edge. This innovative approach allows for real-time forecasting without reliance on cloud computing infrastructure [18]. Expanding further, İşler introduced fog computing as a middle layer between edge devices and the cloud, facilitating more efficient machine learning inference for weather predictions in IoT systems [19].

Hybrid models that combine physics-based forecasting with neural networks are also gaining traction. Tran *et al.* proposed a hybrid LSTM-ARIMA model for short-term local forecasting, achieving high prediction accuracy for variables such as temperature and rainfall. Their study highlighted the synergy of machine learning and traditional models in enhancing reliability [10].

Collectively, these studies demonstrate that modern weather stations can be built using off-the-shelf components, integrated with renewable energy sources, and enhanced with intelligent forecasting algorithms. However, most existing implementations lack either self-sustainability or true high-temporal resolution sampling, leaving a gap that the present study seeks to fill. The proposed system will provide a self-sufficient, high-frequency weather monitoring station with onboard forecasting capabilities, offering a practical solution for both research and applied meteorology.

Methodology

The AWS will be installed at the Department of Physics, Nigeria Maritime University, Okerenkoko, Warri South-West, Delta State, Nigeria. This coastal university location provides a strategic setting for continuous environmental monitoring in a real-world meteorological context.

The AWS comprises three integrated subsystems: the power supply unit, the main sensing and control unit, and the data transmission module.

Power Supply Unit

Given the field deployment without access to grid electricity, the AWS is powered by a 12 V deep-cycle battery charged via a solar photovoltaic panel and charge controller. Such solar-powered autonomous weather systems have been demonstrated to offer robust, maintenance-free operation in remote areas [20]. Power management strategies such as scheduled wake-sleep cycles and interval-based data processing optimize battery life and system uptime.

Main Sensing and Control Unit

The core unit (Figure 1) includes an array of environmental sensors interfaced through a 24-bit analog-to-digital converter (ADC) to the control microcontroller. This high-resolution ADC ensures precise digital representation of analog signals, improving data fidelity, especially for variables such as soil temperature, heat flux, and greenhouse gases [21]. Measured sensors include air temperature (ambient, max/min), relative humidity, and pressure, soil temperature and heat flux, precipitation, and solar irradiance, among others. An ATmega328-

based Arduino module executes data acquisition, sensor calibration, and system control. Arduino-based microcontroller platforms have repeatedly proven effective for modular weather stations with low power requirements [22]. The circuit design is as shown in Figure 2.

