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IoT Based Multi-Parameter Environmental Monitoring System for Smart Cities

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Abstract

In this paper, a cost-effective Internet of Things system for real-time environmental monitoring in smart cities is proposed, which overcomes the limitations that exist in the traditional centralized system. The proposed system is designed to measure the Air Quality Index, Total Dissolved Solids of water, and soil moisture using a BME680 sensor, a TDS sensor, and capacitive sensors, respectively, connected to an ESP32 microcontroller for processing and transmission of data over Wi-Fi to a web interface. This allows public access without the need for any special software and captures the variations in the smart city environment, including the AQI peaks due to traffic. The proposed open-standard system (Wi-Fi, HTTP, JSON) is scalable for smart city implementation and can be extended in the future to include machine learning algorithms for AQI forecasting. Performance analysis of the proposed system using simulated data from Katraj, Pune, shows its sensitivity to both short-term and long-term variations.

Keywords: Internet of Things; Air Quality Index; Total Dissolved Solids; Environmental Monitoring; Smart Cities; ESP32.

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Introduction

Smart city environments are based on the theories of transparency, traceability, and evidence-based decision-making. These theories are imperative in ensuring that the development process occurs without diminishing human health and ecological sustainability. In some rapidly urbanizing areas of India, factors such as traffic corridors, industrial activities, population growth, construction activities, and unorganized disposal of waste contribute to high air pollution, fluctuating water quality, and soil degradation. These trends emphasize the need for continuous environmental monitoring rather than periodic monitoring. The traditional monitoring framework usually depends on centralized laboratories or government-established measurement stations. Although technically sound, these approaches have numerous operational drawbacks. The measurements are usually taken after a considerable amount of time and are processed manually before being made available. For the residents, this means that they have access to up-to-date environmental information that is either delayed or not available at all. The lack of real-time availability of information leads to a situation of information asymmetry, making it difficult for the residents to check on their own the environmental conditions of their dwelling.

Another issue is that the current systems have limited geographical reach. For example, in a city, there may be only one or two AQI stations that can represent the whole area. However, the air quality in areas around highways, markets, schools, industries, and residential areas can be very much different. Therefore, the overall air quality data may not be a reliable source for making decisions at the local level. As a result, citizens are not aware of the changes in the environmental conditions of their surrounding areas. The IoT offers a scalable and economically viable solution to overcome these challenges. IoT allows the deployment of multiple small-scale monitoring nodes, each of which has the capability of sensing, processing, and transmitting real-world data with little human intervention. With the integration of embedded electronics and wireless communication, the IoT acts as an intermediary between physical environmental factors and digital analytical platforms. The distributed nature of IoT devices ensures that data acquisition takes place at the source, thus eliminating the need for central installations. This feature is particularly useful in the development of smart cities, where economic viability may not support large-scale solutions.

The data from the sensors is collected at regular intervals, and the readings are calibrated to minimize errors. The readings are then converted to units that can be interpreted. The ESP32 package encapsulates the data in a JSON message and sends it to an online interface using HTTP communication. The online interface is the human-machine interface and allows users to access the data from any device connected to the internet. This system does not require any specialized software or technical knowledge, making it accessible to the public.

The current architecture uses simulated data on a weekly basis for Katraj, Pune, as there was an incomplete physical setup at the time of the reporting. The simulated data is realistic in the sense that it follows actual patterns, such as high air quality index (AQI) values during peak traffic hours, variations in total dissolved solids (TDS) values based on variations in municipal water supplies and irregularities in soil moisture values based on irrigation patterns or climatic variations.

The goal of the system is not only to provide basic environmental data but also to provide a basis for data-informed awareness, policy, and potentially automated response actions. If implemented on a larger scale, a network of such IoT nodes could help with environmental mapping at high resolutions, early event detection, quality verification for urban planning, and encourage citizen-led environmental accountability. The system could also serve as a data generation tool to aid research in areas such as pollution prediction.

