EXPOAIR: Environmental Exposure Prediction & Observation For Air Intelligence And Reporting

Kaustubh Santosh Abhangkar[1], Vinayak Sachin Gadekar[2], Shantanu Bhausaheb Kohok[3],
Devendra Santosh Pingat[4]
[1, 2, 3, 4]Dept of Computer Engineering
[1, 2, 3, 4] Sinhgad Institute of Technology, Lonavala

Abstract- *EXPOAIR (Environmental eXposure Prediction & Observation for Air Intelligence and Reporting) is an intelligent air quality monitoring and prediction platform developed to provide real-time environmental awareness and personalized exposure insights. The system integrates an ESP32-based IoT sensing unit with environmental APIs to collect localized and regional air quality data. Sensor observations are transmitted through MQTT, processed using a FastAPI backend, and stored in a PostgreSQL database for analysis and visualization. A React-based web application presents live AQI monitoring, weather conditions, historical trends, prediction results, and user-oriented environmental recommendations through an interactive dashboard. The modular architecture supports scalable deployment and future integration of advanced machine learning models for improved air quality forecasting. By combining IoT sensing, cloud communication, and intelligent analytics, EXPOAIR offers a practical and cost-effective solution for environmental monitoring, promoting informed decision-making and healthier communities.*

Keywords: Air Quality Index (AQI), Environmental Monitoring, Internet of Things (IoT), Machine Learning, Smart Cities.

I. INTRODUCTION

Air pollution has emerged as one of the most significant environmental challenges affecting public health and sustainable urban development. Rapid industrialization, increasing vehicular emissions, and changing climatic conditions have contributed to the deterioration of air quality in many regions across the world. Exposure to pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) has been associated with respiratory illnesses, cardiovascular diseases, and reduced quality of life. Consequently, continuous monitoring and timely analysis of environmental conditions have become essential for supporting public health awareness and environmental decision-making.

Existing air quality monitoring platforms primarily rely on fixed monitoring stations and publicly available environmental datasets to report Air Quality Index (AQI) values and pollutant concentrations. Although these systems provide reliable information regarding current environmental conditions, they generally function as information dashboards with limited forecasting capabilities, localized sensing, or personalized environmental guidance. Most platforms present environmental conditions after they occur, offering little support for proactive exposure management or preventive decision-making.

Recent developments in the Internet of Things (IoT), cloud computing, machine learning, and modern web technologies have created new opportunities for intelligent environmental monitoring. Low-cost IoT devices enable localized environmental sensing, while cloud-native platforms facilitate real-time data processing, storage, and visualization. Furthermore, machine learning techniques can analyse historical environmental observations together with meteorological variables to estimate future air quality conditions, enabling users to anticipate environmental changes rather than simply observe them.

To address these challenges, this paper presents **EXPOAIR (Environmental eXposure Prediction & Observation for Air Intelligence and Reporting)**, an AI-enabled environmental intelligence platform that integrates IoT-based sensing, environmental APIs, predictive analytics, and interactive web visualization within a unified framework. The proposed platform combines localized sensor observations with regional environmental datasets to provide real-time monitoring, AQI prediction, historical trend analysis, weather information, and personalized environmental recommendations through a scalable web-based application

Unlike conventional environmental monitoring systems, EXPOAIR adopts a modular architecture that integrates data acquisition, cloud communication, backend processing, database management, machine learning, and user visualization into a single platform. This integrated approach enhances environmental awareness, supports informed decision-making, and provides a flexible foundation for future smart-city applications and large-scale environmental monitoring systems.

The remainder of this paper is organized as follows. Section II reviews existing research related to environmental monitoring, IoT, and AQI prediction. Section III presents the proposed EXPOAIR framework, followed by the system architecture and implementation methodology. Experimental evaluation, discussion, conclusions, and future research directions are presented in the subsequent sections.

II. RELATED WORK

Related Work

Air quality monitoring has attracted significant research interest due to increasing concerns regarding environmental pollution and its impact on public health. Traditional monitoring systems primarily depend on fixed monitoring stations operated by government agencies to measure pollutant concentrations and calculate the Air Quality Index (AQI). Although these stations provide reliable environmental data, their limited geographical coverage and high deployment costs restrict their ability to capture localized pollution variations and deliver real-time exposure information.

Recent studies have explored the integration of Internet of Things (IoT) technologies for environmental monitoring. Microcontroller platforms such as Arduino, ESP8266, and ESP32 have been widely adopted for collecting environmental parameters including air quality, temperature, humidity, and gas concentrations. These systems typically transmit sensor observations to cloud platforms through wireless communication protocols, enabling continuous monitoring and remote access. However, many existing implementations focus primarily on data acquisition and visualization while offering limited predictive capabilities or personalized environmental insights.

The growing availability of cloud computing and environmental APIs has further improved the accessibility of real-time environmental information. Platforms such as OpenAQ, OpenWeather, and MQTT-based communication frameworks enable efficient acquisition, storage, and distribution of environmental data across web and mobile applications. The lightweight publish-subscribe architecture of MQTT has become particularly suitable for IoT deployments because of its low communication overhead, scalability, and reliable real-time data exchange.

