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IoT-Based Smart Weather Station Using ESP32 for Real-Time Environmental Monitoring

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Abstract*: This research paper proposes development of IoT based Smart Wheater station leveraging ESP-32-WROOM-32 devkit. The system integrates with multiple sensor modules that collect real-time data for Wheater monitoring. The sensors deployed are DHT22 for temperature and humidity measurement, BMP180 for barometric pressure, MQ135 for air quality, LDR for luminous intensity. The graphical user interface was created through which the forecasted data was visualized using gauges, line charts and heatmaps. Interface comes with on/off feature through which user can access the system remotely. The proposed system comes with an accurate tracking, cost effective yet scalable solution to the real-world application such as smart agriculture, pollution detection, Wheater monitoring. The research also highlighted the versatility, reliability and efficiency of ESP-32-WROOM-32 in IoT applications. Future upgradation of the system may include integration with additional sensors, cloud base data storage and AIML predictive analytics for further advancements of the system.*

Keywords: Smart Wheater

I. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Studying weather in real-time assists with agricultural needs as well as both disaster response activities and city organization development. The traditional weather monitoring systems provide dependable results but they face multiple obstacles which include high installation costs and scaling limitations and restricted availability of real-time data.[1] The impediments to these systems prevent their deployment in remote underdeveloped locations. Environment monitoring transitioned during the IoT era because it delivered cost-effective and extendable and open access solutions. The Wi-Fi enabled ESP32-WROOM-32 microcontroller together with IoT-based weather stations enables remote data fetching and visualization operations. The improved environmental data collection quality is enhanced through these systems which also provide access to straightforward weather information interfaces that present up-to-date weather updates.[2]

1.2 PROBLEM STATEMENT

Local monitoring of traditional systems remains limited since they cannot access the internet because of connectivity issues. Traditional meteorological stations cost a lot money for installation and continuous maintenance activities. The data obtained from traditional systems proves virtually inaccessible in real time which makes it insufficient for strategic decision-making processes. This research aims to resolve previous identified shortcomings while constructing an IoT suitable smart weather station through three specific objectives.[3]

1.3. OBJECTIVES

1. The system will combine ESP32-WROOM-32 modules with inexpensive hardware to construct the new weather monitoring system.

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2. A real-time monitoring system can be built by uniting sensors such as DHT22 for temperature/humidity and BMP180 along with MQ135 for air quality and a light-dependent resistor (LDR) module which allows data viewing through graphical interfaces.[4]
3. The system will deliver monitored sensor readings through Wi-Fi connection while letting users track data inputs from any desired location.
4. The system performance assessment evaluates the ESP32-WROOM-32's operation when integrating multiple sensors and transmitting data. References include.[5][6]

II. LITERATURE REVIEW

2.1. EXISTING SYSTEMS

Weather monitoring systems in the IoT era bring comprehensive environmental data collection solutions through future-ready advanced technology which delivers time-sensitive scalable and budget-friendly capabilities. Using IoT with weather monitoring solves major problems of traditional platforms by eliminating delayed manual data collection and providing lower operational costs and extended scalability. According to Murthy et al. (2023) the MQTT protocol delivers sensor data effectively to cloud platforms which provides distributed sensors with uninterrupted communication capabilities. The system performs localized weather assessment that specifically benefits weather monitoring in urban areas and precision farming operations.

The research by Bella et al. (2023) proved the effectiveness of IoT technology in disaster management through their sustainable development of a weather station with Wi-Fi-enabled ESP32 microcontrollers. Real-time datacollection happens through systems that unite signals from multiple sensors such as detectors for temperature and humidity and rainfall along with air pressure assets. These platforms operate through cloud platforms to show dashboards to users online. These installed systems provide authorities with the ability to distribute quick advance warnings for severe weather that minimizes vulnerabilities to people and property losses.

Weather monitoring through the Internet of Things has experienced essential advancements

1. Real-Time Data Transmission and Visualization

The modern implementation of IoT systems produces an instantaneous data refreshment process. According to Ferdin Joe and John Joseph (2019) Thing Speak acted as their chosen platform to display sensor data which could be viewed remotely through web or mobile platforms. Time-sensitive applications require such real-time dataaccess because it enables timely flood prediction and wildfire monitoring operations.