In summary, this work contributes an affordable, scalable, and technology enabled approach to environmental monitoring. It acknowledges the limitations of current infrastructure and provides a platform where citizens, institutions, and municipal bodies may collaborate through shared data visibility. While prototype deployment and calibration against certified instruments are still required, the system demonstrates clear potential for real-time environmental transparency in smart city environments

Literature Review

Environmental monitoring using the Internet of Things is a field that has received a great deal of interest as it is able to continuously provide data and can be remotely accessible in real-time without necessarily requiring the presence of personnel in the field. Al-Fuqaha et al. discuss in detail the overall architecture of internet of things and explain how the sensing, communication, and application levels work in these networks. Internet of things architecture can be used to provide large-scale smart city solutions through efficient data exchange. In essence, internet of things technology provides a good foundation for city-scale monitoring in terms of growth and compatibility.

Air quality monitoring is another area which has received paramount attention because of the increasing pollution level in cities. This is largely caused by vehicles and industrial units. Dutta et al. demonstrate an IoT solution to monitor the air parameters related to AQI and then display them on the web. They also establish the fact that it is possible to monitor the trend of air pollution using inexpensive sensors and Wi-Fi sensors. Despite the extensive knowledge provided by these solutions, the sole focus is on air and no other parameters including effects on environmental sustainability.

IoT-based water quality monitoring is also on the rise for the provision of safe drinking water and the detection of pollutants in the water supply chain. Vijayakumar and Ramya proposed a smart water monitoring system based on the use of IoT sensors that monitor TDS and pH levels on a constant basis. Such a system also offers remote monitoring of water quality information to identify any irregular changes. Nevertheless, such systems remain standalone in nature and do not combine water quality information with any air or soil factors.

The literature on monitoring soil moisture is primarily found in smart agriculture and irrigation systems. Nandhini et al. demonstrate that IoT-based monitoring of soil moisture optimizes irrigations and avoids water waste. The authors mention that capacitive sensors used for monitoring soil moisture and IoT platforms work efficiently for providing decision-supporting data. The subject matter of these papers primarily covers agricultural lands and do not cite general soil properties of urban and semi-urban areas, which have different properties including vegetation and microclimate. Multi-parameter environmental monitoring for smart cities has been discussed by Zanella et al., who emphasized the importance of distributed sensing and scalable IoT architectures for urban applications [1-8]. Their studies underline the need for intel-grated systems capable of monitoring multiple environmental parameters simultaneously to obtain a holistic view of urban conditions. Based on the literature we have surveyed, it is obvious that there are IoT systems for air, water, and soil, but these are discrete and unrelated. There is little if any development of a cost-effective solution for the combination of air, water, and soil parameters within one system. Just such a solution is the aim of the system we are proposing: ESP32-based IoT sensing of air quality, water quality, and soil moisture, all graphed real-time on a web interface.

Hardware Component and Technology

Espressif Systems created the low-cost, low-power ESP32 system-on-chip (SoC) microcontroller especially for embedded and IoT applications. Its dual-core, 32-bit Tensilica Xtensa LX6 CPU can run at up to 240 MHz

ESP 32

The ESP32 is ideal for sensor-based monitoring systems since it supports a variety of communication interfaces, including Wi-Fi (802.11 b/g/n), Bluetooth, UART, SPI, I2C, and ADC. By eliminating the need for an external communication module, the microcontroller's inbuilt Wi-Fi capabilities lower system complexity and power consumption. ESP-IDF, the Arduino IDE, and other development environments can be used to program it.

By eliminating the need for an external communication module, the microcontroller's inbuilt Wi-Fi capabilities lower system complexity and power consumption. ESP-IDF, the Arduino IDE, and other development environments can be used to program it. The ESP32 is extensively utilized in wireless sensor networks, smart city applications, and real-time environmental monitoring because of its processing power, connection features, and affordability.