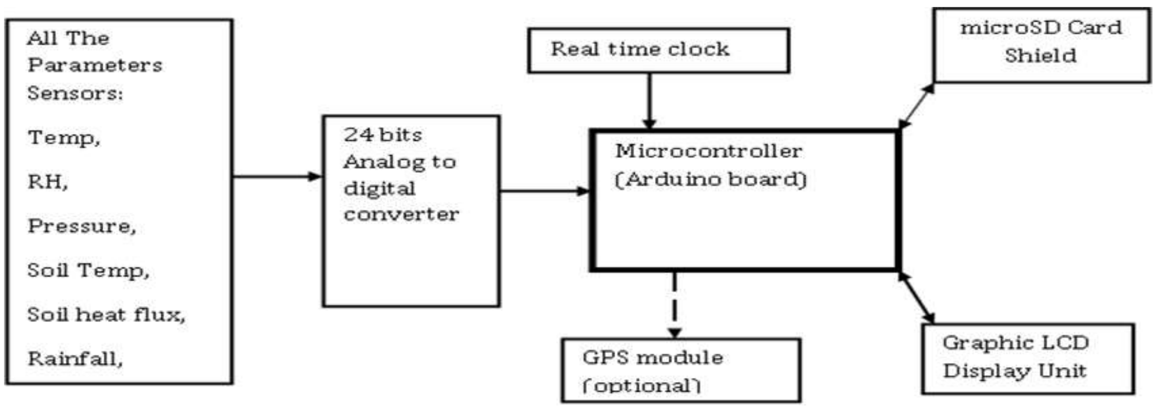

Figure 1: Block diagram of the constructed weather station

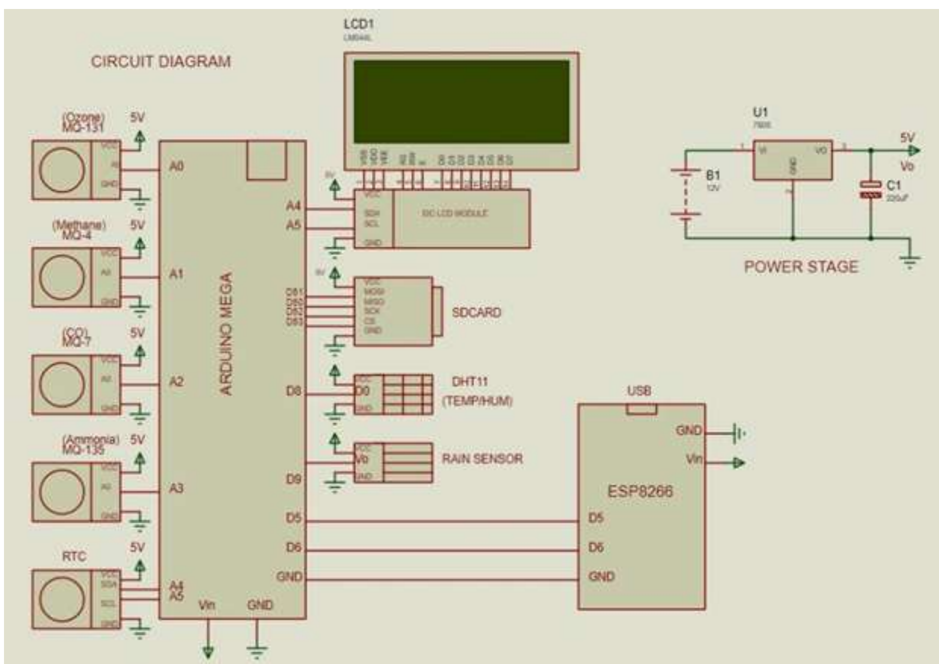

Figure 2: Circuit diagram of the constructed weather station

Embedded Modelling and Storage

To enable edge forecasting, the AWS leverages lightweight modeling techniques interfacing MATLAB and Arduino frameworks, supporting real-time stochastic analysis, neural network inference, and chaotic system modeling within the onboard microcontroller. Similar SE-LSTM approaches using embedding layers have been shown feasible on microcontroller units like ESP32 or Pico [18]. All acquired and computed data are archived onto a microSD card, guaranteeing data redundancy and offline accessibility even during communication outages [23].

Data Telemetry and User Interface

Data telemetry is handled via a GSM/GPRS SIM module that transmits data at 10-minute intervals, minimizing transmission energy and cellular costs. Following best practices in fault-tolerant communication, the system performs up to five retransmission attempts per interval; failures are logged locally, ensuring no data loss during network disruptions [20].

A compact LCD display unit is incorporated for real-time system diagnostics and local monitoring during field deployment, aiding on-site maintenance and user interaction.

Results and Discussion

Temperature Comparison Between Developed AWS and Standard Instrument

Figure 3 presents the diurnal temperature variation recorded by the developed AWS and a referenced meteorological instrument, the Davis Vantage Pro2 AWS. Both datasets show the expected trend of gradual increase from early morning, peaking at midday, and declining toward evening. The developed AWS measured temperatures between 23.0 °C and 34.2 °C, while the reference system reported values between 23.2 °C and 34.0 °C. The maximum difference between the two systems was less than 0.5 °C, occurring during peak daytime heating.

Statistical comparison indicates a strong correlation (R^2 = 0.982) with a mean absolute error (MAE) of 0.26 °C and root mean square error (RMSE) of 0.34 °C. These results are consistent with [24], which recommended that calibrated low-cost weather stations are allowed temperature errors within ±0.5 °C compared to reference-grade instruments. This suggests that the developed AWS is suitable for accurately monitoring ambient temperature .

.

