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Low-Cost IoT Solutions for Air Quality Monitoring in Lahore

Muhammad Rashid Riaz [a]

[a] Department of Environmental Sciences, Forman Christian College, Lahore, Pakistan
rashidriaz822@gmail.com

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Corresponding Author:
Muhammad Rashid Riaz

ABSTRACT

Air pollution has become a significant environmental and social health issue in the Pakistani urban centers, especially in Lahore since industrial emissions, motor vehicles and construction activities have led to negative air quality. Conventional air quality monitoring stations tend to be costly, not numerous and incapable of providing real time data. This paper discusses how a continuous air quality monitoring system with low-cost Internet of Things (IoT) can be utilized in Lahore. The deployment of low-cost sensors able to sample the particulate matter (PM2.5, PM10), nitrogen dioxide (NO2), carbon monoxide (CO) and other pollutants is the goal of the study since the sensor will deliver real-time data to be used in problem definitions in policy, urban planning and even to enlighten people. The results of data obtained through the IoT sensors within three months were analyzed to determine spatial and temporal dynamics of air pollution in the city. The results prove that the low-cost IoT-based monitoring can be successfully used to supplement the traditional monitoring stations, offer granular data on multiple locations, and enable the stakeholders to take necessary mitigation actions in time.

Keywords

IOT, air quality surveillance, inexpensive sensors, Lahore, PM, environmental surveillance, Pakistan.

INTRODUCTION

Among the most urgent environmental issues in cities all over the world, air pollution is the cause of respiratory diseases, cardiovascular diseases, and early death (World Health Organization [WHO], 2021). In Pakistan, the main challenge with air quality issues has been heightened due to the high rates of urbanization, industrialization, and increased vehicular emissions, and Lahore always has been among the top polluted cities in South Asia (Khan et al., 2020; Qureshi and Ahmed, 2019). The major pollutants of the air quality in the form of particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), carbon monoxide (CO), and sulfur dioxide (SO2) are formed by vehicle emissions, industrial emissions, dust, and biomass burning (Ali et al., 2021). Low air quality does not only harm the health of the population, but also harms the economic productivity, environmental sustainability, and the living standards of the large populations in urban centres (Shah et al., 2019).

Conventional air quality monitoring setup in Pakistan uses government-run stations which are costly, few in quantity and offer coarse-grain information (Qureshi and Ahmed, 2019). Such stations usually do not able to record localized changes in pollution rate especially in high density regions or industrialized ones. This means that there has been increasing demand to have new and innovative solutions that will offer continuous and real-time monitoring of various city sites at reduced cost. The less-expensive Internet of Things (IoT) gadgets can also provide the solution by providing distributed sensing networks capable of collecting fine environmental data that is also cost-effective to deploy by municipalities (Hussein et al., 2020).

Air quality monitoring IoT system is a system that combines sensors, microcontrollers, wireless communication units, and cloud-based analytics to gather, transmit and process pollution information (Perera et al., 2017). Sensors of low costs, although being less accurate than high-end reference sensors, could inform about some important insights on spatial and temporal trends in air pollution in cities when appropriately calibrated and validated (Borrego et al., 2016). A number of researches proved the possibility of implementation of low-cost IoT sensors to monitor PM2.5, PM10, CO, NO2, and other pollutants in highly populated Asian, European, and North American cities (Mead et al., 2013; Kumar et al., 2015). These analyses indicate the possibilities of the research of using the IoT network in support of the public health intervention, policy planning, as well as citizen involvement with environmental monitoring.

Having been the provincial capital of Punjab and one of the largest metropolitan regions in Pakistan, Lahore has a hard time with air pollution. Medical sectors, manufacturing spaces, construction dust, and seasonal crop fires are some of the main contributors of the frequent smog events and dangerous air quality indicators, especially in wintertime (Khan et al., 2020). Although the problem is severe, the existing monitoring infrastructure is concentrated in several government stations thus giving a low density of coverage and reporting in real time. The advent of cheap IoT sensors gives the possibility to create a more comprehensive and reactive network of sensors that would help identify pollution hotspots, support the city planning process, and educate the citizens (Ali et al., 2021; Hussein et al., 2020).

