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Smart Environmental Solutions: Integrating IoT for Environmental Health and Sustainability

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Abstract

This research introduces an IoT-enabled environmental monitoring device designed for real-time measurement of pollutants and critical environmental parameters. Integrated with multiple sensors and an ESP32 system-on-chip (SoC) development board, the device transmits data via Wi-Fi, facilitating remote monitoring and reporting. It monitors pollutants like ozone, methane, carbon monoxide, and hydrogen gas, and tracks atmospheric pressure, humidity, cloud cover, and light intensity, providing insights into weather patterns, climate change trends, and ecosystem impacts. Real-time data visualization and storage support early disaster warning systems and regulatory compliance. The device contributes to scientific research by providing data for studying pollution sources, atmospheric chemistry, and climate dynamics. Accessible environmental monitoring data fosters public awareness and education, empowering individuals and communities to advocate for clean air policies and adopt sustainable practices, promoting environmental stewardship and the well-being of current and future generations. Tested with a solar-rechargeable battery, it ensures long-term, uninterrupted usage without human intervention.

Keywords: IoT-enabled environmental monitoring, Real-time pollutant measurement, Environmental stewardship, Public health, Sustainable environment

1. Introduction

The escalating concerns regarding air pollution and its detrimental effects on human health and the environment underscore the urgent need for robust monitoring systems capable of real-time data collection and analysis. The existing literature highlights various research problems that emphasize the necessity of developing cost-effective and efficient air quality monitoring solutions.

Indoor environments, where individuals spend a significant portion of their time, are particularly vulnerable to pollution [1]. Additionally, industrial areas face substantial challenges due to air pollution, necessitating the development of effective purification systems [2]. Current monitoring methods exhibit limitations, emphasizing the need for more effective indoor air quality monitoring systems [3]. Furthermore, even some agricultural specific applications such as home-based mushroom cultivation require automated environmental control and monitoring to enhance yield and quality [4].

In outdoor settings, integrating Wireless Sensor Network (WSN) with High Altitude Platform Station (HAPS) presents a promising approach to overcome the weaknesses of traditional monitoring systems [5]. The advent of smart cities further accentuates the need for IoT-based monitoring systems to address air pollution [6]. Moreover, the rise in car usage underscores the importance of intelligent monitoring systems for public transport to enhance safety and reduce environmental impact [7].

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Given the pressing need to detect and monitor airborne pollution hazards, there is growing interest in developing IoT-enabled systems using protocols like LoRa network to enable remote detection and monitoring [8]. Particularly in remote areas, where access to monitoring infrastructure is limited, there is a critical need for effective monitoring systems [9]. Urbanization and industrial development exacerbate air quality issues, necessitating effective monitoring systems to guide policy-making and mitigate health risks [10].

Conventional monitoring systems often face challenges related to cost, accuracy, and scalability, highlighting the necessity for low-cost and adaptable solutions [11-13]. Integrating advanced technologies such as bidirectional recurrent neural networks (Bi-RNN) with IoT offers potential in enhancing the accuracy of air pollution detection [14]. Moreover, the concept of Smart Cities necessitates user-friendly monitoring systems capable of monitoring various pollutants in real-time [15].

Addressing specific environments like university campuses and urban areas further emphasizes the need for cost-effective and energy-efficient monitoring solutions [16, 17]. The absence of comprehensive real-time monitoring systems exacerbates the air pollution problem, underscoring the urgency for scalable IoT-based solutions [18, 19]. Portable sensory systems capable of real-time monitoring offer a promising avenue for addressing environmental and health concerns caused by air pollution [20].

In this work, we propose the development of a low-cost air pollution monitoring system capable of providing real-time data through wireless Wi-Fi and router connectivity. The system aims to bridge existing gaps in monitoring infrastructure by offering a cost-effective and accessible solution for real-time monitoring and analysis of air quality parameters. Through the integration of IoT technology to enhance public awareness, facilitate proactive measures, and ultimately contribute to the mitigation of air pollution-related risks. Real-time data visualization and storage support early disaster warning systems and regulatory compliance. The device contributes to scientific research by providing data for studying pollution sources, atmospheric chemistry, and climate dynamics. Accessible environmental monitoring data fosters public awareness and education, empowering individuals and communities to advocate for clean air policies and adopt sustainable practices, promoting environmental stewardship and the well-being of current and future generations. Tested with a solar-rechargeable battery, it ensures long-term, uninterrupted usage without human intervention

In the subsequent sections of this paper, we delve deeper into a literature survey in the Current Trend, conceptualization, design considerations and potential applications of the device to the evolving challenges and demands of air quality monitoring.