2. Scalability and Modularity

Additional sensors can be easily integrated into IoT networks because of their high adaptability feature. The basic weather station which tracks temperature and humidity can seamlessly incorporate wind speed as well as UV index or air quality sensors without requiring major infrastructure updates. The modular structure of the system enables changes to environmental monitoring requirements due to system evolution.

3. Cost Efficiency and Sustainability

Operational costs and installation prices decrease when people select low-power microcontrollers (such as ESP32 or Raspberry Pi) combined with open-source IoT platforms (including Node-RED and Blynk). The fusion of cloud computing with edge processing enables IoT systems to operate at lower costs thanks to lacking the need for price-tagged hardware.

4. Remote Accessibility and Automation

The system for automatic data collection removes all mistakes that would occur from human-driven information recording. Cloud dashboards let users view historic data together with real-time measurements which benefits farmers and research teams and policy centers in making informed decisions.[8][12]

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2.2 COMPARISON BETWEEN TRADITIONAL WEATHER STATIONS AND IOT-BASED STATIONS

Feature	Traditional Systems	IoT based Systems
Data Accessibility	Localized storage, manual retrieval required	Remote access via cloud interface
Sensor Network	Fixed installations with limited coverage	Distributed, wireless nodes for hyper-local monitoring
Power Consumption	High(grid-dependent)	Low (battery, solar-powered with ESP-32's sleep modes)
Maintenance	Frequent manual calibration	Over-the-air (OTA) updates and self-diagnostics tools
Data resolution	Hourly/daily updates	Real-time streaming (1-5 second intervals)

Table.1. Comparison of system (Source: Author)

IoT systems excel in dynamic environments, such as agricultural zones, where real-time humidity and temperature data optimize irrigation schedules. However, traditional systems remain relevant for long-term climatological studies requiring high-precision instrumentation.[7][10]

2.3. SENSOR TECHNOLOGIES

IoT-based weather monitoring relies on a variety of sensors, each with distinct advantages and limitations. Selecting the right sensor depends on factors such as accuracy, power efficiency, environmental resilience, and long-term reliability. Below is a detailed comparisonofcommonly used sensors in weather monitoring applications.

1. DHT22 (Temperature and Humidity Sensor)

- Accuracy: ±0.5°C for temperature and ±2% RH for humidity under controlled conditions. However, performance degrades in extreme temperatures (>60°C) or high humidity (>80% RH).
- Power Consumption: Low (1.5mA during operation), making it suitable for battery-powered IoT nodes when paired with ESP32's deep-sleep modes.
- Limitations: Slow response time (~2 seconds per reading) and susceptibility to electromagnetic interference (EMI) in industrial environments.
- Best Use Case: Indoor or mild-climate monitoring where extreme conditions are not a concern.

2. BMP180 (Barometric Pressure Sensor)

- Accuracy: ±0.12 hPa, making it reliable for altitude estimation and storm prediction.
- Efficiency: Operates at 3.3V with a standby current of just 5µA, ideal for energy-efficient deployments.
- Reliability Issues: Long-term diaphragm fatigue leads to drift, requiring recalibration every 6–12 months.
- Best Use Case: Weather forecasting and altitude-based applications where periodic recalibration is feasible.

3. MQ135 (Air Quality Sensor)

- Sensitivity: Detects gases like NH_3, CO_2, and benzene (10–1000 ppm range) but lacks selectivity, often requiring calibration against known gas concentrations.
- Power Draw: High (~150mA), necessitating external power management circuits when used with low-power microcontrollers like the ESP32.
- Environmental Interference: Ferdin Joe and John Joseph (2019) found inconsistent readings in high-humidity environments, recommending machine learning-based noise reduction algorithms.
- Best Use Case: Urban air quality monitoring where supplementary data processing is available.

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4. LDR Module (Light Intensity Sensor)

- Response Time: Fast (<100ms), suitable for dynamic light monitoring (e.g., solar irradiance studies).
- Linearity Issues: Non-linear response requires logarithmic correction in firmware for accurate lux measurements.
- Durability: Degrades under prolonged UV exposure, limiting long-term outdoor use without protective coatings.
- Best Use Case: Short-term solar studies or indoor light monitoring where UV exposure is minimal[9][11].