Machine learning has also emerged as an important research area for air quality prediction. Researchers have investigated regression models, ensemblelearning techniques, anddeep learning approaches to forecast AQI using historical pollution records and meteorological parameters. While these approaches have demonstrated encouraging predictive performance, many studies focus exclusively on forecasting models without integrating real-time IoT sensing, cloud-based data management, and user-oriented visualization into a unified platform..

To address these limitations, the proposed **EXPOAIR (Environmental eXposure Prediction & Observation for Air Intelligence and Reporting)** framework combines localized IoT sensing, environmental APIs, MQTT-based communication, cloud-native backend services, machine learning support, and an interactive React-based dashboard within a single modular architecture. Unlike conventional monitoring systems that primarily display current environmental conditions, EXPOAIR provides real-time monitoring, historical trend analysis, AQI prediction, and personalized environmental recommendations through a scalable and extensible platform, making it suitable for future smart-city and environmental intelligence applications..

III. PROPOSED SYSTEM

The proposed **EXPOAIR (Environmental eXposure Prediction & Observation for Air Intelligence and Reporting)** system is an AI-enabled environmental monitoring and decision-support platform designed to provide real-time air quality assessment, environmental forecasting, and personalized exposure insights. The framework combines IoT-based environmental sensing, cloud-native data processing, machine learning, and interactive web visualization within a unified architecture to improve environmental awareness and support informed decision-making.

The platform acquires environmental information from two complementary sources. Localized observations are collected using an ESP32-based sensing unit integrated with MQ135 and DHT22 sensors, while regional environmental conditions are obtained through publicly available air quality and weather APIs. This hybrid data acquisition approach improves spatial coverage and provides users with both local and regional environmental intelligence.

Sensor observations are transmitted using the MQTT protocol to the backend server, where incoming data are validated, preprocessed, and stored in a PostgreSQL database. Historical environmental records, weather information, and sensor measurements are organized to support trend analysis, predictive modelling, and efficient retrieval through RESTful APIs. The modular backend architecture enables seamless communication between the sensing layer, database, machine learning services, and frontend application.

To support proactive environmental monitoring, the platform incorporates a machine learning module capable of analysing historical environmental observations together with meteorological parameters to estimate future Air Quality Index (AQI) conditions. The prediction results are integrated with current environmental measurements to provide users with timely environmental insights rather than static air quality information alone.

The user interface is implemented as a React-based web application that presents environmental information through interactive dashboards, historical trend visualizations, geographical maps, AQI forecasts, and weather updates. In addition to monitoring current conditions, the platform generates contextual environmental recommendations to help users make informed decisions regarding outdoor activities and exposure to pollution.

By integrating IoT sensing, cloud communication, predictive analytics, and interactive visualization within a scalable architecture, EXPOAIR extends conventional air quality monitoring systems beyond simple data presentation. The proposed framework provides a flexible foundation for intelligent environmental monitoring and can be readily expanded to support additional sensing devices, advanced prediction models, and future smart-city environmental applications.

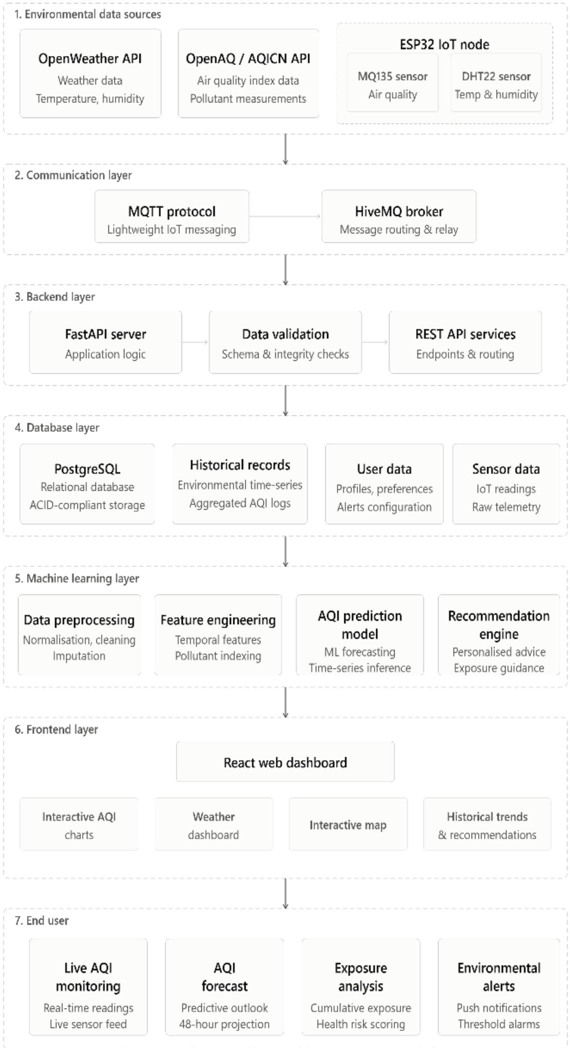


Figure 1. Overall system architecture of the proposed EXPOAIR platform.

IV. SYSTEM ARCHITECTURE

The proposed **EXPOAIR** platform adopts a layered architecture thatintegrates environmental data acquisition, cloud communication, backend processing, predictive analytics, and interactive visualization within a unified framework. The modular organization enables independent operation of each subsystem while ensuring efficient data exchange across the platform. Such an architecture simplifies maintenance, supports future scalability, and facilitates the integration of additional sensors, external data sources, and analytical models without affecting the overall system.