BME680 (Air Quality Sensor)

Bosch Sensor Tec created the integrated environmental sensor known as the BME680 (Fig. 1a). Temperature, humidity, air pressure, and volatile organic compounds can all be measured using it. Changes in air composition are detected by the sensor using a metal-oxide semiconductor gas sensing element, which can then be processed to estimate the AQI. The I2C or SPI interface is used by the BME680 to communicate with the microcontroller, guaranteeing dependable and quick data transfer. This tool has a small size, low energy requirements, and accurate measurement, making it more than adequate for continuous monitoring of air quality indoors and outside. In the system described, BME680 plays a part in monitoring air conditions and providing relevant information regarding the quality of air.

Total Dissolved Solids (TDS) Sensor

The number of dissolved materials in water is measured using the Total Dissolved Solids (TDS) sensor (Fig 1d). It functions based on electrical conductivity, which states that the presence of dissolved salts, minerals, and contaminants increases the conductivity of water. The ESP32's analog-to-digital converter (ADC) transforms the TDS sensor's analog signal output into parts per million (ppm). TDS sensors are frequently used in water quality monitoring applications to identify contaminants and evaluate the safety of drinking water. The TDS sensor in the suggested system allows for ongoing water quality monitoring and offers information on fluctuations brought on by shifts in the water supply or external factor.

Capacitive Soil Moisture Sensor

The capacitive soil moisture sensor (Fig 1c) is used to determine the moisture content of soil by measuring changes in dielectric permittivity. Unlike resistive soil moisture sensors, capacitive sensors are less prone to corrosion and provide more stable readings over time. The sensor outputs an analog voltage proportional to the moisture level present in the soil. The capacitive soil moisture sensor is interfaced with the ESP32 through an ADC pin. It is widely used in environmental monitoring and smart agriculture systems due to its reliability and durability. In the proposed model, the sensor is employed to assess soil condition in urban or semi-urban areas, providing valuable information related to vegetation health and irrigation patterns.

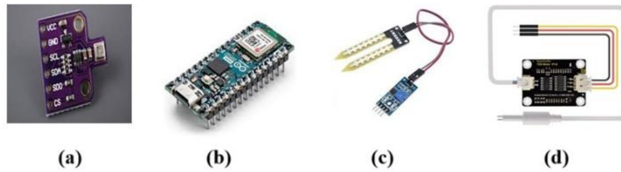

Fig. 1. *(a)Air Quality Sensor (b)ESP 32 (c) Moisture sensor (d) TDS Sensor*

Web-Based Dashboard

A web dashboard is used as the user interaction layer of the proposed system. The dashboard receives data transmitted from the ESP32 via Wi-Fi using HTTP communication. It displays real-time values of air quality, water quality, and soil moisture along with timestamp information.

Workflow Of Proposed Model

Initially, a detailed analysis of the environmental monitoring challenges faced in urban areas was carried out. The focus was on understanding variations in air quality, water quality, and soil moisture in day-to-day surroundings and identifying the limitations of conventional monitoring practices such as delayed reporting, limited coverage, and lack of public accessibility. Questions related to how environmental data is currently measured, how frequently it is reported, and how accessible it is to citizens were carefully examined. Based on this analysis, a detailed review of existing IoT-based environmental monitoring solutions was conducted to understand their capabilities and limitations.