III. METHODOLOGY

3.1 SYSTEM OVERVIEW

The IoT-based smart weather station is intended for real-time environmental parameter monitoring such as temperature, humidity, barometric pressure, air quality, and light intensity. The system is based on the ESP32-WROOM-32 microcontroller as the core, with the incorporation of multiple sensors for data acquisition and wireless transmission to a cloud platform for storage and visualization. The primary objective of this project is to provide a low-budget, scalable, and efficient means of real-time environmental monitoring that can be used for applications in agriculture, city planning, and climate studies. The functional units include the ESP32 microcontroller, environment sensors (DHT22, BMP180, MQ135, LDR), power supply unit, and user interface to show the data. The architecture is the ESP32 interfacing with sensors using GPIO pins, processing the data, and transmitting it over Wi-Fi to a cloud server.

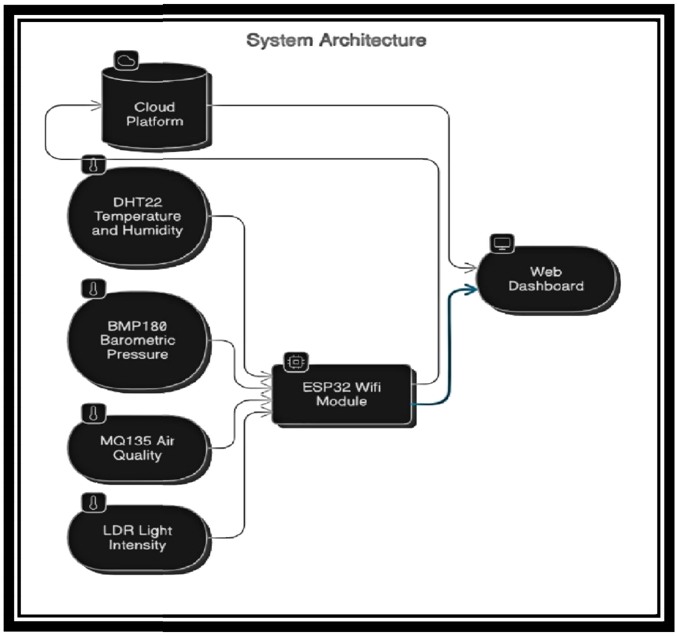

Fig.1. System Architecture (Source: Author)

3.2 HARDWARE COMPONENTS

The hardware configuration is based on the ESP32-WROOM-32 development module and sensors, which were chosen for their precision and compatibility with the microcontroller.

- ESP32-WROOM-32 Dev Module: This is the processing unit, which has a dual-core processor, 520 KB SRAM, and integrated Wi-Fi/Bluetooth. It is responsible for acquiring sensor data, processing, and wireless transmission [13].
- Sensors Used:

- DHT22: A digital temperature and humidity sensor with a -40°C to 80°C (-0.5°C accuracy) temperature range and 0-100% RH (-2% accuracy) humidity range. It is connected through a single-wire digital interface [16].
- BMP180: A barometric pressure sensor with pressure measurement between 300 and 1100 hPa (±1 hPa accuracy), also including temperature measurement. It communicates using the I2C protocol [17].
- MQ135: Air quality parameter such as CO2, NOx, and NH3 detecting gas sensor. It gives an analog voltage proportional to gas concentration, which needs to be calibrated to get accurate values [18].
- LDR Module: Ambient light intensity measuring light-dependent resistor module. It gives analog output, connected to ESP32's ADC pins [14].
- Power Supply: 5V DC power supply USB guarantees stable operation of the ESP32 and sensors.

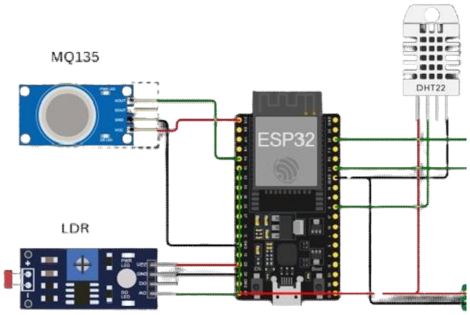

Fig.2. Circuit Diagram (Source: Author)

3.3 SOFTWARE IMPLEMENTATIONS

Firmware Development

Because of its extensive library support and user-friendliness, the Arduino IDE is used to develop the firmware. For more complex customization, alternative environments like ESP-IDF or MicroPython can be used.