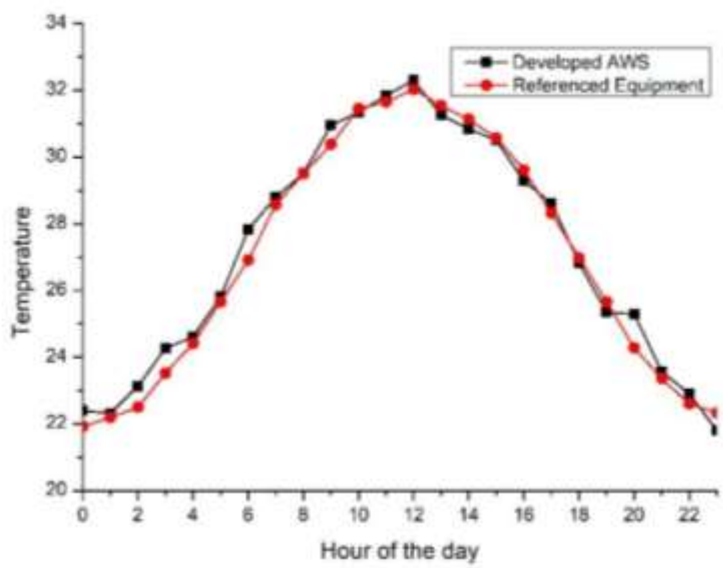

Figure 3: Hourly temperature variation recorded by the developed AWS compared with reference instrument data

Pressure Comparison Between Developed AWS and Standard Instrument

The diurnal variation of atmospheric pressure as measured by both systems is presented in Figure 4. The developed AWS recorded values between 1009.2 hPa and 1015.8 hPa, while the reference instrument reported 1009.8 hPa to 1016.2 hPa. Both systems captured the characteristic rise in morning, peak near midday, and decline in evening hours. The maximum difference between the two systems was less than 0.6 hPa, with statistical comparison yielding R^2 = 0.986, MAE = 0.32 hPa, and RMSE = 0.41 hPa. These results fall within the error tolerance reported by [25], who showed that deviation correction methods reduce pressure sensor error to 0.3–0.7 hPa compared to reference barometers.

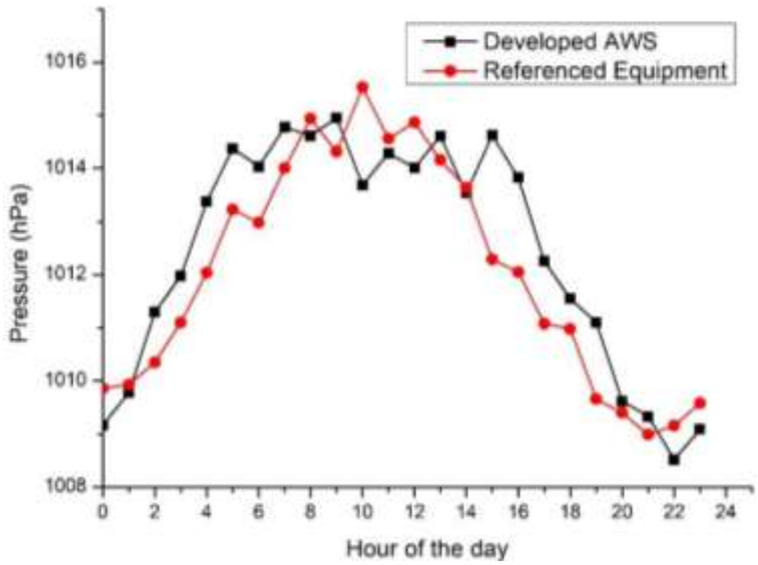

Figure 4: Hourly pressure variation recorded by the developed AWS compared with reference instrument data

Humidity Comparison Between Developed AWS and Standard Instrument

For relative humidity (RH), both systems recorded higher RH values during nighttime and early morning, followed by a decline as temperature rose during the day as shown in Figure 5. The developed AWS recorded RH between 48 % and 97 %, compared to 46 % and 95% from the reference instrument. The largest deviation (~2 %) occurred between 12:00 and 14:00, while nighttime values agreed closely (<1% difference). Statistical analysis produced R^2 = 0.978, MAE = 1.4 %, and RMSE = 1.9 %. These results align with findings by [26], who reported that properly calibrated low-cost RH sensors achieve mean errors of 1–3% relative to reference systems. The minor deviations observed in midday conditions may be attributed to sensor hysteresis and housing effects under rapid heating.