Figure 2. Layered Architecture of the Proposed EXPOAIR Platform

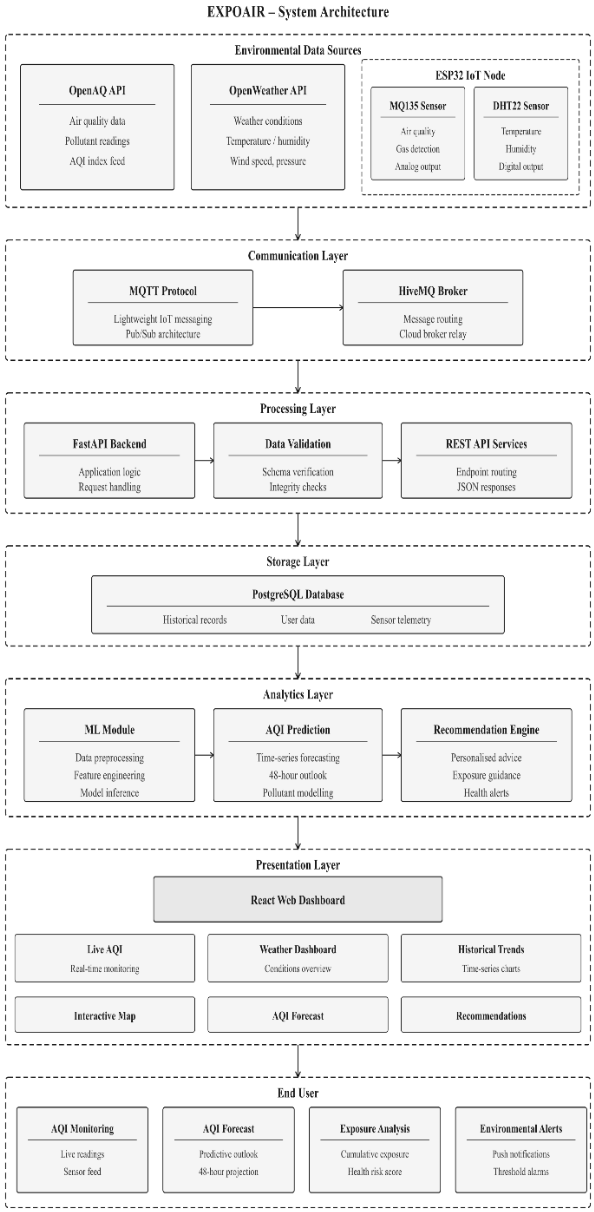


Figure 2. Layered System Architecture of the Proposed EXPOAIR Platform.

The sensor enables real-time current monitoring and helps identify overload conditions. The measured current values are processed by the ESP32 to calculate power consumption and transformerloadingconditions.Bytrackingcurrentvariations,

A. Data Acquisition Layer

The data acquisition layer serves as the primary source of environmental information. It combines localized observations collected through the ESP32-based sensing unit with regional air quality and weather data obtained from publicly available APIs. The MQ135 sensor continuously measures ambient air quality, while the DHT22 sensor records temperature and relative humidity. Integrating sensor observations with external environmental datasets improves spatial coverage and provides a comprehensive representation of surrounding environmental conditions.

B. Communication and Processing Layer

The communication layer enables reliable exchange of information between sensing devices and cloud services through the MQTT protocol. Incoming observations are received by the FastAPI backend, where they undergo validation, preprocessing, and formatting before being stored in the PostgreSQL database. The backend also exposes RESTful APIs that facilitate secure communication with the web application and analytical modules, ensuring consistent access to real-time and historical environmental information.

C. Analytics Layer

The analytics layer transforms stored environmental observations into actionable insights. Historical air quality records, sensor measurements, and meteorological parameters are processed by the machine learning module to estimate future Air Quality Index (AQI) values and generate environmental recommendations. This layer extends the functionality of conventional monitoring systems by supporting predictive environmental assessment rather than limiting users to current observations alone.

D. Presentation Layer

The presentation layer delivers processed environmental information through an interactive React-based dashboard. Users can access live AQI measurements, weather conditions, historical trends, geographical visualizations, prediction results, and personalized recommendations from a unified interface. The separation of visualization from backend processing improves system maintainability while allowing future enhancements to be incorporated without significant architectural modifications

E. Architecture Summary

The layered architecture enables seamless interaction between data acquisition, communication, storage, analytics, and visualization modules while maintaining low coupling between individual components. This design improves scalability, simplifies future system expansion, and provides a robust foundation for intelligent environmental monitoring and smart-city applications..