The code structure includes:

Sensor object and Wi-Fi credential initialization.

A loop function that reads sensor data on a regular basis (every second).

Data transmission to the cloud and formatting.

Cloud Integration & Data Communication

Communication Protocols: By utilizing the ESP32's integrated module, the system transmits data via Wi-Fi. Low-latency communication between the ESP32 and the cloud server is guaranteed by the Blynk protocol, which is based on TCP/IP [16].

Web Interface for Visualization

Frontend Interface: User interface displays the real-time environmental data from the sensors to the web dashboard in analog gauges. It also shows the visualized data in the form of graphs over the time period in different positions. Gauges include the following environmental parameters:Temperature in Celsius, Humidity in percentage, Barometric Pressure in milli-bar, Air Quality in percentage (low value means low quality of gas), Light Intensity in percentage (Low value means high intensity)

Fig.2. User interface to Forecasts the real-time environmental data (Source: Author)

3.4 WORKFLOW AND OPERATION OF THE SYSTEM

At boot-up, the ESP32 initializes sensor and Wi-Fi network and server connectivity. The sendSensor() function acquires values from DHT22, BMP180, MQ135, and LDR once every second. The readings are transmitted to the cloud through virtual pins. Users observe data via the web interface in real time.

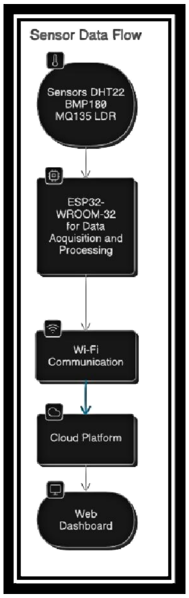

Fig.3. System Workflow (Source: Author)

IV. RESULT AND DISCUSSION

4.1. KEY FINDINGS

The smart Wheater station has at its core, the ESP32-WROOM-32 which is integrated with various sensors to collect and monitor various atmospheric variables. The system monitors various values likes temperature, humidity, barometric pressure, air quality and light intensity.

Temperature and Humidity

The DHT22 sensor took the readings of the temperature and humidity. The temperature readings has range of 15 to 60 degree Celsius. The average humidity level is observed to be 60%. This observation resonates with the routine seasonal change like the temperature peaks during midday hours whereas the humidity is high early morning.These observations were consistent with the patterns observed during diurnal cycle of temperature and humidity fluctuation in urban cities [19]. This is visualized in figure.2.

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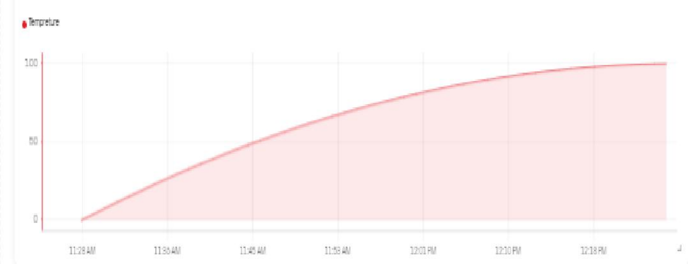

Fig.2. Temperature over time (Source: Author)

Barometric Pressure

The barometric reading has the range between 950 hPa and 1050 hPa. The observed values firmly establish strong correlation between pressure and climate conditions. For instance, after precipitation the dip in atmospheric pressure is observed, validating the existing research [22]. The reading noted by the system is shown in the figure 3 below.

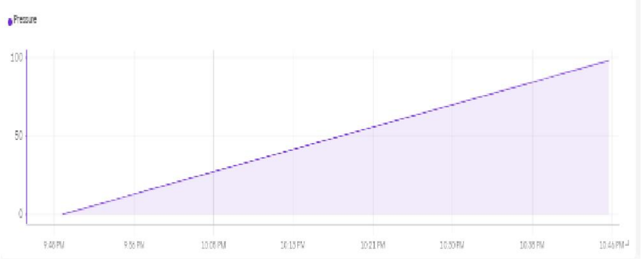

Fig.3. Barometric pressure over time (Source: Author)

Air Quality

The readings of air quality were correctly shown by the MQ135 sensor. The concentration levels got increased during the peak traffic hours in the city. The response to sudden particulate matter spike of the system proves its effectiveness [20]. The figure 4 below depicts the air quality with respect to time.