Current Trend

Numerous approaches have been developed for real-time environmental monitoring. [1] implemented a microcontroller-based system with temperature, humidity, and gas sensors, suitable for field instruments but lacking remote data transfer capabilities. [2] tackled dust contamination in industrial settings using air pumps and filtration for air purification, emphasizing the need for additional monitoring to validate its effectiveness. [3] proposed an indoor air quality monitoring system using IoT technologies for real-time evaluation of parameters such as temperature, humidity, and various pollutants, though modifications are required for outdoor applications. In agricultural contexts, [4] designed an IoT system for mushroom cultivation, integrating sensors for environmental variables and remote access via cloud servers, focusing on optimal growth conditions rather than pollution monitoring.

For broader and wider environmental monitoring, [5] suggested integrating High Altitude Platform Stations (HAPS) with Wireless Sensor Networks (WSN) to leverage the benefits of both terrestrial and satellite communications for extended range and effective data transfer. Similarly, [6] proposed IoT-based devices with

GPS and sensors for assessing gas toxicity levels, addressing pollution from vehicles and fossil fuels, which is essential for developing smart cities. [7] and [8] focused on automobile and networked gas sensor systems, respectively, with [7] integrating sensors to monitor vehicle interior conditions and driver sobriety, and [8] utilizing LoRa protocol for real-time airborne pollution detection, demonstrating high accuracy in identifying volatile organic compounds (VOCs).

Additionally, [9] and [10] highlighted long-range monitoring systems. [9] implemented a system using LoRa and ESP32 microcontroller for remote humidity, temperature, and carbon monoxide monitoring, while [10] introduced Carepol, an IoT-based system for urban CO monitoring, using MEMS technology for scalable, cost-effective sensing stations. Several studies focused on WSNs for air quality monitoring. [11] designed a system with multiple sensor nodes for real-time data collection, and [12] implemented a WSN-based system for detecting pollutants and environmental factors, validated for accuracy and real-time data accessibility. [13] used metal oxide sensors and GPRS for data transmission, validated through field tests for reliability in high-traffic areas.

Advanced data processing techniques were also explored. [14] integrated bidirectional Recurrent Neural Network (RNN) with IoT for pollution forecasting, enhancing detection accuracy through current and historical data analysis. [15] combined multiple sensors into a single platform for environmental monitoring, transmitting data to a central server for real-time access and analysis via an Android application. Finally, [16] developed the DYU Air Box, integrating multiple sensors with ESP32 Wi-Fi for real-time data visualization on a public IoT platform, enhancing campus safety and environmental monitoring.

Despite these advancements, there are notable gaps in the existing literature. Many existing systems, such as those in [1] and [7], focus on specific pollutants or environmental parameters rather than a comprehensive set. Systems tailored for specific applications, like those in [4] and [5], lack versatility for broader environmental monitoring. Furthermore, several studies, including [1] and [8], lack robust remote data transfer capabilities, limiting real-time data accessibility and utility for immediate decision-making. While some systems implement remote data transmission, they often do not emphasize real-time visualization and accessibility for public use and education. Additionally, many solutions are designed for specific environments, such as indoor air quality [3], vehicle interiors [7], or industrial settings [2], and are not easily adaptable to diverse environments like urban, rural, and natural ecosystems. Existing solutions also often rely on traditional power sources, limiting their operational duration and increasing maintenance requirements, as seen in [20]. Finally, few systems integrate advanced analytical tools for predictive insights and public engagement, with notable exceptions like [14].