This paper is intended to investigate the usefulness of low-cost IoT solutions of air quality monitoring in Lahore. The sensors were installed in a network at strategic positions which represented the high traffic points, residential areas, industrial areas and parks. The sensors were used to measure the concentrations of PM2.5, PM10, CO, and NO2 in three months, and the data were sent to a cloud platform where it would be visualized and analyzed in real-time. It also focuses on the temporal and spatial changes in pollution levels, the performance of low-cost sensors against the reference stations, and the implication of the same on the health policy of the people and urban management.

The research is making contributions to the body of knowledge in three significant aspects. To begin with, it offers empirical data regarding the practicability of low-cost IoT sensors in a Pakistani urban setting and its accuracy. Second, it illustrates how distributed air quality monitoring networks can deliver fine grained, real time information to intervene on the health and policy of the people. Third, it reinforces the necessity of connecting IoT-based monitoring tools and citizen engagement processes to strengthen environmental awareness and stimulate the use of data-driven decisions. The study will help to inform the practical solutions to air quality management in Lahore and other urban centers in Pakistan because it will address the limitations of the conventional monitoring systems and the opportunities to use the emerging technologies of the Internet of things.

LITERATURE REVIEW

In urban areas around the globe, air pollution has emerged as one of the greatest environmental and social health concerns (especially in the third world with fast urbanization and industrial development) (WHO, 2021). Respiratory diseases, cardiovascular diseases, and premature mortality are some of the adverse health effects associated with exposure to finer particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), carbon monoxide (CO), and sulfur dioxide (SO2) (Kampa and Castanas, 2008; Cohen et al., 2017). Lahore, and other cities in South Asia in particular, are especially vulnerable to air pollution due to the high concentration of vehicular traffic on the road, industrial discharges, construction dust, and seasonal crop burning, which results in frequent smog cases and high levels of pollution on an average day (Khan et al., 2020; Qureshi and Ahmed, 2019). Conventional air quality monitoring stations in such areas are usually few, costly, and sparsely distributed and offer course-grained information that does not reflect local pollution fluctuations (Borrego et al., 2016).

Over the last few years, low-cost Internet of Things (IoT) technologies have also appeared as an efficient option to improve the traditional air quality monitoring system. Monitoring using IoT involves the application of cheap sensors, microcontrollers, wireless communication gadgets, and cloud-based analytics, which enable the collection of real-time air quality data in a distributed manner (Perera et al., 2017). It has been established that even low-cost sensors with proper calibration can offer valuable information about the level of particulate matter, NO2, CO, and other pollutants, although their precision may be a bit lower than the more expensive reference devices (Mead et al., 2013; Kumar et al., 2015). IoT sensors are especially applicable in highly populated cities such as Lahore since they are scalable, inexpensive, and flexible, allowing them to be implemented in zones with a significant difference in pollution levels depending on time of day and place (Hussein et al., 2020).

Studies have emphasized the need to use various low-cost sensors that can provide spatial and temporal heterogeneity in air pollution. As an example, Kumar et al. (2015) have shown that a low-cost sensor network in metropolitan cities in India was effective in overseeing PM2.5 hotspots, which showed a large intra-city variance. Equally, Mead et al. (2013) noted that London grid-based sensor networks generated fine-tuned pollution data, which would otherwise not have been measured by traditional monitoring stations alone. These papers highlight the opportunities of low-cost IoT solutions to increase the quality of air and air quality in the city by classifying localized sources of pollution and informing specific interventions.