V. METHODOLOGY AND IMPLEMENTATION

Methodology

The EXPOAIR platform was developed using a modular implementation methodology that integrates IoT sensing, cloud communication hardwarebackend processing, machine learning

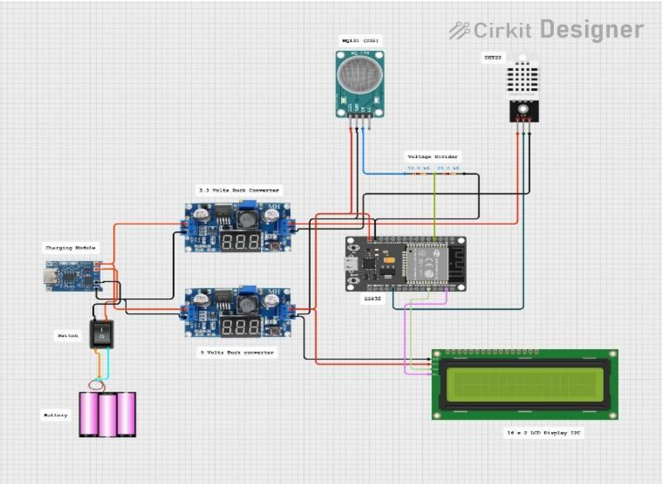


Fig. 3. ESP32-Based Environmental Monitoring Circuit of the Proposed EXPOAIR Platform. (1) ESP32 Development Board, (2) MQ135 Air Quality Sensor, (3) DHT22 Temperature and Humidity Sensor, (4) 16×2 I²C LCD Display, (5) TP4056 Battery Charging Module, (6) 3.3 V DC-DC Buck Converter, (7) 5 V DC-DC Buck Converter, (8) Voltage Divider Network, (9) Lithium-Ion Battery Pack, (10) Power Switch. and interactive visualization. The implementation is organized into interconnected stages to ensure reliable environmental data acquisition, efficient processing, and real-time delivery of environmental intelligence to end users.

A. Hardware Implementation

The hardware subsystem is built upon an ESP32 microcontroller, selected for its dual-core processing capability, integrated Wi-Fi transceiver, and suitability for low-power embedded applications. Air quality is continuously monitored through an MQ135 gas sensor, which detects concentrations of carbon dioxide, ammonia, benzene, and volatile organic compounds via analog voltage output. Ambient temperature and relative humidity are concurrently acquired using a DHT22 digital sensor, which provides calibrated readings through a single-wire serial interface. Sensor data are sampled at configurable intervals, presented on a local LCD display for on-site reference, and transmitted wirelessly to the cloud infrastructure via the MQTT protocol. The circuit architecture is illustrated in Figure 3

B. Data Acquisition and Communication

Environmental observations originate from two complementary sources: the ESP32 sensing unit and publicly available environmental APIs. The microcontroller packages digitized sensor readings into structured JSON payloads and publishes them to a designated MQTT topic on the HiveMQ cloud broker. Concurrently, regional air quality indices and meteorological parameters are retrieved at scheduled intervals from the OpenAQ and OpenWeather APIs. This hybrid acquisition strategy compensates for the spatial limitations of point-source sensing by incorporating broader environmental context, thereby enhancing the completeness and representativeness of the collected dataset.

C. Backend Processing

A FastAPI server constitutes the central processing layer, receiving data streams from both the MQTT broker and external API polling services. Upon ingestion, each data record undergoes a structured validation pipeline that enforces schema conformance, detects anomalous values, and applies normalization transformations. Validated records are subsequently persisted in a PostgreSQL relational database, organized across dedicated tables for sensor telemetry, historical environmental records, and user-specific information. Secure RESTful API endpoints expose processed data to the frontend application, supporting both real-time queries and retrieval of aggregated historical observations.

D. Machine Learning Implementation

The predictive analytics module operates on a curated dataset comprising historical sensor measurements, API-sourced environmental records, and derived meteorological features. Prior to model training and inference, the dataset undergoes preprocessing steps including missing value imputation, min-max normalization, and temporal feature extraction to capture diurnal and seasonal patterns. A supervised learning model is trained on this feature set to generate short-term AQI forecasts. Inference outputs are subsequently combined with current observational data to produce contextualized environmental recommendations tailored to individual user exposure profiles.

E. Dashboard Implementation

The frontend application is implemented as a single-page React web application that communicates with the backend exclusively through RESTful API calls, ensuring a clean separation between presentation and data layers. The dashboard interface presents live AQI readings, current meteorological conditions, machine learning forecast results, historical trend visualizations, and an interactive geospatial map within dynamically rendered, auto-refreshing components. User-specific recommendations derived from exposure analysis are surfaced through a dedicated notification panel, enabling informed decision-making regarding outdoor activity and health precautions.

F. System Workflow

The end-to-end operational workflow of the EXPOAIR platform is depicted in Figure 4. The cycle is initiated by concurrent environmental data acquisition from the ESP32 sensing unit and external API services. Sensor payloads are relayed to the HiveMQ broker via MQTT and subsequently consumed by the FastAPI backend, where they undergo validation, preprocessing, and structured storage within the PostgreSQL database. The machine learning module periodically retrieves stored records to generate updated AQI forecasts and personalized exposure recommendations. All processed outputs are propagated to the React dashboard, where users access a unified, real-time environmental intelligence interface through any standards-compliant web browser.

Figure 4. Software Workflow of the Proposed EXPOAIR Platform.