Fig.4. Air quality over time (Source: Author)

Light Intensity

The range of the reading taken by the LDR module spans from 0 lux to 1000 lux. The highest reading is recorded during afternoon whereas there are very low readings during cloudy or rainy conditions. This observation relates with the dynamics of lights intensity with changing Wheater patterns [21]. The change of light intensity throughout the day is shown in the figure 5 below.

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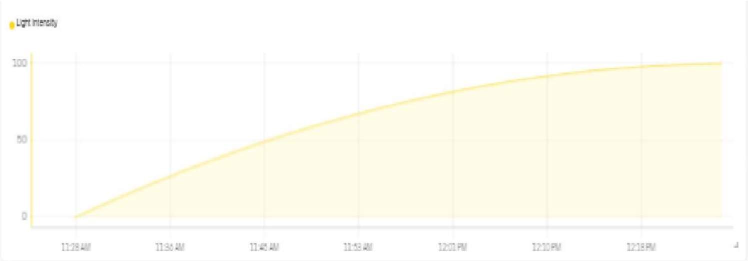

Fig.5. Light intensity over time (Source: Author)

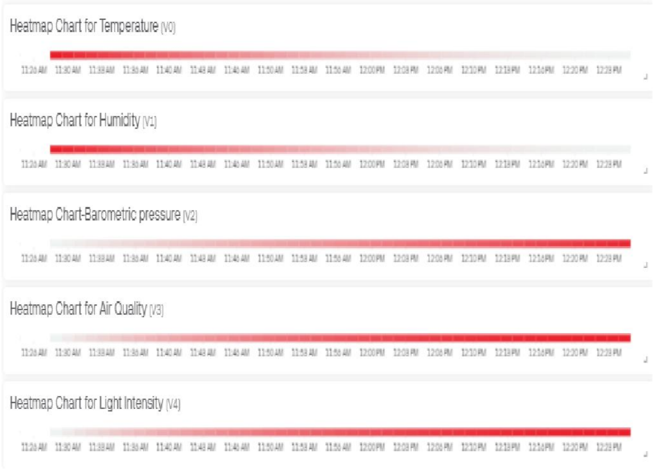

Fig.6. Heatmaps of all parameters (Source: Author)

The heatmap of all the parameters is shown in the figure 6. It clearly proves that the proposed system gives consistent and accurate results. The trend of values is as per the expectations of various researches.

4.2. PARAMETRIC EVALUATION

Accuracy Analysis

Each sensor's accuracy was checked with standard reference measurements. For, DHT22, the maximum deviation turns out as ±0.5 degree Celsius for temperature whereas ±2% for humidity under controlled conditions. The pressure sensor BMP180 showed measurement accuracy within ±1 hPa. The air quality sensor MQ135 was sensitive to various gases which was confirmed by calibrating against known concentrations [23].

Error Analysis

The drift over is a potential source of error. This happens due to prolonged use and environmental interferences like winds or direct sunlight that affects the readings. This issue gets solved by calibration procedures but still discrepancies are observed due to rapid environmental change or system placement.

Latency & Response Time

The system testing revealed an average latency of 1 second, when the data is transmitted from the sensors to the cloud interface. This is consistent with the other IOT based application that use similar microcontroller [24].

Power Consumption

The ESP-32 based system exhibited very low power consumption. The average consumption in active transmission is 160mA whereas in deep sleep mode, it is as low as 10µA. This is one of the important feature of the system as it make the system reliable for sustainable deployment in remote areas where there is limited power supply [21].

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4.3. LIMITATIONS

The proposed system has very minimal limitations. The sensor drift was observed as sensors like DHT22 displayed inaccuracies after prolonged exposure to the environmental factors. Particularly in remote areas with limited access to the internet, the WI-FI connectivity issue persists, which affects the real-time data retrieval process. Lastly, the variability in air quality and light intensity can be observed due to environmental factors like construction activities and seasonal change, indeed affecting the local Wheater patterns.