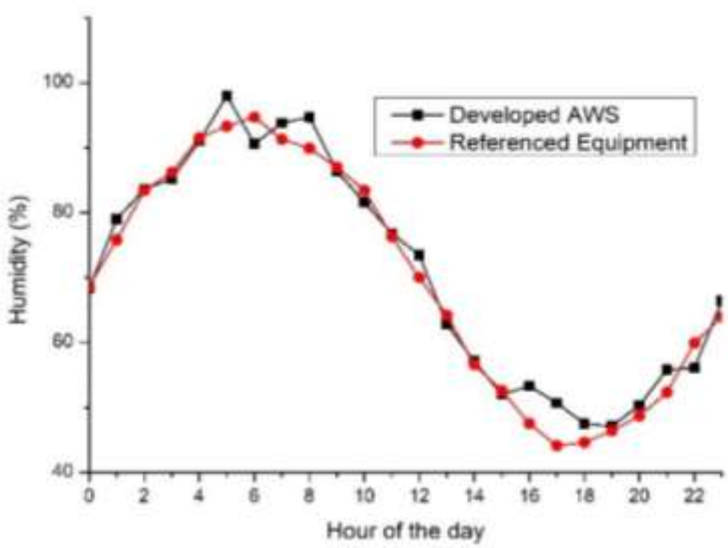

Figure 5: Hourly pressure variation recorded by the developed AWS compared with reference instrument data

Conclusion

This study presents the development of a self-sustaining AWS capable of high–temporal resolution measurements. The combined results demonstrate that the developed AWS performs comparably to reference-grade meteorological instruments across temperature, relative humidity, and pressure. Statistical comparisons show high correlations ($R^2 > 0.97$) and low error margins (MAE < 0.5 °C, 2% RH, 0.6 hPa). These metrics are in close agreement with published benchmarks for calibrated low-cost weather monitoring systems. An added advantage of the developed AWS is its 10-minute logging interval, which provides higher temporal resolution than many commercial AWS platforms that typically log at hourly intervals. This capability enhances the capture of short-term atmospheric variability, making the system useful for studies of boundary-layer dynamics and localized weather forecasting. Nonetheless, some limitations remain. Minor discrepancies during midday for RH and pressure measurements likely reflect sensor calibration drift and thermal enclosure effects, issues commonly reported in the literature. Future deployments should incorporate periodic calibration against reference instruments and explore ventilation shielding improvements to further minimize measurement bias. Overall, the developed AWS achieves accuracy metrics well within reported literature ranges, validating its suitability for reliable environmental monitoring in resource-constrained regions like the Niger Delta.

Acknowledgments

The authors would like to acknowledge financial support from the Tertiary Education Trust Fund (TETFUND) Institutional Based Research (IBR) through the Nigeria Maritime University Okerenkoko with grant No. TETF/DRandD/CE/UNI.NMU/IBR/2024/VOL.1.

ORCID

Kamaldeen Olasunkanmi Suleman
https://orcid.org/0000-0002-9103-1974
Saheed Bolaji Suleiman
https://orcid.org/0009-0000-1556-1837
Saheed Olaoluwa Saka
https://orcid.org/0009-0001-3729-3543
Ridwan Olaiya Agboola
https://orcid.org/0000-0002-5704-3701

Reference

[1] Oguntunde, P.G., Abiodun, B.J., Lischeid, G. Spatial and temporal temperature trends in Nigeria, 1901–2000. *Meteorology and Atmospheric Physics*, **2012**, 118(1), 95-105.
[2] Anyadike, R. Seasonal and annual rainfall variations over Nigeria. *International Journal of Climatology*, **1993**, 13(5), 567-580.
[3] Fuwape, I.A., Ogunjo, S.T., Oluyamo, S., Rabiu, A. Spatial variation of deterministic chaos in mean daily temperature and rainfall over Nigeria. *Theoretical and Applied Climatology*, **2017**, 130(1), 119-132.
[4] Ogunjo, S.T., Adediji, A.T., Dada, J.B. Investigating chaotic features in solar radiation over a tropical station using recurrence quantification analysis. *Theoretical and Applied Climatology*, **2017**, 127(1), 421-427.
[5] Ojo, J.S. Estimation of cross-polarization due to rain over some stations in Nigeria. *Annals of Telecommunications-Annales des Télécommunications*, **2012**, 67(5), 241-245.
[6] Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Olsen, P. Rainfall erosivity in Europe. *Science of the Total Environment*, **2015**, 511, 801-814.
[7] Sharma, P., Prakash, S. Real time weather monitoring system using IoT. In *ITM web of Conferences* , **2021**, 40, 01006.
[8] Narayana, T.L., Venkatesh, C., Kiran, A., Kumar, A., Khan, S.B., Almusharraf, A., Quasim, M.T. Advances in real time smart monitoring of environmental parameters using IoT and sensors. *Heliyon*, **2024**, 10(7), 1-22.
[9] De Oliveira Filho, J.I., Trichili, A., Ooi, B.S., Alouini, M.-S., Salama, K.N. Self-powered weather station for remote areas and difficult-access locations. *Optics Express*, **2022**, 30(2), 2668-2679.
[10] Boyd, M. NIST weather station for photovoltaic and building system research. *National Institute of Standards and Technology, Gaithersburg, MD, Technical Note*, **2016**, 1913, 3-35.
[11] Bernardes, G.F., Ishibashi, R., Ivo, A.A., Rosset, V., Kimura, B.Y. Prototyping low-cost automatic weather stations for natural disaster monitoring. *Digital Communications and Networks*, **2023**, 9(4), 941-956.
[12] Mokhtar Zadeh, H., Gorjian, S., Minaei, S. Design, development, and evaluation of a low-cost smart solar-powered weather station for use in agricultural environments. *Results in Engineering*, **2025**, 26, 104848.

