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Spatio-Temporal Environmental Monitoring using Hybrid Machine Learning Models: A Predictive Framework for Urban Air Quality Assessment

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Abstract: *Air pollution remains one of the most critical environmental challenges faced by rapidly urbanizing regions across the globe. With increasing vehicular emissions, industrial activities, and population density, urban centers like Mumbai are witnessing a continuous decline in air quality, which poses significant threats to public health and environmental sustainability. Accurate forecasting of air quality is therefore essential for implementing timely mitigation strategies and policy measures.*

In this study, we propose a novel hybrid machine learning framework that integrates statistical time series forecasting (ARIMA) with ensemble learning (Random Forest Regression) to enhance the accuracy and reliability of air quality predictions. The model processes multi-dimensional spatio-temporal datasets consisting of key air pollutants such as PM2.5, PM10, NO_2, SO_2, CO, and O_3, collected from open-source platforms and IoT-enabled monitoring stations within the Mumbai Metropolitan Region. The proposed system incorporates data pre-processing techniques for noise reduction and missing value imputation, followed by feature engineering to extract temporal patterns and spatial influences. ARIMA effectively models the seasonal and linear trends in pollutant concentrations, while the Random Forest algorithm captures complex nonlinear relationships across various locations and environmental variables. Empirical results demonstrate that the hybrid model significantly outperforms standalone predictive methods in terms of Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R^2 score, indicating its robustness and applicability for real-world deployment.This research not only contributes a scalable solution for urban environmental monitoring but also supports governmental bodies and smart city initiatives in developing adaptive air quality management systems. Future enhancements may include the integration of deep learning architectures such as LSTM and the use of GIS-based dynamic visualization tools for interactive spatio-temporal air quality mapping.

Keywords: Air Quality Prediction, Machine Learning, ARIMA, Random Forest, Environmental Monitoring, Spatio-Temporal Data, Smart Cities