4.4. FUTURE APPLICATION

Considering the versatile nature of the proposed system, it has wide spectrum of application but some of the prominent applications are listed below.

- Smart Cities: There could be better city planning and management if the system is integrated with urban infrastructure.
- Agriculture: Irrigation schedules can be optimized by monitoring various environmental parameters and help the farmers in precision agriculture.
- Pollution Monitoring: The system is an cost effective option for continuous monitoring of the air quality for schools, homes, colleges etc.
- Climate Change Studies:With predictive analytics, various trends and patterns can be observed indeed helping in research.
- Disaster Management: The sudden and abrupt changes in Wheater can be tracked by continuous monitoring systems, hence aiding in disaster forecasting and mitigation.

There is innumerable scope for future enhancements. The system could be integrated with AI and ML along with database for predictive analytics based on historical readings. Additionally, the solar powered systems and LoRa WAN can be included to get over the connectivity and power dependencies, which would eventually help in remote area deployments. Development to the user side could include development of mobile application and compatible voice assistant for improved accessibility and usability [22] [23].

Hence, the proposed system demonstrates feasibility as well as effectiveness. The system has given expected outcomes, low error rate, low latency and low power consumption. It poses minimal limitations whereas it has wide scope of application. The system not only gives real time monitoring but also open avenues for many future advancements in environmental monitoring technologies.

V. CONCLUSION

It is a possibility to develop and deploy an ESP32-WROOM-32-based system for an intelligent weather station that is IoT-capable and can surpass the limitations of typical weather observation systems. The goals outlined in the introduction, for example, designing a low-cost real-time system with remote monitoring, were achieved satisfactorily. The system employed sensors of various kinds—temperature and humidity sensing by DHT22, pressure sensing by BMP180, sensing of air quality by MQ135, and sensing of light intensity by an LDR module under a single set of sensors as end-to-end environmental sensing. The measurements of the system guaranteed that the system was taking environmental measurements successfully.

Temperature and humidity were recorded by the DHT22 sensor with corresponding day-time variation, from the mid-day maximum temperature to dawn maximum humidity. BMP180 sensor logged barometric pressure fluctuation similarly, with corresponding weather activity like rain. MQ135 sensor logged variation of air quality with more pollutants during peak times. LDR module logged constant light intensity reading, corresponding to day-light fluctuation in a day. Heatmap graphical plot of all the parameters verified the system to render constant and stable outputs. Parametric validation of the system verified the system to be zero-latency and power-sustainable. Sensors were sub-optimal with zero or negligible divergence from nominal reference values and were almost zero. 1-second average delay in data transmission to the cloud interface was on par with other IoT systems. ESP32 platform also showed

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improved power consumption with active transmission power consumption of 160mA and 10µA deep sleep mode power, hence ideal for remote installations.

The DHT22 sensor drifted over time while working under normal operating conditions. Real-time data losses should have been anticipated due to low bandwidth rural connectivity Wi-Fi interference. Environmental priorities, such as seasonal variances, construction, and other activities, were factors incorporated into the air quality and air quality variation light intensity readings. However, its applicability potential is great. Usage towards supporting smart city technologies have potentials to create through reporting information relating to city development priorities in all expression, enabling city governance capacities and smart solutions. It has possibilities in use for automated irrigation system and its use in exact agriculture farming practices. Its low-cost rendering suits a powerful alternative for real-time air quality monitoring in housing and schools. Future development will include the feasibility of anticipating using AI and machine learning from historical data for prediction of environmental and weather conditions. In addition, using solar energy and ultimately creating a LoRaWAN connectivity would allow for energy-efficient use for rural communities. The development and integration with a mobile app and voice assistant would also assist with usability and other functions needed.

overall, it succeeded in prototyping and building an IoT-based intelligent weather station and proving its efficiency and feasibility to monitor the environment in real-time. It is a technological innovation in environmental monitoring since it possesses a low rate of error, latency, and power consumption, and possesses excellent potential applications. Its potential will even be increased and maximized further by sustained improvement in connectivity, power efficiency, and data processing.

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