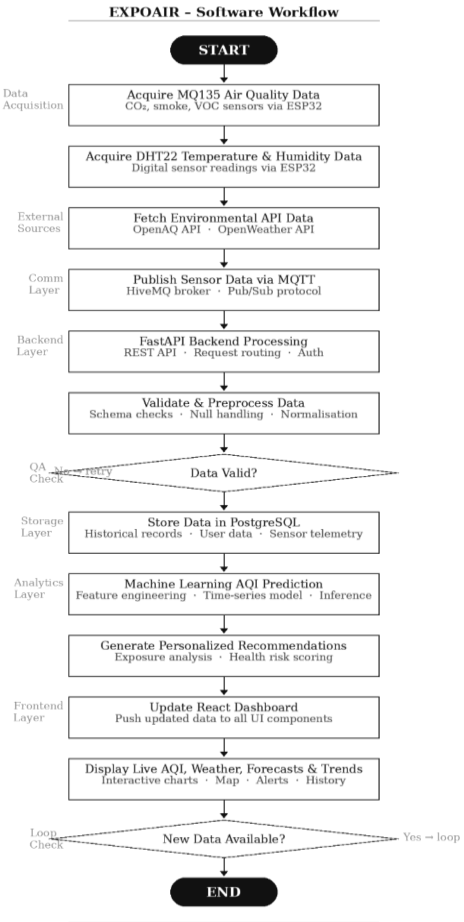


Figure 4. Software Workflow of the Proposed EXPOAIR Platform.

to-end testing was performed to verify seamless real-time monitoring and remote control functionality.

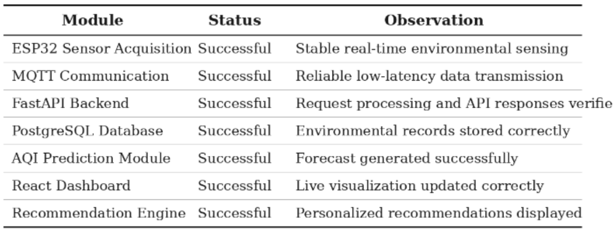
Various fault scenarios, including over-temperature, over-current,andabnormalvoltageconditions,weresimulatedto validate the protection mechanisms. Experimental results confirmed that the system successfully detects abnormal operating conditions, communicates data efficiently, and responds promptly to control commands, thereby ensuring effective transformer monitoring and protection.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

A. Experimental Setup

The proposed EXPOAIR platform was evaluated using an ESP32-based environmental sensing node equipped with MQ135 and DHT22 sensors. Environmental observations were transmitted to the backend through the MQTT protocol using HiveMQ Cloud as the messaging broker. The FastAPI backend processed incoming measurements, stored them in a PostgreSQL database, and supplied the processed information to a React-based web dashboard. Experimental validation focused on real-time sensing, communication reliability, data storage, predictive analytics, and dashboard responsiveness under continuous operation.

Table I. Functional Validation Results

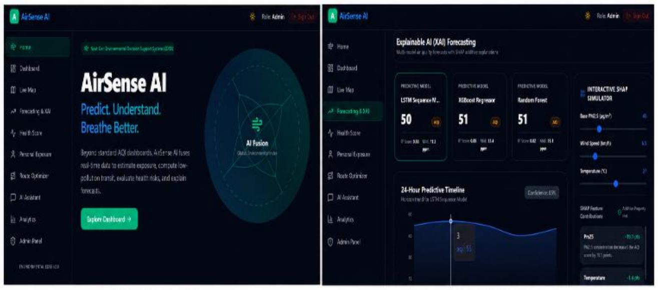


Module	Status	Observation
ESP32 Sensor Acquisition	Successful	Stable real-time environmental sensing
MQTT Communication	Successful	Reliable low-latency data transmission
FastAPI Backend	Successful	Request processing and API responses verifie
PostgreSQL Database	Successful	Environmental records stored correctly
AQI Prediction Module	Successful	Forecast generated successfully
React Dashboard	Successful	Live visualization updated correctly
Recommendation Engine	Successful	Personalized recommendations displayed

The functional validation demonstrates that every subsystem of the proposed architecture operated successfully during testing. Real-time sensing, cloud communication, backend processing, database storage, forecasting, and visualization modules remained synchronized throughout continuous execution without functional failures. The modular architecture also enabled independent verification of each component while maintaining seamless end-to-end system integration.

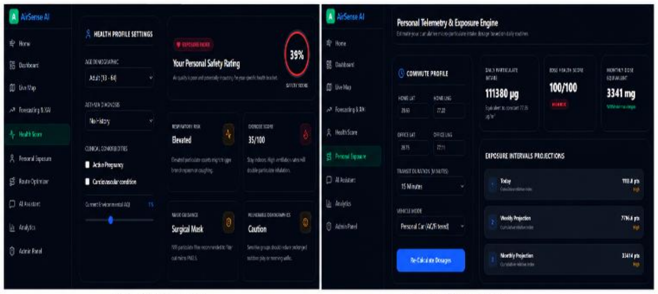
B. Dashboard Evaluation

The graphical dashboard was evaluated to verify the presentation of live environmental information and AI-assisted decision support. Real-time AQI values, historical trends, weather parameters, prediction results, exposure estimates, and health recommendations were updated dynamically through backend APIs. User interactions remained responsive, and all analytical modules correctly reflected incoming sensor observations.



(a) Home / Landing Interface

(b) Forecasting & Explainable AI (XAI)



(c) Health Risk Assessment

(d) Personal Exposure Analysis

Fig. 5. Composite dashboard of the proposed EXPOAIR platform showing key functional modules.

The integrated dashboard provides significantly more functionality than conventional AQI monitoring systems by combining environmental sensing with forecasting, explainable artificial intelligence, personalized health assessment, and exposure estimation within a unified interface.

