MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/

IoT-enabled Smart Weather Stations: Innovations, Challenges, and Future Directions

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KEYWORDS

Weather Station
Internet of Things
Renewable Energy
LoRa Technology
Sensors

ARTICLE HISTORY

Received 15 March 2024
Received in revised form 23 March 2024
Accepted 27 March 2024
Available online 8 April 2024

ABSTRACT

The evolution of the Internet of Things (IoT) has ushered in innovative approaches facilitated by breakthrough technologies. This paper presents a comprehensive review of recent advancements in smart weather stations, focusing on IoT-enabled solutions. The integration of Internet of Things (IoT) technologies has revolutionized traditional weather monitoring systems, enabling seamless data collection, analysis, and dissemination. Commercially available automated weather stations offer cost-effective solutions for comprehensive meteorological data collection. However, challenges such as limited local deployment and reliance on expensive options persist, hindering comprehensive monitoring efforts. The critical need for improved data collection methods is underscored to enhance the accuracy of weather forecasts and address evolving climatic conditions. Climate change impacts, including shifts in weather patterns and rising temperatures, highlight the importance of effective weather monitoring for agriculture, infrastructure, and national security. Additionally, the dependence on non-renewable energy sources for electricity generation emphasizes the environmental and economic implications of energy production. In response to these challenges, numerous IoT based smart weather station systems have been proposed by earlier researchers. The introduction of IoT-enabled smart weather stations represents a significant advancement in weather monitoring technology. These stations leverage IoT technologies to collect, analyse, and visualize meteorological data in real time. In order to identify the challenges and prospects in this area of technology, the purpose of this study is to present a thorough analysis of the suggested designs as well as to compare, evaluate, and assess the outcomes, contributing to the development of robust and efficient weather monitoring systems.

1. INTRODUCTION

The Internet of Things (IoT) is a fast-changing landscape, and innovative approaches with wide-ranging effects have been made possible by the confluence of breakthrough technologies in various field such as in home security [1-2], smart classroom [3-5], environment monitoring [6-12], natural disaster monitoring [13], smart manufacturing [14], smart microgrid [15-18], and others. One of the aspects is the implementation of IoT is in smart monitoring of weather conditions for weather forecasting in weather stations. In the weather station design, the integration of Low Range Wide Area Network (LoraWAN) technology and solar power not only enhances the efficiency

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https://doi.org/10.56532/mjsat.v4i2.293

and autonomy of the weather station but also aligns with the global pursuit of sustainable and eco-friendly IoT solutions. The Internet of Things (IoT) is a network of smoothly communicating, interconnected gadgets that gather and share data, providing previously unattainable opportunities for automation and decision-making in real time [1,4,8,9]. Lora WAN is the preferred communication protocol because of its extensive coverage as well as low power consumption [1]. The weather station can work well and have a longer battery life thanks to this technology, which is essential for continued operation in isolated or off-grid areas. Solar energy has been selected as the main energy source for weather station, highlighting its dedication to environmental sustainability [13]. The weather station may become independent and self-sufficient by using solar energy, which also lessens its environmental impact and decreases its reliance on conventional sources of power. This integration is in line with international initiatives to switch to more sustainable and clean energy sources.

The scalability, environmental friendliness, and dependability of solar energy highlight its importance in Internet of Things applications [1]. The weather station can function constantly by using solar power even in places where accessibility to conventional power systems is restricted. This feature not only makes the station more reliable, but it also advances the larger goal of building IoT infrastructure that is robust and sustainable. There were numerous smart weather station systems proposed by different researchers. Hence, this paper aims is to review various different smart weather station systems that comprised of sensors and communication module in order to measure and monitor meteorological parameters and provide GUI layout for the result obtained as well as to discuss the challenges and prospect in this field of technology.

2. PREVIOUS WORKS

The project in [19] utilizes an Atmega328p microcontroller to collect data from sensors and employs LoRa communication for wireless transmission from a transmitter to a receiver. An ESP32 Wi-Fi module facilitates the display of transmitted data on a web application, allowing 22 user access. The system incorporates a LoRa shield as a node, sending data to a LoRa gateway for further processing. Leveraging LoRa's long-range capabilities (up to 10 km) and low power consumption, the system ensures extended device lifespan. The NodeMCU connects LoRa to the cloud, storing data digitally within the web application for different days. The transmitted data includes parameter levels, organized into frames with corresponding physical locations, establishing an efficient and comprehensive IoT-based data collection, transmission, and storage system.

The experiment in [20] focuses on studying the effects of global warming by monitoring physical variables like temperature, pressure, light intensity, heat, CO2 concentration, ozone concentration, and humidity. Sensors connected to an Arduino-based IoT system collect data, which is transmitted wirelessly using LoRa. The LoRa module connects to a LoRaWAN Gateway and then to the internet. A Raspberry Pi 3 B+ reads and visualizes the data using Network Thing, and the information is analysed on a PC. The system provides students with easily accessible and visually appealing outputs on a computer monitor, enhancing the learning experience.

The weather monitoring system project in [21] is an IoT device built on the Arduino IDE. Sensors including BMP180, light sensor, and raindrop sensor module are connected to an Arduino Nano, which processes and transmits the collected data. The Arduino Nano is equipped with a LoRa module and an inbuilt Wi-Fi module for ESP32. After making the connections, the Arduino Nano is programmed to transmit information to a web server where data on pressure, altitude, temperature, light intensity, and rainfall can be monitored. A LED on the board indicates rainfall. The hardware, while not extensive, is highlighted by the use of ESP32 and Arduino Nano with eLua firmware for Wi-Fi capabilities. The firmware is based on the Espressif NON-OS SDK and utilizes a file system based on spiffs.