The proposed IoT-enabled environmental monitoring device addresses these gaps through several innovative features. It integrates multiple sensors to monitor a wide range of pollutants, including ozone, methane, carbon monoxide, and hydrogen gas, as well as critical environmental parameters like atmospheric pressure, humidity, cloud cover, and light intensity. This comprehensive approach fills the gap identified in existing literature that often focuses on limited parameters. Utilizing the ESP32 SoC development board for Wi-Fi data transmission, the device ensures real-time remote monitoring and reporting, enhancing accessibility and utility of the data for immediate decision-making, disaster warning, and regulatory compliance. Designed for adaptability, the device can be deployed in various settings, including urban, rural, and natural environments, providing insights into weather patterns, climate change trends, and ecosystem impacts. This versatility surpasses the narrow focus of many existing systems. Equipped with a solar-rechargeable battery, the device ensures long-term, uninterrupted operation without human intervention, addressing the energy dependency and sustainability issues prevalent in existing solutions. By offering real-time data visualization and storage, the device supports public awareness, education, and engagement. It empowers individuals and communities to advocate for clean air policies and adopt sustainable practices. Additionally, the device contributes valuable data for scientific research on pollution sources, atmospheric chemistry, and climate dynamics, fostering environmental stewardship and the well-being of current and future generations.

The proposed IoT-enabled environmental monitoring device not only fills the significant gaps in current literature but also advances the field by providing a comprehensive, sustainable, and accessible solution for real-time environmental monitoring and public engagement.

2. Methodology

The simplified block diagram of the proposed monitoring system is a shown in Figure 1.

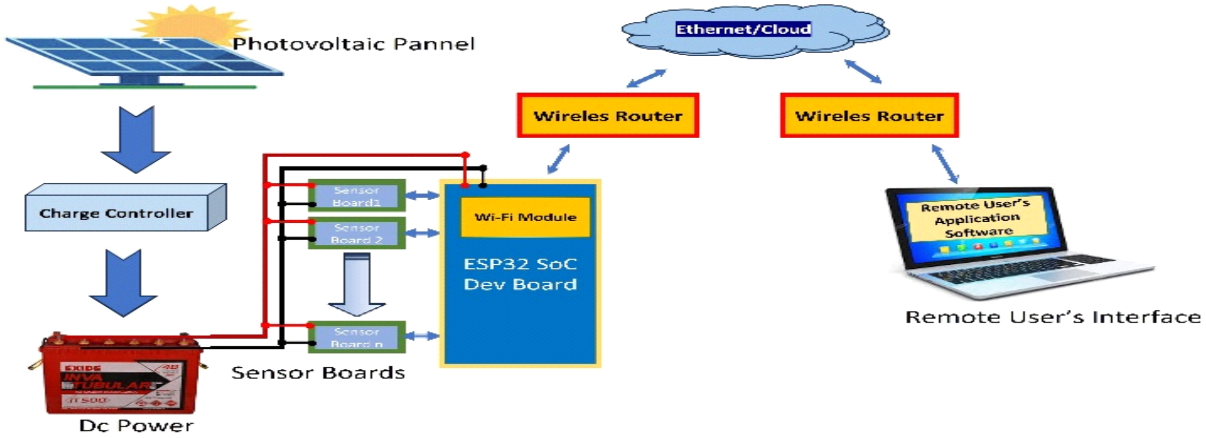

Figure 1: Block Diagram of the Proposed IoT Environmental Health Monitoring System.

The hardware infrastructure centres on the ESP32 Dev Kit, housing the ESP32-S3 system on a chip (SoC). This advanced SoC integrates a 2.4 GHz Wi-Fi and Bluetooth Low Energy (Bluetooth LE) module, coupled with a high-performance dual-core microprocessor (Xtensa 32-bit LX7) and various peripherals. Figure 2 illustrates the functional block diagram of the ESP32-S3 SoC.

Firmware development was executed in C++ using the PlatformIO IDE to program the SoC. This approach facilitated seamless communication via Websocket through the onboard Wi-Fi module, enabling acceptance of control commands from a remote LabVIEW User Interface. Data exchange transpired intranet or ethernet-wise, allowing for real-time data upload and download.