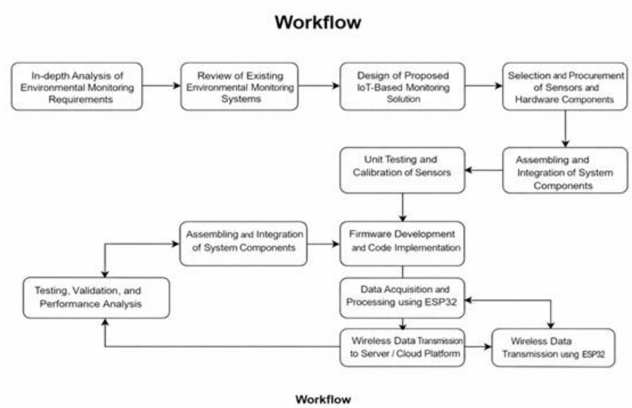

Fig. 2. *Workflow of the proposed system*

After evaluating the existing systems, a feasible IoT-based solution was proposed that supports real-time monitoring of Air Quality Index (AQI), Total Dissolved Solids (TDS) in water, and soil moisture using low-cost sensors. The proposed system integrates environmental sensors with an ESP32 microcontroller for data acquisition, processing, and wireless communication. The necessary hardware components were then shopped. Before system integration, individual unit testing and sensor calibration were done when the components arrived. To facilitate data collecting and transmission to the server, firmware development and code implementation were completed along with the assembly of the components in accordance with the system design. The system was tested in simulated urban settings following successful integration, and the data gathered was examined to assess system performance. The complete workflow of the proposed system is illustrated in Fig. 2 as a flow diagram.

Proposed Model

The proposed model implements a completed IoT-based multi-parameter environmental monitoring system designed for smart city applications. The system continuously monitors air quality, water quality, and soil moisture using low-cost sensors integrated with an ESP32 microcontroller. The primary objective of the model is to enable real-time environmental data acquisition and remote visualization through a web-based dashboard.

The system architecture consists of three major components: sensing units, processing and communication unit, and a visualization layer. For air quality monitoring, the BME680 sensor is employed to measure temperature, humidity, and the concentration of VOCs, which are further processed to estimate AQI. The Total Dis-solved Solids sensor returns a measure of electrical conductivity in water and converts it to ppm to present dissolved impurities. Soil condition is sensed by a capacitive soil moisture sensor that estimates the moisture content based on the variation in dielectric permittivity within the soil.

All sensors are interfaced to ESP32 using appropriate analog and digital communication channels. In turn, the ESP32 microcontroller acts as the central processing unit of the system, handling sensor data acquisition, calibration, and conversion to meaningful engineering units. After processing, the sensor readings are packaged in a structured JSON format containing parameter values along with timestamp and location information.

The processed data is transferred to an online web interface via Wi-Fi connectivity using HTTP communication. The online interface allows for the real-time representation of AQI, TDS, and soil moisture levels using graphical representation and trend graphs. This enables remote monitoring of environmental conditions using any internet-connected device. The data is transferred at defined time intervals to guarantee continuous monitoring while preserving efficient power consumption.

When the system was in operation, the variations in environmental parameters measured weekly in Katraj, Pune, were realistic for all parameters that were being measured. The Air Quality Index indicated high levels of air polluting the functioning of the system, the environmental parameters measured on a weekly basis in Katraj, Pune, showed realistic variations for all the parameters being measured. The Air Quality Index indicated high levels of air pollution during peak traffic hours, the Total Dissolved Solids varied according to the variations in the water supply, and the soil moisture content varied according to the irrigation schedule and environmental conditions. Taken together, these results prove that the system can measure both short-term and long-term variations in the environment.

The developed model is expected to be modular and scalable. More sensor nodes can be added at various locations and can be integrated into the same dashboard. The use of open communication protocols such as HTTP and JSON ensures that the model is cloud-compatible and can be used with future analytical tools. In general, the proposed model has shown a feasible, low-cost, and scalable approach for real-time environmental monitoring during peak traffic hours, the Total Dissolved Solids varied according to the variations in the water supply, and the soil moisture content varied according to the irrigation schedule and environmental conditions. Taken together, these results prove that the system is capable to measure both short-term and long-term variations in the environment.

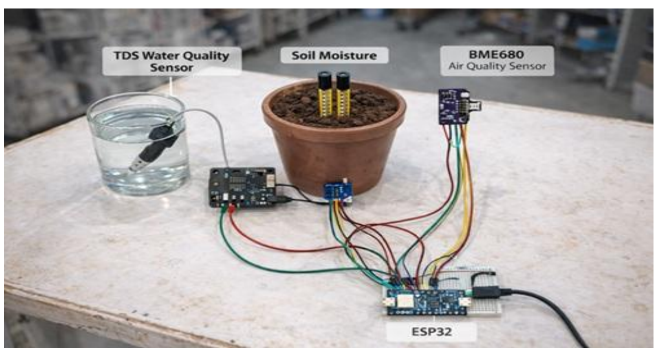

***Fig. 3a**. Proposed workflow as illustration*

***Fig. 3b.** Web Dashboard*

Comparative Analysis

Based on the comparative analysis that has been presented in Table 1, the proposed model for environmental monitoring has several benefits over the existing models based on IoT.