The study [22] was conducted in Unsoed Electrical Engineering Laboratory in Purbalingga, Central Java. A laptop, the Arduino software (IDE), the Proteus software, the ThingSpeak web, a multimeter, a thermometer, a hygrometer, a barometer, and a digital anemometer were among the tools used as shown in Fig 4. Components including the LoRa gateway LG01 915 MHz, LoRa shield 915 MHz, Arduino UNO Rev3, power bank, raindrop sensor, anemometer sensor, DHT11, BMP180, jumper cables, PCB boards, and USB connectors were used in the experimental setup. With both components running at a frequency of 915 MHz, the system design emphasised the function of the LoRa shield as a node transmitting data to the LoRa gateway. During the implementation phase, sensors and LoRa nodes were designed, the LoRa gateway was built, the upload procedure to the ThingSpeak cloud server was configured, and the Arduino UNO and LoRa shield were designed as LoRa nodes. To guarantee that sensor data was displayed accurately on the cloud server, changes were made to ThingSpeak's source code and settings.

The proposed LoRa-based weather monitoring system in [23] comprises cost-effective weather stations strategically deployed across diverse locations within a large agricultural field, collaboratively observing meteorological conditions. Illustrated in Fig 1, the system model adheres to the LoRa network architecture, wherein each weather station serves as an end device autonomously collecting meteorological data. These weather stations transmit their collected data to a network server via gateways. Notably, the LoRaWAN specification accommodates the utilization of multiple gateways, each capable of receiving messages from any end device within its range. The gateways play a pivotal role by aggregating data packets 25 from the dispersed weather stations and subsequently forwarding them to the network server through an IP connection. This decentralized and scalable architecture ensures comprehensive coverage, efficient data transmission, and centralized processing for informed decision-making in agricultural management based on real-time meteorological insights.

The low-cost weather monitoring station in [24] uses affordable components and on-board Wi-Fi to transmit real-time weather data from the measurement location to a remote access point. A custom web application allows users to monitor the data on various devices. The Raspberry Pi 3 Model B serves as the central component, functioning as both the data logging unit and sensor interface for parameters like wind speed, wind direction, rain, air temperature, humidity, atmospheric pressure, and solar radiation. The station records continuous weather data, storing it in a micro-SD memory card and transferring it to a database server. Users can access the stored data in real time through the web application, ensuring fast data transfer and direct communication with the weather monitoring station.

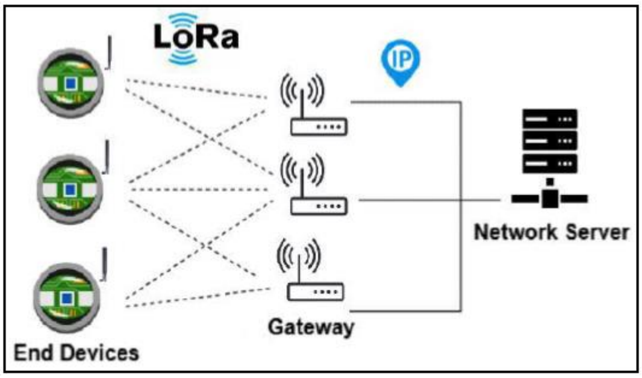

Fig. 1. System model of the agricultural weather monitoring [23]

This IoT based climate checking framework in [25] is created utilizing incredible advancement stage Raspberry Pi board as illustrated in Fig 2. Raspberry Pi board is useful to limit the framework equipment. So here in this undertaking utilization of any outside microcontroller, ADC and correspondence module is kept away from. This framework utilizes temperature and humidity sensor DHT11, light intensity sensor (LDR), rainwater level measuring sensor created utilizing checked scale with ULN2803, pressure and altitude sensor (BMP180). This load of sensors is interfaced with GPIO header of Raspberry Pi board. To get constant checking of information from sensors Ethernet network is utilized.

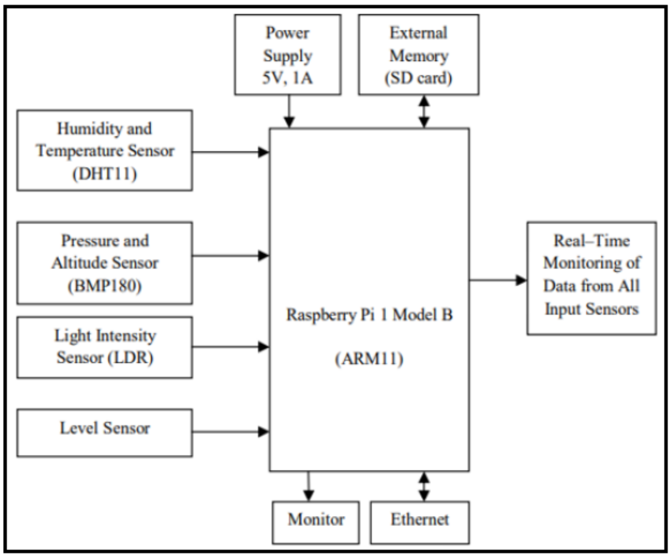

Fig. 2. Block diagram of complete system [25]

The automated weather station in [26] comprises a thermometer, an anemometer, a wind vane, a LDR, and a microcontroller as shown in Fig 3. These components are interconnected, with the thermometer measuring temperature, the anemometer measuring wind speed, and the LDR determining sunlight intensity. The microcontroller serves as the central unit, converting analog signals from the sensors to digital format using its embedded Analog-to-Digital Converter. The weather data is stored in the Erasable Programmable Read Only Memory (EPROM) on the microcontroller, capable of retaining information during power interruptions. Additionally, a GSM module is connected to enable remote weather monitoring.