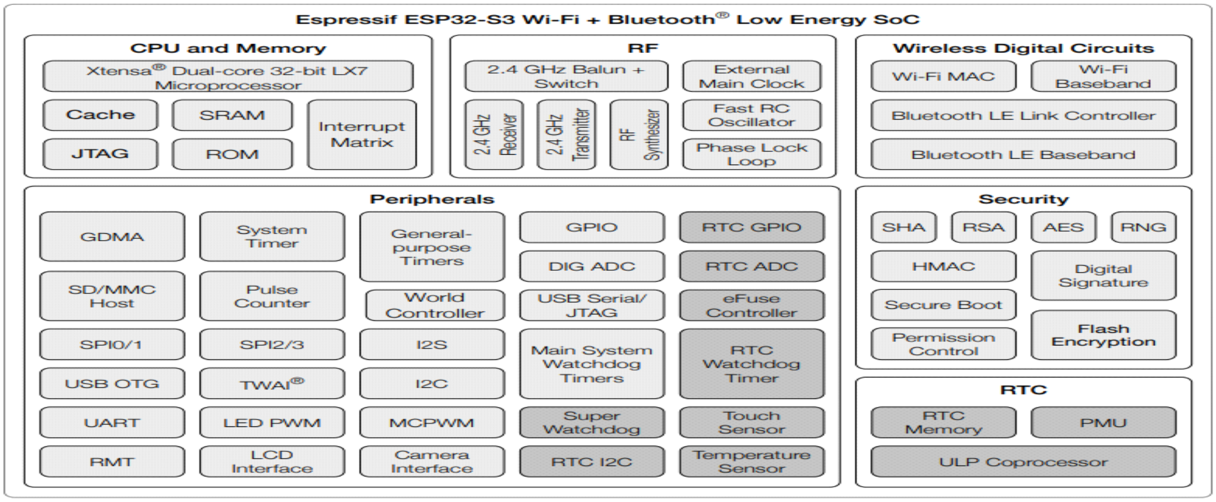

Figure 2: The functional block diagram of the ESP32-S3 SoC (Source:Datasheet,esp32-s3_datasheet_en.pdf espressif.com)

For network stability and reliability, a TP-Link 3G/4G wireless router, TL-MR3420, was configured to reserve an IP Address for the MAC Address of the Wi- Fi module of the Esp32 SoC device thereby bolstering the device connection to the network and ensuring seamless data transmission and remote monitoring.

The LabVIEW remote user interface was meticulously crafted using NI LabVIEW 2022 Q3, operating on Windows 11, to provide intuitive device control, showcase real-time graphs of dose and dose rate, and facilitate data storage and retrieval, among other essential functions. This user-friendly interface significantly enhanced the usability of the IoT air quality monitoring device, enabling storage and real-time visualization of both graphs and instantaneous data values with utmost efficiency.

Firmware development was conducted in C++ using the PlatformIO IDE to program the SoC device. This programming enabled communication via WebSocket through the onboard Wi-Fi module, facilitating control command acceptance from a remote LabVIEW User Interface. Data exchange can occur via intranet or ethernet, enabling real-time data exchange. Additionally, various sensor were interfaced with the microcontroller. These sensor modules include the DHT22 humidity and ambient temperature, MQ131 Ozone gas sensor, MQ5 methane, natural gas sensor, Tsl2561 Light Sensor, MQ9 carbon monoxide gas sensor module, MQ8 Hydrogen Gas sensor module, MQ2 smoke, methane, butane gas sensor ,DHT11 Temperature and humidity sensor module, BMP80 atmospheric pressure sensing module.

A Tp-Link 3G/4G wireless router, TL-MR3420, was configured to reserve an IP Address for the MAC Address of the Wi-Fi module of the IoT Environmental Health Monitoring System, ensuring consistent IP address allocation post for each connection on the subnet. This configuration enhanced the stability and reliability of the device connection to the network, critical for seamless data transmission and remote monitoring.

The LabVIEW remote user interface was developed using NI LabVIEW 2022 Q3, operating on Windows 11, to provide device control, real-time graphs of various air pollutants and other sensor data as well.