Unlike other models, which concentrate on a single parameter of the environment, the proposed model combines air quality (AQI), water quality (TDS), and soil moisture measurement into a single IoT platform. This is important for smart city applications because it gives a more holistic assessment of the environment. The proposed system is capable of real-time data acquisition and visualization through a web-based interface. This allows users to monitor environmental parameters on a real-time basis and track both short-term and long-term trends.

With the use of low-cost sensors and the ESP32 microcontroller, the system can provide affordability while still being functional. The system is also scalable as it is easy to add more sensor nodes to the system. The application of standardized communication protocols such as Wi-Fi, HTTP, and JSON ensures that the system is compatible with the existing infrastructure of smart cities. This will ensure smooth integration with future analytics and alert systems.

Table 1. *Comparative analysis*

Aspects	Our Proposed Model	Paper [1]	Paper [2]	Paper [3]
Application Domain	Multi-parameter environmental monitoring for smart cities (Air, Water, Soil)	IoT-based air quality monitoring	IoT-based water quality monitoring	IoT-based soil moisture monitoring
Technology and Components	ESP32, BME680 sensor, TDS sensor, capacitive soil moisture sensor, Wi-Fi, web dashboard	Microcontroller, gas sensors, temperature & humidity sensors, cloud server	Microcontroller, TDS and pH sensors, cloud platform	Microcontroller, soil moisture sensor, wireless module
Monitoring Parameters	AQI, water TDS, soil moisture	Air quality parameters only	Water quality parameters only	Soil moisture only
Data Acquisition Method	Periodic sensor sampling with on-board preprocessing	Continuous gas sensing	Continuous water quality sensing	Periodic soil moisture sensing
Communication Technology	Wi-Fi with HTTP and JSON data format	Wi-Fi / GSM-based data transmission	Wi-Fi-based cloud upload	Wireless sensor communication
Data Visualization	Online web-based dashboard accessible via browser	Cloud dashboard or mobile application	Mobile application or web interface	Dashboard for irrigation monitoring
Scalability	Supports multiple nodes and distributed deployment	Limited scalability for air monitoring only	Limited to water networks	Primarily field-specific deployment
Smart City Suitability	Designed for integrated smart city deployment	Focused only on-air quality	Focused only on water systems	Primarily agricultural use
Key Contribution	Unified monitoring of air, water, and soil using a single IoT platform	Air quality trend analysis	Continuous water quality assessment	Soil moisture-based irrigation support

Conclusion

In this paper, we have designed and implemented a low-cost IoT-based multi-parameter environmental monitoring system that can easily support smart city applications. The platform permits continuous air quality, water quality, and soil moisture monitoring based on low-cost sensors connected to an ESP32 microcontroller.

The gathered sensor data is further processed and transmitted via Wi-Fi to an online web dashboard. The abovementioned arrangement would facilitate the user in accessing environmental information remotely in real time at any instant. The proposed system significantly proves that environmental parameters such as the Air Quality Index, Total Dissolved Solids in water, and soil moisture in percentage can be gathered and visualized using a single IoT framework. A web dashboard visualizes the monitored data in a clear and user-friendly manner, enabling users to observe the variation in the environment with time without using special tools or by physical presence at the monitoring site.

The model allows for easy scalability and can support the addition of multiple sensing nodes, which can be distributed across different sites. Using common communication protocols and simple data representations, the system can ensure compatibility without being complex and unreliable. Finally, the developed system allows for the creation of an efficient and viable solution for enhancing environmental awareness in urban regions. This can enable citizens and the authorities to monitor environmental situations and make sound, data-driven decisions concerning the development of intelligent cities.

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