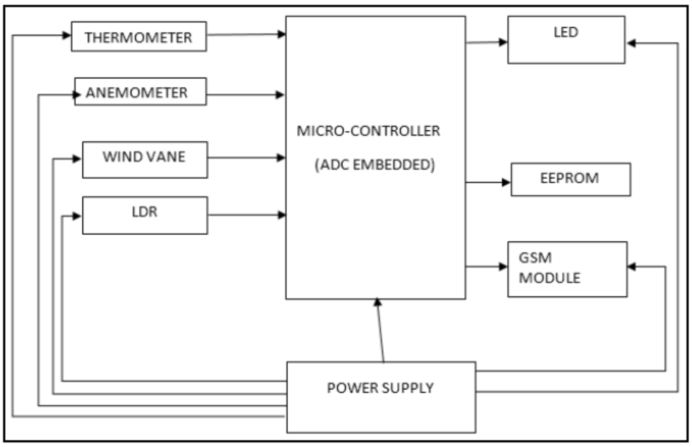

Fig. 3. Block Diagram of Automated Weather Station [26]

The University of Colombo developed an automated weather station [27] featuring built-in data logging and USB communication. In the study, wireless technology, specifically 802.11 b/g Wi-Fi, was chosen for its economic and technological advantages. The focus on communication method selection cantered on achieving an extensive range of communication, allowing data exchange globally via IP addresses. The chosen Raspberry Pi 3, known for low power consumption and built-in Wi-Fi, aligns with the goal of creating an energy-efficient solution. The study also explored data logger methods on a webpage, emphasizing the importance of presenting sensor data graphically for user-friendly comprehension. To optimize cost, the system utilized free data hosting websites offering cloud space for sensor data, making the system universal and economical.

To detect environmental parameters, the system in [28] integrates both digital and analogue sensors, such as DHT11, BMP180, LDR, and a marked scale with ULN2803. These sensors send their data to a Raspberry Pi, which acts as the base station. As a server, the Raspberry Pi receives input data from the sensors and stores it in text and CSV files. The processed data is subsequently transmitted by the Raspberry Pi using its integrated Wi-Fi capability. The data on the environmental parameters is shown on the receiving end by a laptop that connects to the server. With this configuration, sensor data can be transmitted and monitored in real time, giving the laptop user a clear and comprehensive overview of all measured parameters.

The smart weather station described in [29] combines various hardware components and software algorithms to collect, process, and transmit meteorological data. It employs sensors like BME280 for temperature, humidity, and pressure, an anemometer for wind speed, BH1750 for lighting, and MQ-2 for gas detection. Additionally, it utilizes a microcontroller (PIC18F45K22), RTC module (DS1307), GSM/GPRS module (SIM800l), and LCD display for user interaction. These components communicate using protocols like I2C, SPI, and UART, with power options including DC supply, solar panels, or batteries for versatility. Software-wise, the microcontroller operates with multiple threads managing settings, data acquisition, transfer, and transmission to the ThingSpeak database via HTTP POST requests. Users interact through the LCD display, setting parameters and receiving notifications. Once configured, the station autonomously conducts measurements, displaying progress and sending completion notifications via SMS. Prototype development and testing are done on a protoboard using tools like the Ready for PIC environment to ensure functionality and performance before deployment. Overall, this integrated approach creates a versatile and autonomous smart weather station suitable for various environmental conditions and applications.

The smart weather station in [30] utilizes a comprehensive procedure and methodology to gather, process, and transmit meteorological data effectively. It employs a range of sensors, including the DHT11 for temperature and humidity, a rain sensor for raindrop detection, and the BMP180 for barometric pressure readings. These sensors are connected to an ESP32 microcontroller, which serves as the central processing unit. The ESP32 processes the data from the sensors before transmitting it to the IOTA network via a Wi-Fi module. Additionally, the system utilizes the ThingSpeak cloud-based IoT analytics platform to store, analyse, and visualize sensor data in real-time, providing users with accessible insights into local weather conditions. The hardware prototype is constructed with careful consideration of power supply options, sensor integration, and data transmission protocols to ensure reliability and efficiency. Overall, this system represents a practical and affordable solution for automated weather monitoring, facilitating informed decision-making in various applications such as precision agriculture, disaster management, and environmental monitoring.

The IoT weather station developed by the University of Florida's MistMakers team in [31] employs a systematic approach to gather, process, and transmit meteorological data effectively. Central to its hardware architecture is the Particle Photon Microcontroller Unit (MCU), coupled with the SparkFun Photon Weather Shield for sensor integration. Power is sourced from a solar panel charging a LiPo battery, ensuring uninterrupted operation even in the absence of direct sunlight as demonstrated in Fig 4. Data collected by the weather station is uploaded in real-time via Wi-Fi to the Weather Underground database, with a backup mechanism using Adafruit's SD Card reader in case of Wi-Fi connectivity issues. Additionally, the system incorporates an external watchdog timer to monitor the MCU's functionality and reset it if any anomalies are detected. The packaging and assembly of the weather station prioritize durability and water resistance, enhancing its robustness in outdoor environments. The second-generation design further refines the system by integrating existing boards, improving sensor connectivity, and introducing features like compatibility with Xenon and Argon for mesh networking capabilities. Careful PCB design and testing procedures ensure the functionality and reliability of the weather station, addressing challenges such as sensor connectivity issues and voltage compatibility. Overall, this approach emphasizes modularity, reliability, and resilience, making the IoT weather station suitable for real-world deployment in various environmental conditions.