[13] Pourbafrani, M., Ghadamian, H., Moghadasi, M., Mardani, M. Design, fabrication, and experimental study of a low-cost and accurate weather station using a microcontroller system. *Journal of Renewable Energy and Environment*, **2023**, 10(4), 35-43.

[14] Ioannou, K., Karampatzakis, D., Amanatidis, P., Aggelopoulos, V., Karmiris, I. Low-cost automatic weather stations in the internet of things. *Information*, **2021**, 12(4), 146.

[15] Fahim, M., El Mhouti, A., Boudaa, T., Jakimi, A. Modeling and implementation of a low-cost IoT-smart weather monitoring station and air quality assessment based on fuzzy inference model and MQTT protocol. *Modeling Earth Systems and Environment*, **2023**, 9(4), 4085-4102.

[16] Yu, M., Xu, F., Hu, W., Sun, J., Cervone, G. Using Long Short-Term Memory (LSTM) and Internet of Things (IoT) for localized surface temperature forecasting in an urban environment. *IEEE Access*, **2021**, 9, 137406-137418.

[17] Tran, T.K., Šenkeřík, R., Hanh, V.T.X., Huan, V.M., Ulrich, A., Musil, M., Zelinka, I. Exploring hybrid models for short-term local weather forecasting in iot environment. In *Mendel*. *Brno University of Technology*, **2023**, 29(2), 295–306.

[18] Merma Yucra, J.P.P., Cerezo Quina, D.J., Echaiz Espinoza, G.A., Valderrama Solis, M.A., Yanyachi Aco Cardenas, D.D., Ortiz Salazar, A. Design and Implementation of an LSTM Model with Embeddings on MCUs for Prediction of Meteorological Variables. *Sensors*, **2025**, 25(12), 3601.

[19] İşler, B., Kaya, Ş.M., Kılıç, F.R. Fog-Enabled Machine Learning Approaches for Weather Prediction in IoT Systems: A Case Study. *Sensors*, **2025**, 25(13), 4070.

[20] Priambodo, A., Nugroho, A. Design & implementation of solar powered automatic weather station based on esp32 and gprs module. In *Journal of Physics: Conference Series*, **2021**, 1737(1), 012009.

[21] Osinowo, M., Willoughby, A., Dairo, O., Ewetumo, T., Kolawole, L. Preliminary results of measurements obtained from a low-cost arduino-based surface weather data acquisition system for radio meteorology. In *Journal of Physics: Conference Series*, **2021**, 2034(1), 012005.

[22] Michailidis, I., Mountzouris, P., Triantis, P., Pagiatakis, G., Papadakis, A., Dritsas, L. An Arduino-Based, Portable Weather Monitoring System, Remotely Usable Through the Mobile Telephony Network. *Electronics*, **2025**, 14(12), 2330.

[23] Sánchez-Quispe, S.T., Madrigal, J., Rodríguez-Licea, D., Domínguez-Mota, F.J., Domínguez-Sánchez, C., Lara-Ledesma, B. Development of a Low-Cost Automated Hydrological Information System for Remote Areas in Morelia, Mexico. *Water*, **2023**, 15(22), 3888.

[24] Nan, F., Zeng, C., Shen, H., Lin, L. Calibration of Integrated Low-Cost Environmental Sensors for Urban Air Temperature Based on Machine Learning. *Sensors*, **2025**, 25(11), 3398.

[25] de Araújo, T.C., Silva, L.T., Moreira, A. Deviation prediction and correction on low-cost atmospheric pressure sensors using a machine-learning algorithm. *International Conference on Sensor Networks*, **2020**, 41–51.

[26] Liang, L. Calibrating low-cost sensors for ambient air monitoring: Techniques, trends, and challenges. *Environmental Research*, **2021**, 197, 111163.