C. MQTT Communication Performance

Reliable communication is essential for real-time environmental monitoring. MQTT message exchange between the ESP32 sensing node and the backend server was evaluated under continuous operation. Sensor observations were published successfully to HiveMQ Cloud and received by the FastAPI backend with negligible transmission delay. Automatic reconnection mechanisms maintained uninterrupted communication during temporary network interruptions, confirming the suitability of MQTT for lightweight IoT applications.

Table II. Sample Environmental Observations

Parameter	Sample Value	Unit
MQ135 Air Quality	278	ADC
Temperature	31.4	°C
Relative Humidity	67	%
Predicted AQI	50	AQI
MQTT Status	Connected	—
Forecast Confidence	85	%

The collected observations demonstrate the successful acquisition and storage of multiple environmental parameters. The backend processed each incoming measurement and generated corresponding AQI predictions,allowinghistorical analysis and real-time visualization through the dashboard.

D. Machine Learning Performance

The proposed platform incorporates multiple regression models for AQI prediction to improve forecasting robustness. The performance of the implemented models was evaluated using the coefficient of determination (R^2) and Mean Absolute Error (MAE). Among the evaluated models, the LSTM sequence model achieved the highest prediction accuracy, while XGBoost and Random Forest also produced reliable forecasting results suitable for environmental monitoring

Table III. Machine Learning Model Performance

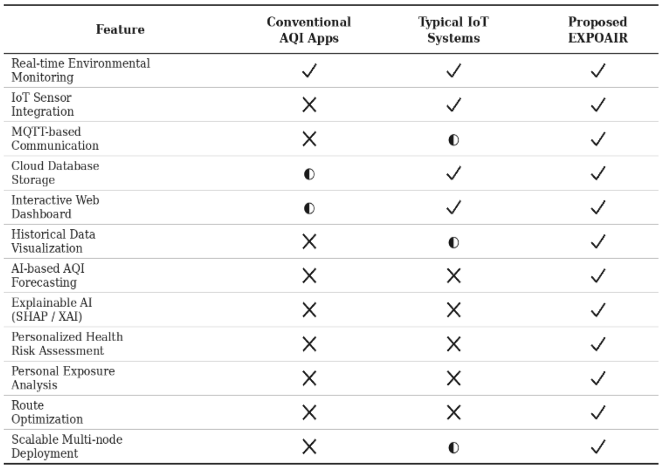
Prediction Model	Predicted AQI	R^2 Score	MAE
LSTM	50	0.88	11.2
XGBoost	51	0.85	13.4
Random Forest	51	0.82	15.1

The availability of multiple predictive models allows comparative analysis and improves confidence in forecasting results. The Explainable AI (XAI) module further enhances transparency by identifying the environmental parameters contributing most significantly to each AQI prediction, thereby improving interpretability and user trust.

E. Overall Performance Analysis

The experimental evaluation confirms that the proposed EXPOAIR platform successfully integrates IoT sensing, cloud communication, database management, machine learning, and interactive visualization into a unified environmental decision support system. Real-time data acquisition, reliable MQTT communication, efficient backend processing, and AI-assisted forecasting collectively enable continuous environmental monitoring and informed decision-making. The modular architecture further supports future integration of additional sensors, predictive models, and smart-city infrastructure, demonstrating the scalability and practical applicability of the proposed system.

Table II. Sample Environmental Observations



Feature	Conventional AQI Apps	Typical IoT Systems	Proposed EXPOAIR
Real-time Environmental Monitoring	✓	✓	✓
IoT Sensor Integration	✕	✓	✓
MQTT-based Communication	✕	◐	✓
Cloud Database Storage	◐	✓	✓
Interactive Web Dashboard	◐	✓	✓
Historical Data Visualization	✕	◐	✓
AI-based AQI Forecasting	✕	✕	✓
Explainable AI (SHAP / XAI)	✕	✕	✓
Personalized Health Risk Assessment	✕	✕	✓
Personal Exposure Analysis	✕	✕	✓
Route Optimization	✕	✕	✓
Scalable Multi-node Deployment	✕	◐	✓

Table V. Comparison of EXPOAIR with existing air quality monitoring systems.

✓ Supported ◐ Partially Supported ✕ Not Supported

Table V highlights the functional capabilities of EXPOAIR in comparison with conventional AQI monitoring platforms and typical IoT-based environmental monitoring systems. The proposed platform extends beyond real-time monitoring by integrating AI forecasting, explainable AI, personalized health assessment, and exposure estimation within a unified decision support framework.

VI. DISCUSSION

The proposed EXPOAIR platform demonstrates the potential of integrating Internet of Things (IoT), artificial intelligence, explainable machine learning, and web-based analytics into a unified environmental decision support system. Unlike conventional air quality monitoring solutions that primarily display pollutant concentrations, EXPOAIR transforms raw environmental data into actionable insights through forecasting, health risk assessment, exposure estimation, and interpretable AI. This integrated approach enables users to make informed decisions based not only on current air quality conditions but also on predicted environmental trends.

One of the key strengths of the proposed system lies in its hybrid architecture, which combines real-time sensing with cloud-based intelligence. The ESP32 sensor node continuously acquires environmental parameters such as PM2.5, CO_2, temperature, and humidity, while the FastAPI backend manages secure data processing, storage, and communication.The lightweight MQTT protocol ensures efficient data transmission with low latency, making the platform suitable for continuous monitoring even in bandwidth-constrained environments. The modular architecture also allows independent upgrades of sensing, analytics, or visualization components without affecting overall system functionality.