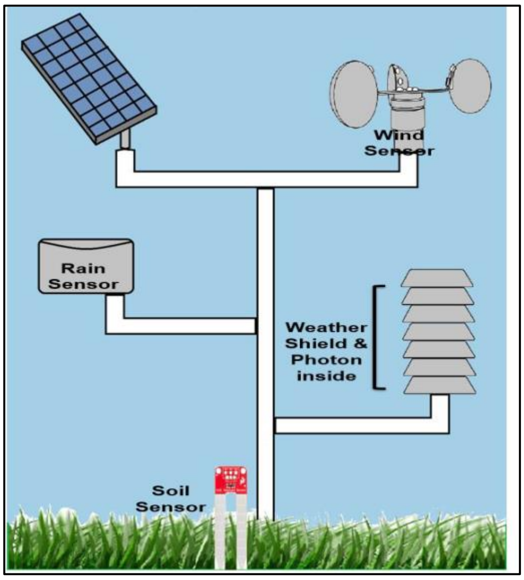

Fig. 4. Full Weather Station Design [31]

The weather station system in [32] encompasses both hardware and software implementations to gather and transmit meteorological data. In the hardware implementation, components such as Arduino Uno microcontroller boards, ZigBee circuits, and various sensors including wind speed, barometric pressure, rain, dust, and temperature/humidity are utilized. These components are chosen for their compatibility, reliability, and cost-effectiveness. The Arduino Uno serves as the central processing unit, while ZigBee technology facilitates wireless communication between the transmitter and receiver nodes. The software implementation involves programming the Arduino microcontrollers using the Arduino C programming language. Once programmed, the microcontrollers transmit data serially to the ZigBee modules for communication. The system's operation is depicted in a flowchart, outlining the process from data collection to transmission via ZigBee technology. The experimental evaluation involves testing the weather station system with Arduino Uno and ZigBee technology, validating its functionality and performance. Through this systematic approach, the weather station system demonstrates its capability to collect and transmit meteorological data effectively, offering a low-cost solution for weather monitoring applications.

The proposed weather watch system in [33] is designed to provide accurate and cost-effective monitoring of various weather parameters, particularly for assessing conditions relevant to solar plant operations. Utilizing a combination of sensors including the DHT22 for temperature and humidity, air pressure sensor for wind speed measurement, LDR for light intensity, and rain sensor, the system aims to capture crucial environmental data. Additionally, current and potential sensors are incorporated to assess the overall performance of the solar plant. These sensors are connected to an Arduino Uno microcontroller, which processes the data and transmits it to a cloud server via a WIFI transmitter. Key considerations in the system's design include accuracy, power efficiency, and durability to ensure reliable operation in diverse weather conditions. By employing a blend of economical sensors and sophisticated data processing techniques, the system offers a practical solution for monitoring weather conditions pertinent to solar plant management.

The implemented IoT-based system in [34] utilizes a microcontroller, LPC2138, as its main processing unit, which interacts with various sensors and devices. The system's architecture involves retrieving data from sensors such as temperature, humidity, wind direction, wind speed, and rain quantity sensors, which are connected to the microcontroller. The LPC2138 employs a 128-bit wide memory interface and a unique accelerator architecture for efficient 32-bit code execution. It processes the sensor data and utilizes a GPRS module, SIM800L, to transmit the analyzed data to the internet. The SIM800L module operates on quad-band GSM/GPRS frequencies and supports various coding schemes, ensuring reliable data transmission. Notably, the system leverages power-saving techniques to minimize current consumption during operation, facilitating long-term deployment. Overall, this system provides a robust framework for real-time monitoring and analysis of environmental parameters, crucial for applications ranging from weather forecasting to agriculture and beyond.

The weather monitoring system in [35] employs a transmitter-receiver architecture utilizing Arduino microcontrollers for data collection and transmission. The transmitter, positioned outdoors, integrates multiple sensors including DHT22 for temperature and humidity, BMP180 for air pressure, QS-FS for wind speed, and a rain gauge for rainfall measurement. These sensors collect data which is then transmitted wirelessly to the receiver located indoors. The receiver, equipped with an Ethernet Shield, processes the incoming data, sending it to a database via the internet. Additionally, the system utilizes a real-time clock module and a piezo-buzzer for alarm functionality. Software-wise, Arduino IDE is used for coding the microcontrollers, with data being stored in a MySQL database and made accessible online through Xampp. The system also leverages social media platforms like Twitter and Facebook for weather updates. The transmitter's process flow involves data validation, classification of rainfall, calibration for wind speed and humidity, conversion of rainfall counts to rate, determination of weather conditions, and updating time and date before sending data to the receiver. This comprehensive approach enables real-time monitoring and dissemination of weather data, crucial for various applications including agriculture, disaster management, and urban planning.

The methodology employed in [36] weather monitoring system utilizes a Raspberry Pi 3 microcomputer along with DHT11 and BMP280 sensors for collecting temperature, humidity, and air pressure data as shown in Fig 5. The Raspberry Pi 3 is chosen for its affordability, numerous GPIO pins for sensor interfacing, and robust processing capabilities. The DHT11 sensor provides cost-effective yet accurate measurements of temperature and humidity, while the BMP280 sensor from Bosch offers precise readings of barometric pressure and temperature. Data collected by these sensors are transmitted to the uBeac IoT platform through the Raspberry Pi's GPIO pins, where cloud-based services facilitate data visualization and analysis. uBeac enables users to access organized weather data for quick interpretation, enhancing decision-making processes. Furthermore, the platform supports integration with various sensors and allows centralized monitoring of multiple weather monitoring systems through a single dashboard, enhancing scalability and efficiency in weather monitoring applications.