3. Results and Discussion

The IoT Environmental Health Monitoring System, integrated with the LabVIEW Remote User Interface (LRUI) (Figure 3), effectively meets its goal of providing real-time data on various environmental factors such as temperature, humidity, pressure, light intensity, and gas concentrations (e.g., ozone, methane, CO). The user-friendly LRUI enhances device usability, enabling real-time monitoring through dynamic graphs, historical data retrieval, and customizable alerts. This functionality supports both research and environmental management.

3.1 System Performance and Scalability

The system updates data at 1 Hz, offering timely insights without overwhelming the platform's processing capacity. The design accommodates future sensor expansions, which would allow the monitoring of additional pollutants like particulate matter. This scalability depends on maintaining compatibility with communication protocols and ensuring adequate power supply from the photovoltaic cell-powered Li-ion battery.

3.2 Comparative Analysis

Compared to systems using HTTP-based data exchanges [6], [12] and [18], our use of Websocket enables efficient, full-duplex data transfer, reducing unnecessary payload and improving real-time performance. Additionally, this system’s ability to monitor multiple parameters simultaneously offers a more comprehensive solution than many existing alternatives.

3.3 Real-World Applications

This system’s versatility extends to industrial, urban, and rural settings. It helps industries monitor emissions, aids city planners with real-time pollution data, and supports farmers by tracking environmental factors affecting agriculture.

4. Conclusion and Recommendations

The IoT Environmental Health Monitoring System, with its real-time data visualization and scalable design, stands out as a powerful tool for environmental monitoring. Future improvements should focus on expanding sensor capabilities, enhancing power management, and integrating predictive analytics to maximize the system’s impact across diverse applications.

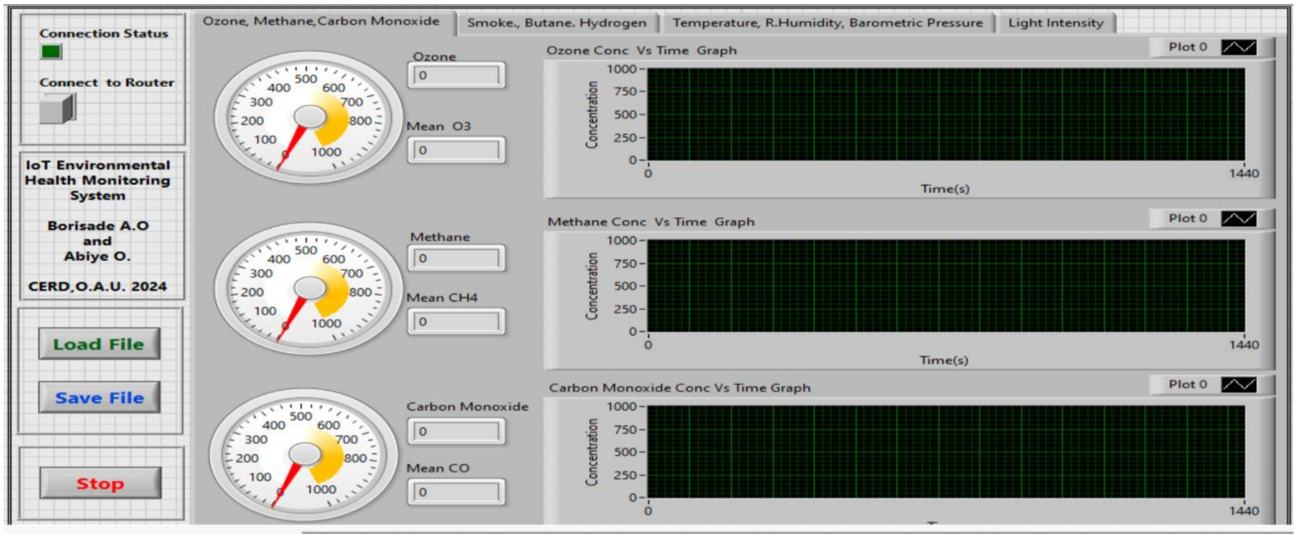

Figure 3. Remote User’s Interface for the Proposed IoT Environmental Health Monitoring System

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