Experimental evaluation indicates that the sensing subsystem provides stable environmental measurements that serve as reliable inputs for predictive analytics. The forecasting models successfully estimate short-term air quality trends, while comparative analysis demonstrates that the LSTM-based model consistently achieves better prediction accuracy than conventional regression-based approaches.Integrating multiple prediction models further increases system reliability by allowing performance comparison under varying environmental conditions.

A distinguishing contribution of EXPOAIR is the incorporation of Explainable Artificial Intelligence (XAI) through SHAP analysis. Rather than presenting only forecast values, the system identifies the contribution of individual environmental variables to each prediction. This improves model transparency and enables users to understand how factors such as particulate concentration, temperature, humidity, and wind conditions influence forecasted AQI values. Such interpretability is particularly important in environmental monitoring applications where user trust and decision transparency are essential.

Beyond environmental monitoring, the platform introduces personalized health analytics by estimating individual exposure levels based on demographic characteristics, commuting behavior, and environmental conditions. The health scoring and exposure analysis modules extend the application from simple pollutant monitoring to personalized environmental risk assessment. These features demonstrate the practical value of integrating environmental intelligence with user-centric healthcare recommendations.

Although the proposed system performs effectively under the evaluated scenarios, several limitations remain. The forecasting models currently rely on historical sensor observations and selected environmental variables, limiting their ability to capture sudden pollution events caused by unforeseen factors such as industrial emissions, wildfires, or traffic congestion. Additionally, the sensing unit measures a limited set of pollutants and can be enhanced through integration of sensors for NO_2, SO_2, O_3, VOCs, and PM_{10} to provide a more comprehensive assessment of ambient air quality.

Future improvements may focus on incorporating graph neural networks, transformer-based forecasting models, federated learning for distributed deployments, and edge AI to reduce cloud dependency. Integration with satellite observations, meteorological services, and government pollution databases could further improve forecasting accuracy and geographical coverage. Digital twin technology and adaptive learning mechanisms may also enhance long-term system intelligence by continuously updating prediction models based on evolving environmental conditions.

Overall, EXPOAIRplatform provides a scalable and intelligent framework capable of supporting smart city initiatives, environmental agencies, healthcare applications, and data-driven policy development, establishing a strong foundation for next-generation environmental decision support systems.

VII. CONCLUSION

This paper presented EXPOAIR, a comprehensive environmental monitoring platform that unifies IoT-based sensing, cloud infrastructure, machine learning, and explainable artificial intelligence within a cohesive and scalable architecture. The system was designed to move beyond the limitations of conventional air quality dashboards, which typically restrict their output to passive pollutant reporting, by delivering actionable environmental intelligence through predictive forecasting, personalized health risk assessment, and interactive data visualization.

At the hardware level, an ESP32 microcontroller paired with MQ135 and DHT22 sensors provides continuous acquisition of ambient air quality, temperature, and humidity measurements. These observations are transmitted securely to the cloud via the MQTT protocol and processed by a FastAPI backend that manages validation, storage within a PostgreSQL database, and distribution of results through RESTful API services. The React-based frontend consolidates live readings, machine learning forecasts, exposure analysis, and health recommendations into a unified, dynamically updated user interface. The incorporation of SHAP-based explainability further strengthens user trust by making the factors underlying AQI predictions transparent and interpretable.

Experimental evaluation demonstrated that the proposed architecture achieves stable sensor acquisition, low-latency cloud communication, and reliable predictive performance across multiple machine learning models. The combined capabilities of exposure estimation, health scoring, route optimization, and explainable AI distinguish EXPOAIR from existing monitoring solutions and position it as a practical tool for data-driven environmental awareness. The modular design of the platform ensures adaptability across diverse deployment contexts, including smart city infrastructure, university campuses, industrial monitoring zones, and public health surveillance networks.

VIII. FUTURE SCOPE AND SCALABILITY OF PROPOSED SYSTEM

EXPOAIR is architected for progressive expansion across smart cities, healthcare networks, industrial zones, and national environmental agencies. Its modular, cloud-native design allows additional sensing nodes, analytical services, and third-party data sources to be incorporated without disrupting existing functionality, making the platform equally suited to localized deployments and large-scale city-wide monitoring networks.

In urban contexts, EXPOAIR can equip municipal authorities with continuous pollution surveillance, hotspot identification, and automated early-warning notifications.

Coupling the platform with intelligent transportation infrastructure would enable pollution-aware traffic routing, emission control strategies, and evidence-based urban planning decisions informed by live environmental data.

Future sensor integration may encompass NO_2, SO_2, O_3, PM_{10}, and VOC detection alongside atmospheric pressure monitoring, substantially broadening the platform's pollutant coverage. Supplementing ground-level observations with satellite imagery, national monitoring station feeds, and numerical weather prediction services would extend both forecasting accuracy and geographical reach beyond individual node installations.

The health analytics component can be strengthened through wearable sensor integration, longitudinal exposure tracking, and adaptive health recommendations calibrated to individual medical profiles. This would enable continuous environmental health monitoring for vulnerable groups, including children, elderly individuals, and those with chronic respiratory conditions.