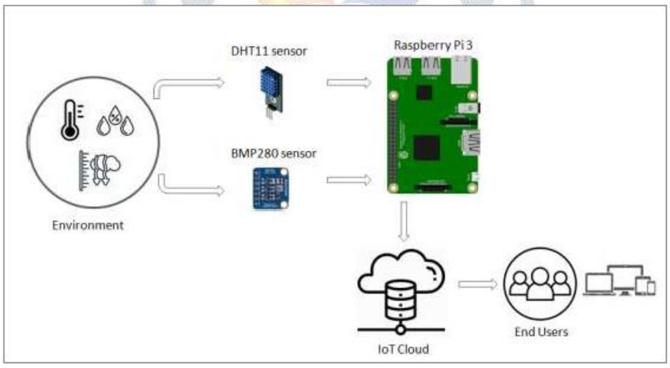

Fig. 5. System Architecture [36]

The methodology for constructing the weather station module in [37] involves several key steps. Firstly, the parameters to be monitored are identified, and an appropriate API service is selected to acquire accurate data from the internet. Then, the necessary components, including the NodeMCU ESP8266 microcontroller, the 128*64 OLED display, a mini breadboard, jumper wires, and a power supply, are gathered as per the circuit diagram requirements. Using the Arduino IDE, the ESP8266 board is coded to collect data from the sensors and display it on the OLED display. The NodeMCU ESP8266 is connected to Wi-Fi to enable data transmission. The components are assembled on the mini breadboard, following the circuit design, which involves connecting the pins of the OLED display to the ESP8266. Once the hardware setup is complete, the program code is uploaded to the ESP8266 board. The code includes configurations for Wi-Fi connection, API integration, and data display on the OLED screen. The system then functions to collect atmospheric data, such as temperature and humidity, and displays it in real-time on the OLED display. Additionally, the system can be utilized as a digital clock or a weather forecasting module, enhancing its versatility and practical applications.

The project in [38] aimed to develop a solar-powered smart weather monitoring and alert system that could be remotely controlled and monitored via a GSM network. Conducted at the Faculty of Technology, Southeastern University in 2021, the system utilized various sensors to measure real-time weather parameters, including temperature, humidity, rainfall, wind speed, wind direction, pressure, light, and CO2 levels. The hardware components comprised an Arduino Uno microcontroller, sensors (such as DHT11 for temperature and humidity, FC37 rain drop sensor for rainfall detection), I2C liquid crystal display, and GSM900A module. Software requirements included Arduino Uno software for programming and Altium Designer for design purposes. All sensors were connected to the Arduino Uno, which collected data and displayed it on the LCD screen while simultaneously transmitting it to the GSM module. Users could request weather data by sending a predefined message to the GSM module, enabling remote access to real-time weather information. The system operated autonomously, requiring no human intervention, thus offering a fully automated method for weather data monitoring.

The proposed system in [39] is an IoT-based solution for advanced weather monitoring, capable of measuring various parameters such as temperature, humidity, wind speed, light intensity, UV radiation, carbon monoxide levels, soil moisture, and rainfall as shown in Fig 20. The system utilizes sensors like DHT11, Anemometer, LDR, GY8511 solar sensor, MQ7, Hygrometer, ultrasonic sensor, and raindrop sensor to collect real-time data. One of the key features is its compact and portable design, allowing easy installation on rooftops or deployment in remote locations. Moreover, the system operates on low power consumption, enabling integration with solar cells for eco-friendly and long-term monitoring in areas with limited access to power. The collected data is transmitted to a web page for graphical visualization and can be accessed from anywhere globally. Additionally, the system includes an app for providing weather updates and warnings to users. To enhance weather prediction, the system employs Raspberry Pi and an API for data analysis. The hardware requirements include Arduino Uno, Node MCU, various sensors, and middleware languages like C, C++, and Python. Servers with root access, frontend and backend development tools, and databases are also needed for system implementation. The system operates in a 4-tier model, encompassing environment monitoring, sensor devices, data acquisition, decision making, and warning notification. Overall, the proposed system offers numerous advantages such as cost-effectiveness, ease of deployment, remote accessibility, and efficient weather forecasting, benefiting sectors like agriculture and environmental monitoring.

The IoT-enabled weather monitoring system in [40] utilizes a range of sensors and components to measure various weather parameters such as temperature, humidity, light intensity, and rainfall. The system is built around a microcontroller, either an Arduino Uno or an ESP8266, which processes the data collected by the sensors and communicates it over Wi-Fi using the Blynk app as portrayed in Fig 21. The hardware components include sensors like DHT11 for temperature and humidity, BMP180 for pressure, and a rain sensor for detecting rainfall. The system architecture allows for easy deployment and monitoring of local weather conditions in real-time from anywhere via the internet. This setup is valuable for a variety of applications, including agriculture, aviation, and environmental monitoring, providing essential data for informed decision-making and enhancing productivity and safety in various fields.

The proposed weather monitoring system in [41] utilizes a combination of sensors and components to measure various atmospheric parameters such as temperature, pressure, humidity, rainfall, wind speed, and wind direction. These sensors are calibrated to provide accurate readings, and their outputs are processed by a microcontroller. The system employs a transmitter section, consisting of the controller, sensors, and Wi-Fi module, to collect data and transmit it to a main server. The receiving section includes a router, web server, and website, where the data is continuously displayed with a refreshing rate of 10 seconds. The data is stored in a MySQL database and displayed on the website using a PHP script. This system finds applications in agriculture, dam management, trekking, wind energy generation, and logistics, where real-time weather information is crucial for decision-making and operational efficiency. The methodology involves sensor calibration, signal conditioning, data processing, wireless transmission, database management, and web-based display, enabling users to monitor and analyze weather conditions remotely and make informed decisions based on the collected data.