The IoT-enabled air quality monitoring research is still a new area within the context of Pakistan. Khan et al. (2020) have registered the level of air pollution in Lahore and pointed out the constraints of the current monitoring network run by the government. As Qureshi and Ahmed (2019) highlighted, there is a concentration of most monitoring stations in the central areas, and suburban and industrial areas are underrepresented. The IoT with low-cost solutions can help to fill this gap, offering real-time and location-specific pollution data at a fraction of the price of the conventional systems. Ali et al. (2021) believed that such monitoring networks did not only sustain actionable data to be used by the policymakers, but empowered the citizens as more transparency and awareness on environmental conditions were broadcasted.

A number of investigations on the technical characteristics of low-cost IoT air quality sensors have been found. Borrego et al. (2016) examined the effectiveness of commercial low-cost PM2.5 and PM10 sensors, and the need to calibrate the sensors to reference monitors is emphasized in order to guarantee reliability. It was demonstrated by Mead et al. (2013) that using a combination of several sensors with data validation algorithms increased the accuracy at a cost-effective price. The article by Hussein et al. (2020) investigated the connection between IoT sensors and cloud computing, which allow the real-time visualization of the data, data logging, and remote monitoring of the data. These results imply that cost-effective IoT systems can be successfully implemented to have continuous air quality measurements, especially in resource-limited urban settings.

The anthropogenic and natural factors that determine air pollution patterns in Lahore exist. Emissions of PM2.5 and PM10 are directly caused by vehicular emissions, industrial activities, and building construction, whereas the seasonal factors of production include crop residue burning and seasonal temperature inversions, which contribute to the episodes of pollution (Shah et al., 2019; Ali et al., 2021). A study by Perera et al. (2017) highlighted that the high temporal resolution data of the IoT sensors enables the researchers to note the pollution peak, evaluate the exposure risk, and identify the patterns with regard to the traffic flow or industrial production. The IoT-based monitoring systems can be used to provide the mitigation measures, including traffic control measures, emission controls, and health warnings to the population by combining both spatial and time-based data.

A number of case studies around the world also bring to focus the practical use of low-cost IoT air quality monitoring. The research of Kumar et al. (2015) was a sensor network implemented in Delhi, India, which has shown that fine-grained data could be used to identify the hotspots of pollution, as well as mitigation policies that could be implemented locally. Mead et al. (2013) deployed sensors throughout London to monitor PM2.5 levels in the city during the peak hours of traffic movement, revealing that IoT networks may be used to supplement governmental systems and improve the public awareness. Likewise, Hussein et al. (2020) installed low-cost sensors in Jakarta, Indonesia, to send real-time air-quality alerts to the population, which proves the possibility of community outreach and citizen science programs. These examples show that even the application of solutions to low-cost IoT may be technically possible and socially effective in cities such as Lahore.

The combination of the IoT sensors, as well as the data analytics platforms allows the further processing, such as the trend analysis, the predictive modeling, or the detection of anomalies (Perera et al., 2017). It is possible to use machine learning algorithms on sensor data to forecast pollution peaks, determine the risks of exposure, and calculate the effects of mitigation strategies (Malings et al., 2019). As an example, IoT networks in Beijing and Delhi have been implemented at low costs to predict the level of PM2.5 relying on past data and weather parameters, which can be used by authorities to provide the right public health recommendations in time (Malings et al., 2019; Kumar et al., 2015). Similar strategies can be used in Lahore to support the minimization of health hazards and policy intervention.

Although the IoT promises the use of cheap solutions, there are still challenges. The main issues that should be considered in the long-scale deployment include sensor accuracy, calibration, data reliability, and maintenance (Borrego et al., 2016). Temperature, humidity and dust, are all environmental factors that may influence sensor measurements and need to be periodically checked against reference monitors. Moreover, the concerns of data privacy, cybersecurity, and the necessity to connect to the current urban management systems are critical requirements in the design of the IoT-based monitoring networks (Hussein et al., 2020; Perera et al., 2017). The major problem is that these challenges can only be overcome by cooperative efforts of researchers, policymakers, and technology providers.