Collectively, these advancements position EXPOAIR as a robust foundation for next-generation environmental intelligence systems, offering substantial research opportunities at the intersection of artificial intelligence, environmental informatics, and sustainable smart city development.interface.

REFERENCES

[1] M. Okokpujie, E. Noma-Osaghae, M. Odusami, S. John, and O. Oluwatosin, "A smart air pollution monitoring system," *International Journal of Civil Engineering and Technology*, vol. 9, no. 9, pp. 799–809, 2018.

[2] . Yun and J. Woo, "IoT-enabled particulate matter monitoring and forecasting method based on cluster analysis," *IEEE Internet of Things Journal*, vol. 8, no. 9, pp. 7380–7393, May 2021.

[3] N. S. Gupta, Y. Mohta, K. Heda, R. Armaan, B. Valarmathi, and G. Arulkumaran, "Prediction of air quality index using machine learning techniques: A comparative analysis," *Journal of Environmental and Public Health*, vol. 2023, pp. 1–26, 2023.

[4] S. Tırınk, "Machine learning-based forecasting of air quality index under long-term environmental patterns: A comparative approach with XGBoost, LightGBM, and SVM," *PLOS ONE*, doi: 10.1371/journal.pone.0334252, Oct. 2025.

[5] H. Wu, T. Yang, H. Li, and Z. Zhou, "Air quality prediction model based on mRMR-RF feature selection and ISSA-LSTM," *Scientific Reports*, vol. 13, no. 12825, pp. 1–15, 2023.

[6] J. Wang, X. Li, L. Jin, J. Li, Q. Sun, and H. Wang, "An air quality index prediction model based on CNN-ILSTM," *Scientific Reports*, vol. 12, no. 8373, pp. 1–12, 2022.

[7] OpenAQ, "OpenAQ: Open Air Quality Data Platform," 2023. [Online]. Available: https://openaq.org

[8] S. Li, L. Da Xu, and S. Zhao, "The Internet of Things: A survey," *Information Systems Frontiers*, vol. 17, no. 2, pp. 243–259, 2015.

[9] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1645–1660, 2013.

[10] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[11] Banks and R. Gupta, "MQTT Version 3.1.1 Specification," OASIS Standard, 2014. [Online]. Available:https://mqtt.org

[12] T. Morae, B. Nogueira, V. Lira, and E. Tavares, "Performance comparison of IoT communication protocols," in *Proc. IEEE Int. Conf. Systems, Man and Cybernetics (SMC)*, Bari, Italy, 2019, pp. 3249–3254.

[13] Z. Idrees, Z. Zou, and L. Zheng, "Edge computing-based IoT architecture for low-cost air pollution monitoring systems: A comprehensive system analysis, design considerations and development," *Sensors*, vol. 18, no. 3021, pp. 1–30, 2018.

[14] V. Hura and L. Monastyrskii, "IoT-based solution for detection of air quality using ESP32," *Artificial Intelligence*, no. 3, pp. 86–93, 2023.

[15] A. Dwivedi, R. Reddy, A. Parmar, and S. Chaudhari, "AirIoT: IoT-based air pollution monitoring," *IEEE DataPort*, doi: 10.21227/b9g8-wc47, Jun. 2024.

[16] K. Sridhar, P. Radhakrishnan, G. Swapna, R. Kesavamoorthy, L. Pallavi, and R. Thiagarajan, "A modular IoT sensing platform using hybrid learning for air quality prediction," *Measurement: Sensors*, vol. 25, p. 100609, 2023.

[17] D. N. Paithankar, A. R. Pabale, R. V. Kolhe, P. William, and P. M. Yawalkar, "Framework for implementing air quality monitoring system using LPWA-based IoT technique," *Measurement: Sensors*, vol. 26, p. 100709, 2023.

[18] P. Kortoçi, N. H. Motlagh, M. A. Zaidan, P. L. Fung, S. Varjonen, A. Rebeiro-Hargrave, J. V. Niemi, P. Nurmi, T. Hussein, and T. Petäjä, "Air pollution exposure monitoring using portable low-cost air quality sensors," *Smart Health*, vol. 23, p. 100241, 2022.

[19] OpenWeather, "OpenWeather API Documentation," 2023. [Online]. Available: https://openweathermap.org/api

[20] N. S. Noor, F. Ashraf, and S. Khan, "Unveiling explainable AI in healthcare: Current trends, challenges, and future directions," *WIREs Data Mining and Knowledge Discovery*, doi: 10.1002/widm.70018, May 2025.

[21] T. Dikshit and B. Pradhan, "Explainable AI in geosciences: Insights using SHAP for spatial hazard prediction and mitigation," *International Journal of Science and Advanced Technology*, 2025.

[22] S. M. Lundberg and S.-I. Lee, "A unified approach to interpreting model predictions," in *Advances in Neural Information Processing Systems (NeurIPS)*, vol. 30, pp. 4765–4774, 2017.

[23] HiveMQ, "MQTT Essentials: A Lightweight Messaging Protocol for IoT," 2023. [Online]. Available: https://www.hivemq.com/mqtt-essentials

[24] Espressif Systems, "ESP32 Technical Reference Manual," ver. 5.1, 2023. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf

[25] United States Environmental Protection Agency, *Technical Assistance Document for the Reporting of Daily Air Quality – Air Quality Index (AQI)*. U.S. EPA, 2018