The study in [42] conducted at the Unsoed Electrical Engineering Laboratory focused on implementing a weather monitoring system using LoRa technology. The equipment utilized included a laptop, Arduino software, Proteus software, various sensors such as thermometer, hygrometer, barometer, and digital anemometer, LoRa gateway LG01 915 MHz, LoRa shield 915 MHz, Arduino UNO Rev3, power bank, anemometer sensor, rain drop sensor, DHT11, BMP180, jumper cables, PCB boards, and USB connectors. The system architecture involved using the LoRa shield as a node to send data to the LoRa gateway, which operates at a frequency of 915 MHz. The implementation phase included designing the Arduino UNO and LoRa shield as LoRa nodes, designing the LoRa gateway, designing the sensors and LoRa nodes, and configuring the upload process of data to the ThingSpeak cloud server. This involved adjusting the ThingSpeak source code and configuration to accurately display sensor data. Overall, the methodology involved integrating hardware components, configuring communication protocols, and setting up data transmission to enable remote weather monitoring via the ThingSpeak platform.

The system architecture in [43] comprises hardware, software, and cloud components, designed to enable wireless environmental sensing and data transmission using LoRaWAN technology. The hardware consists of a wireless sensor node composed of a Power Management Unit (PMU), sensing unit, microcontroller unit (MCU), and communication unit. These components work together to collect environmental data, process it, and transmit it to the LoRaWAN gateway. The software, developed using Arduino IDE, plays a crucial role in managing power consumption by putting the MCU and sensors into sleep mode when not in use, thereby optimizing energy efficiency. The LoRaWAN gateway uploads the received data to the cloud platform, The Things Network (TTN), where it can be accessed and analyzed. The hardware prototype utilizes components such as the Sodaq Mbili, Microchip ATmega 1284p MCU, RN2483 LoRaWAN communication module, and various sensors. Deployment involves placing wireless sensor nodes in indoor and outdoor locations, powered by sustainable energy sources like solar panels and batteries, and configuring the LoRaWAN gateway to transmit data to the TTN. This system enables real-time monitoring of environmental parameters and can be deployed for various applications, including environmental research, smart agriculture, and urban monitoring.

The proposed system in [44] is a weather monitoring framework that integrates various sensors connected to a microcontroller (MCU) and communicates via LoRa technology. The system aims to gather real-time environmental data such as temperature, humidity, air pressure, dew point, rainfall, and altitude. In this setup, sensors are interfaced with the MCU, which collects the data and sends it to a receiver node via LoRa transmission. The receiver node, comprising an ESP32 and LoRa module, receives the data and transmits it to the web server or Thingspeak platform. This allows users to monitor weather conditions remotely through a web browser or mobile application. The system is designed to be low-cost, automated, and wireless, making it suitable for applications such as agricultural monitoring, urban planning, and personal weather tracking. The hardware components are enclosed in waterproof enclosures to protect them from environmental factors like rain. The implementation involves carefully connecting the components using jumper wires and ensuring tight connections to avoid data errors. The gateway node utilizes ESP32 with in-built Wi-Fi capability to transmit data to users via web servers or IoT platforms. Overall, the system facilitates efficient and accurate monitoring of weather conditions in real-time, providing valuable insights for various applications.

The system in [45] entails the development of both software and hardware components, focusing on weather data collection and transmission. The methodology involves several crucial steps: firstly, the creation of a block diagram outlining the input, processing, and output elements of the system, which includes sensors such as the DHT11 and rain sensor, controlled by an Arduino board acting as the project's central controller. The Arduino, along with a LoRa SX1278 module, serves as a transmitter, sending data to an ESP32 receiver. Upon receiving data, the ESP32 processes it and connects to a WiFi network for data uploading to the ThingSpeak application as shown in Fig 27. Schematic diagrams are then constructed using Fritzing software to illustrate the hardware connections, ensuring proper calibration for accurate functionality. This comprehensive approach ensures seamless data collection, transmission, and visualization for monitoring weather conditions effectively.

The system in [46] involves the deployment of a LoRaWAN network for remote data transmission, specifically focusing on weather monitoring using nodes equipped with sensors. The methodology encompasses two primary phases: gateway deployment and node implementation. Gateways, serving as bridges between nodes and network servers, are constructed using Raspberry Pi and Dragino LoRa Shield. Configuration involves setting location, frequency, spreading factor, and other parameters. Nodes, built with Dragino LoRa shields and Arduino UNO boards, are configured to transmit data from sensors such as the DHT11 for temperature, humidity, and luminosity sensing. The nodes are registered on The Things Network (TTN) along with applications, enabling data visualization and analysis as shown in Fig 28. Additionally, security measures such as double AES encryption and duty cycle restrictions ensure data integrity and fair spectrum usage. This comprehensive approach ensures the setup of a robust LoRaWAN network for efficient data transmission and monitoring, with emphasis on simplicity and flexibility in deployment and application.

The experimental setup in [47] involves the deployment of a portable weather monitoring system consisting of various sensors connected to a Weather Shield designed for SparkFun RedBoard or Arduino Uno as shown in Fig 6. The system incorporates sensors for measuring temperature, humidity, barometric pressure, rainfall, wind speed, and wind direction. These sensors are connected to the Weather Shield, which acts as an interface for data collection. The entire setup is powered by a 9V battery for outdoor operation. NodeMCU, an open-source IoT platform, facilitates data communication and enables sharing of sample data with a public channel on the ThingSpeak IoT application and API. The results of the experiment are depicted graphically, showing the variations of temperature, humidity, atmospheric pressure, rainfall, wind speed, and wind direction over time. This methodology enables real-time monitoring of weather conditions using an integrated system that combines hardware sensors, data communication platforms, and visualization tools for analysis and interpretation of the collected data.