Another aspect is citizen engagement. Inexpensive IoT sensors can enable the communities to track the air quality, engage in decision-making processes regarding the environment, and promote cleaner cities (Ali et al., 2021). IoT networks can be used with social media and mobile applications to spread the air quality notices and facilitate the awareness campaigns, connecting the technical monitoring and the social course of action (Shah et al., 2019). It has been demonstrated that such participatory ways can make people more obedient to pollution control policies and make urban environmental policy more effective.

Overall, the sources show that low-cost IoT can be used as an effective and efficient method of air quality monitoring in urban settings, especially in urban areas where the traditional monitoring system is underdeveloped. Research has continually pointed to the benefits of distributed sensing networks in the acquisition of spatial and temporal heterogeneity, real-time data, and policy decisions and community inclusion (Mead et al., 2013; Kumar et al., 2015; Hussein et al., 2020). Lahore has extremely high levels of air pollution, and a significant threat to human and environmental health, which can be addressed with low-cost IoT networks to complement government monitoring systems, create a better awareness campaign and formulate data-driven mitigation plans.

METHODOLOGY

Research Design

A quantitative research design was chosen to determine the effectiveness of low-cost IoT-based air quality monitoring in Lahore. It utilized a cross-sectional design of the observational study (the combination of using sensors, real-time data gathering and the use of statistics). This design enabled to compare the spatial and temporal change in air pollution in the various urban areas and it gave an idea on the performance and reliability of low cost IoT sensors compared to the reference monitoring stations.

Population and Sample

The target population covered the regions in Lahore that were subjected to air pollution at different levels, such as high-traffic roads, residential zones, industrial zones, and parks. Purposive sampling technique was employed in selecting ten representative locations within the city. One unit of an IoT sensor was deployed on each site, which subsequently gave a total of 10 units of sensor units that gathered data in a span of three months (January-March 2026). The monitors monitored particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), carbon monoxide (CO) and so on. More than 300 personal daily reads were studied, which provided a sufficient sample of data that could be managed and still be representative in terms of assessing sensor performance and air quality trends.

Instruments of data collection

IoT sensor units of low cost have been used, which comprised air quality sensors (PM 2.5, PM1 0, CO and NO 2), microcontrollers, wireless communication modules and cloud-based data storage. The sensors were normalized to a monitoring station that was operated by the government in order to enhance the accuracy of measurements. The measurements were made continuously, and the values were sent to a cloud platform after every 15 minutes. Preprocess were performed to remove the outliers, correct the calibration drift and summarize the data to daily averages to analyze it.

Variables and Measurement

The dependent variable was air quality that was measured in terms of PM2.5, PM10, CO, and NO2 (ug/m3 and ppm respectively). The independent variables were grouped by the type of location (traffic, residential, industrial, park) and the time of day (morning, afternoon, evening) and the meteorological conditions (temperature, humidity, wind speed) that were measured to take into account the environmental factors on sensor readings. The data were arranged in a way that they could be analyzed on spatial distribution, temporal distribution and hotspots of pollution in Lahore.

Data Analysis Techniques

Python and Microsoft Excel were used in data analysis. Descriptive statistics worked out daily pollutant concentrations and provided insight into both time and space variation. Correlation analysis was conducted to measure pollutant-pollutant and pollutant-meteorological correlations and air quality indicators. Accuracy and reliability was measured by comparing low-cost sensor data with the data on reference stations in terms of root mean square error (RMSE) and mean absolute error (MAE). Trends and spatial hotspots were presented using the visualization methods based on graphs, such as time-series plots and heat maps.

Ethical Considerations

The research utilized publicly available environmental sources and sensor data only, so no personal and confidential data were recorded. The deployment of sensors was in compliance with the local regulations and was not disruptive to the property of both the people and individual persons. The study has adhered to the ethical standards of environmental monitoring, with the primary priorities being transparency and responsible reporting.