Fig. 6. The system’s prototype [47]

The system in [48] aims to develop a weather monitoring system utilizing multiple sensors to continuously observe environmental parameters via Wi-Fi connectivity. The system architecture includes three modes, each representing a different set of sensors: Mode 1 for temperature and humidity sensing using the DHT11 sensor, Mode 2 for barometric pressure measurement using the BMP180 sensor, and Mode 3 for rain detection using a raindrop sensor. These sensors are connected to a NodeMCU, which serves as the gateway for data transmission to a local network and display on a webpage. The hardware setup involves connecting the sensors to the NodeMCU pins and providing power through a USB connection. The system operates by collecting data from the sensors, processing it using Arduino code, and displaying the results on a webpage using HTTP. Verification and uploading of code to the NodeMCU are performed through the Arduino IDE, followed by accessing the results via a web browser using the IP address provided by the system. The final webpage displays temperature, humidity, pressure, and rain values, providing real-time monitoring of weather conditions. This approach offers a simple yet effective method for weather monitoring, leveraging the capabilities of IoT technology and multiple sensors to ensure accurate and reliable data collection.

Henceforth, a comprehensive overview of research pertaining to IoT-enabled Smart Weather Stations has been summarized succinctly in Table 1. This table distils key findings, methodologies, and outcomes from various studies, providing a clear and structured presentation of the collective knowledge in this domain. By condensing the information into a table, readers can easily grasp the breadth of research, compare different approaches, and identify trends or gaps in the current understanding of IoT-enabled smart weather stations. This method of presentation facilitates efficient data comprehension and aids researchers, practitioners, and enthusiasts alike in navigating the complexities of this evolving field.

Table 1. Summary of selected research related to IoT-enabled smart weather stations.

No.	Author (s) & Year	Title of Research Paper	Variables Studied/ Research Design	Equipment/ Instruments/ Apparatus used for Experiments/Analysis/ Characterization, etc.	Important Findings	Limitations of Study
[19]	L. T. Tushar Chaudhari, 2022.	Lora based wireless weather station BRM6919	Parameters measured includes air pressure, temperature, humidity geographical locations. It also shows wireless transmission using LoRa and user-visible information on the website	Atmega328p, LoRa ,ESP-32, NodeMCU	The system leverages LoRa's long-range capabilities (up to 10 km) and low power consumption, which is crucial for establishing an efficient and comprehensive IoT-based data collection, transmission, and storage system.	Dependency on LoRa Network, high ESP32 power consumption and prototype susceptible to weather impact on wireless transmission.
[20]	I. Putra, et al, 2020.	Utilizing LoRa for IoT based mini weather station	Parameters measured includes temperature, pressure, light intensity, heat, CO2 concentration, ozone concentration, and humidity	Sensors, Arduino, LoRa module and gateway.	Primary focus on studying the effects of global warming.	Sensor accuracy and calibration, power source dependency, limited geographical range, and susceptible to weather conditions impact.
[21]	[21] R. Sai Manasa, et al, 2023.	LoRa based Wireless Weather Station with WebServer,	Parameters measured includes light intensity, rain drop heat, pressure, altitude, temperature, with rainfall indicator.	Arduino Nano, ESP32, LoRa module, BMP180 light sensor, raindrop sensor module, eLua firmware (for Wi-Fi capabilities), Espressif NON-OS SDK-based firmware, SPIFFS (File system based on spiffs).	The project's central focus is on creating a wireless weather monitoring system using LoRa technology. Sensor data from BMP180, a light sensor, and a raindrop sensor connected to an Arduino Nano is transmitted to a web server. The integration of ESP32 with built-in Wi-Fi, along with the use of eLua firmware, enhances connectivity, enabling remote monitoring of key weather parameters like pressure, altitude, temperature, light intensity, and rainfall.	Limited Sensor Variety, having a single LED for rainfall indication, provides binary rain/no rain information and lacks the ability to quantify rainfall intensity.
[22]	Eko Murdyantoro, et al, 2019.	Prototype weather station uses LoRa wireless connectivity infrastructure.	Parameters measured includes temperature, humidity, wind speed, Rainfall, atmospheric pressure and altitude.	Arduino, thermometer, hygrometer, barometer, digital anemometer	The project successfully implementation of a prototype weather station using LoRa wireless connectivity infrastructure with the standardize measurement apparatus.	Frequency of constant sensing limitation and power source dependency.
[23]	H. Soy And Y. Dilay, 2021.	A Conceptual Design of LoRa based Weather Monitoring System for Smart Farming	Parameters measured includes temperature, humidity, rainfall, wind speed, wind direction, and atmospheric pressure.	Microcontroller network server, LoRaWAN, and sensors:	The most important aspect of this project is the development of a decentralized and scalable LoRa-based weather monitoring system. This system involves strategically deploying cost-effective weather stations across diverse locations within a large agricultural field.	The effective range of the LoRa network may be limited, affecting the coverage of the weather monitoring system. Interference from other devices or environmental factors could impact the reliability of data transmission. Power consumption of weather stations may be a limitation, especially if they are in remote locations without easy access to power sources.