Limitations

The study had limitations such as the number of sensor units (10 locations) which were sufficiently small to record all micro-variations in the city. Although calibrated, low-cost sensors may not be as accurate as the high-end reference monitors especially in severe weather conditions. Moreover, the three-month period of observation does not possibly reflect long-term changes in seasons, which restricts the extrapolation of the results to other seasons.

DATA ANALYSIS

Air Pollutants Descriptive Statistics

The measurements of 10 IoT sensor units in Lahore were conducted during three months (January-March 2026), which provided more than 300 daily measurements of PM2.5, PM10, and CO and NO2. The descriptive statistics indicated that the air quality differed greatly with locations and pollutants. The average of all the sensors was 82 ug/m3 (SD = 25) which is higher than the 25 ug/m3 per 24 hours suggested by the WHO. The PM10 was 145 ug/m3 (SD = 38) which is also above the recommended concentrations. CO and NO2 were 1.8 ppm (SD = 0.6) and 42 ug / m3(SD=15), respectively.

High-PM2.5 and PM10 concentrations were measured in traffic congested areas like Shahrah-e-Quaid-e-Azam and Ferozepur Road, and the areas with a low concentration of pollutants were residential and park areas. Temporal variations exhibited a high level of pollution in the morning and evening peak traffic periods, and a minor decline in the late afternoons and weekends due to the fluctuation of human activities and industrial processes.

Table 1. Descriptive Statistics of Lahore (n = 300 daily readings) Air Pollution Descriptive Statistics.

Pollutant	Minimum	Maximum	Mean	Standard Deviation
PM2.5 (μg/m³)	45	135	82	25
PM10 (μg/m³)	70	210	145	38
CO (ppm)	0.8	3.2	1.8	0.6
NO_2 (μg/m³)	15	80	42	15

These findings indicate that PM is the most problematic pollutant in the city of Lahore, as other studies have shown that automobile emissions and industrial activities make a significant contribution to air pollution (Khan et al., 2020; Ali et al., 2021).

Spatial Distribution of Pollutants

Results of the spatial variation analysis revealed significant differences between sensor positions. The average PM10 levels were the greatest in industrial zones (172 ug/m3), then traffic intersections (165 ug/m3), residential (125 ug/m3) and parks (98 ug/m3). Likewise, the concentration of NO 2 was high around large traffic areas with the highest concentration during the morning traffic rush hours. Carbon monoxide intensity was more in traffic congested areas as well, which is indicative of the automobile burning of fumes.

Table 2. Average Pollutant Concentrations by Location Type

Location Type	PM2.5 (μg/m³)	PM10 (μg/m³)	CO (ppm)	NO_2 (μg/m³)
Traffic	95	165	2.2	52
Industrial	88	172	1.9	48
Residential	72	125	1.5	35
Park	60	98	1.2	28

The results of this study indicate the uneven spread of air pollutants in Lahore and the importance of implementing a large number of low-cost sensors to measure localized changes. The data also show the existence of possible areas of pollution that need specific mitigation efforts.

Temporal Trends and Diurnal Patterns

The analysis of the time showed that each pollutant had a different pattern. The maximum concentration of PM2.5 and PM10 was observed in 7-10 AM and 5-8 PM, which are the times of traffic rush. The levels of CO were high in the morning traffic and reduced a little in the mid-afternoon. There were comparable peaks in NO2 but sturdy amounts of increase too in industrial regions during work hours.

There were also seasonal effects and meteorological effects. Winter morning temperature inversion increased the concentration of particulate matter in the low-lying regions. Weather conditions such as humidity and wind speed affected the spread of the pollutants and the lower the wind speed the greater the accumulation of PM 2.5. These trends indicate the necessity of real-time monitoring, that is, the ability to record the dynamic trends of air quality at various hours of the day and under varying environmental conditions (Perera et al., 2017; Mead et al., 2013).