3. CHALLENGES AND PROSPECTS

IoT-enabled Smart Weather Stations represent a transformative approach to monitoring and predicting weather patterns with unprecedented precision and efficiency. By integrating Internet of Things (IoT) technology into traditional weather monitoring infrastructure, these stations offer a plethora of opportunities to enhance weather forecasting, optimize resource management, and bolster resilience against climate-related challenges. However, amidst these prospects lie significant challenges, ranging from data accuracy and reliability to connectivity issues and sustainability concerns. In this context, exploring the challenges and prospects of IoT-enabled smart weather stations becomes imperative for harnessing their full potential in shaping a more informed, adaptive, and resilient society. Summarise below are the possible challenges and prospects faced in this field:

- Power management: A lot of these systems depend on sensors and microcontrollers, both of which require electricity to function. Effective power management is essential, particularly for systems installed in outdoors or remote locations with restricted access to power sources. Rechargeable batteries and solar panels are popular alternatives, although optimising power use and guaranteeing a steady power supply continue to pose difficulties [49].
- Reliability and range of data transmission: IoT weather monitoring systems frequently need to send data over long distances, particularly in rural or agricultural environments. Wireless communication usually uses LoRa and Wi-Fi technologies. But sustaining low power usage while guaranteeing dependable data transmission over long distances presents difficulties, especially in regions with obstructions or interference.
- Sensor calibration and accuracy: Reliable weather data collection and analysis depend on accurate sensor readings. It might be difficult to calibrate sensors so that accuracy and consistency are guaranteed in a variety of environmental circumstances. To ensure data integrity, factors including signal interference, environmental changes, and sensor drift must be carefully considered.
- Data processing and analysis: Gathering raw sensor data is just the first step; there are further difficulties in processing and analysing the data in order to get insightful conclusions. This entails managing substantial data quantities, putting effective data processing methods into practice, and presenting the data in an understandable manner for decision-making and interpretation.
- Environmental concerns: Temperature extremes, humidity, precipitation, and physical damage from weather events are just a few of the environmental concerns that outside weather monitoring systems have to deal with. One of the biggest challenges in hardware design is creating weatherproof enclosures and robust devices that can survive extreme environmental conditions without losing functionality.
- Cost and affordability: One of the biggest challenges in creating scalable, dependable IoT weather monitoring systems is keeping them affordable. It takes considerable thought and optimisation to strike a balance between the cost of physical parts, communication technologies, and continuous maintenance and the usefulness and efficiency of the system.
- Integration with artificial intelligence and machine learning: In the realm of IoT-enabled smart weather stations, future advancements can be propelled by a synergistic integration of artificial intelligence (AI) and machine learning (ML) techniques [50]. Firstly, developing ML algorithms to dynamically optimize sensor calibration and data fusion processes can enhance the accuracy and reliability of weather data collected by these stations. Additionally, AI-driven predictive models can be employed to anticipate weather patterns more effectively, enabling timely and precise forecasts. Furthermore, leveraging ML algorithms for data analytics can unveil hidden insights from vast volumes of weather data, facilitating the discovery of complex relationships and patterns that may enhance our understanding of meteorological phenomena. Moreover, implementing AI-based anomaly detection mechanisms can automatically identify and mitigate data anomalies, ensuring data quality and integrity. Additionally, exploring reinforcement learning techniques to optimize the energy consumption and operational efficiency of these stations could lead to more sustainable and cost-effective deployments. Lastly, there is a need to investigate federated learning approaches to enable collaborative model training across distributed networks of Smart Weather Stations while preserving data privacy and security. By embracing the fusion of AI and ML technologies, IoT-enabled Smart Weather Stations can evolve into intelligent systems capable of delivering more accurate forecasts, enhancing resilience, and facilitating informed decision-making in various sectors, including agriculture, transportation, and disaster management.
- Integration with advanced IoT technology: For the advancement of IoT-enabled Smart Weather Stations, future efforts should focus on integrating advanced IoT technologies to enhance their capabilities [51-52]. Firstly, exploring the potential of edge computing can enable real-time data processing and analysis directly at the sensor nodes, reducing latency and improving responsiveness. Additionally, incorporating advanced wireless communication protocols such as 5G or LoRaWAN can enhance data transmission efficiency and reliability, especially in remote or harsh environments. Furthermore, integrating sensor fusion techniques can combine data from multiple sensors to provide more comprehensive and accurate weather observations. Moreover, implementing self-configuring and self-healing network architectures can enhance the scalability and resilience of IoT-enabled Smart Weather Stations, ensuring uninterrupted operation even in the face of network disruptions or component failures. Additionally, leveraging blockchain technology can enhance data security and integrity, enabling trustworthy sharing and exchange of weather data among multiple stakeholders. Furthermore, exploring the integration of renewable energy sources and energy harvesting techniques can enhance the sustainability and autonomy of these stations, reducing their dependency on external power sources. Lastly, there is a need to explore the integration of advanced sensors and actuators, such as

hyperspectral imaging or drone-based sensors, to expand the range of weather parameters that can be monitored and analysed. By embracing these advanced IoT technologies, Smart Weather Stations can evolve into highly capable, resilient, and adaptable systems, empowering various industries with actionable insights for better decision-making and resource management in the face of dynamic weather conditions.

4. CONCLUSION

The collection of publications provided presents a wide range of strategies and techniques for creating weather monitoring systems that make use of Internet of Things technology. Every research addresses different elements including power management, sensor integration, data transmission, and user interface, and provides insightful information about the design, implementation, and usage of these systems. The potential for these publications to improve weather monitoring capabilities in several fields, such as environmental research, disaster management, urban planning, and agricultural, presents opportunities. Real-time data gathering and remote accessibility are made possible by the deployment of IoT, which improves decision-making and makes it easier to take preventative action in response to changing weather conditions. Additionally, the use of open-source platforms and inexpensive components highlights how accessible and affordable these systems are, making them appropriate for a variety of uses. These weather monitoring systems' usefulness and feasibility are further increased by factors like power efficiency, real-time data visualisation, and remote accessibility.

All things considered, these publications offer insightful information and useful techniques for creating and putting into use smart weather monitoring systems that have a great deal of potential for real-world application and social impact.

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