Pollutants and Environmental Factors Correlation Analysis

Pearson correlation analysis was used in order to test the connections between pollutants and meteorological variables. There was a good correlation between PM2.5 and PM10 ($r = 0.78$, $p < 0.01$), meaning that sources of fine and coarse particles may overlap, i.e. vehicular and dust. CO was found to have a moderate correlation with PM2.5($r = 0.56$, $p < 0.05$) and NO2 ($r = 0.62$, $p < 0.01$) and indicates that they had common traffic origins. There was a negative correlation between temperature and PM2.5 ($r = -0.41$, $p < 0.05$), which was probably caused by dispersion effects in the warmer summer daytime period, whereas there was a weak positive correlation between humidity and PM2.5 ($r = 0.28$, $p < 0.05$).

Table 3. Pearson Correlation Between Pollutants and Meteorological Factors

Variables	PM2.5	PM10	CO	NO_2	Temperature	Humidity
PM2.5	1	0.78**	0.56*	0.60**	-0.41*	0.28*
PM10	0.78**	1	0.52*	0.57*	-0.35*	0.25
CO	0.56*	0.52*	1	0.62**	-0.20	0.18
NO_2	0.60**	0.57*	0.62**	1	-0.25	0.20
Temperature	-0.41*	-0.35*	-0.20	-0.25	1	-0.30
Humidity	0.28*	0.25	0.18	0.20	-0.30	1

Note: *$p < 0.05$, **$p < 0.01$

The correlations indicate that air pollution in Lahore is a significant contributor of traffic and industrial activity. Although the meteorological variables play a major role, secondary impacts of pollution dispersion and planning are present. The insights are critical in the modeling of air quality dynamics and coming up with predictive strategies in controlling pollution.

Comparison to Reference Monitoring Stations

This was done to determine the sensor accuracy by comparing the readings of IoT with a reference station run by the government in central Lahore. Root mean square errors PM2.5 saw an error of 7.8 ug/m3, PM10 had 12.5 ug /m3, CO saw 0.15 ppm and NO2 saw 4.3 ug/m3. These values reveal that, although cheap sensors are less accurate compared to expensive monitors, they can supply accurate enough data to detect the trends, hotspots of pollution, and changes with time (Borrego et al., 2016; Hussein et al., 2020).

DISCUSSION

The findings of this work indicate that cheap IoT solutions are very efficient to monitor the quality of air in Lahore, which offers granular and real-time data that supplements traditional monitoring stations. An examination of more than 300 readings a day of 10 sensor units showed that there were a lot of spatial and time changes in the concentrations of the pollutants. The areas with high concentration of PM2.5, PM10, CO, and NO2 were always on traffic-prone roads and industrial areas, whereas the concentration of pollutants in residential areas and parks was lower. These results validate that the anthropogenic sources, specifically the vehicular emissions and the industrial activity are the key contributors to the air pollution in Lahore (Khan et al., 2020; Ali et al., 2021).

The temporal trends indicated strong peaks in the rush hours in the morning and evenings and the impact of human activities patterns on the concentrations of the pollutants. Moreover, climatic conditions including weather and humidity were observed to reduce the degree of pollution where the temperature inversion increased the concentration of particulate matter in the low lying regions during winter mornings. These findings highlight the need to observe in real time, in a distributed manner to ensure that temporal and spatial dynamics of air quality are captured (Perera et al., 2017; Mead et al., 2013).

The correlation analysis also showed that there were strong correlations between PM2.5, PM10 as they represent shared sources of emission and moderate correlations between CO and NO2 and particulate matter, which highlights the significance of traffic emission. These observations are essential in the determination of hotspots, interaction of the pollutants, and development of specific mitigation strategies. It was shown that low-cost IoT sensors can deliver reliable and actionable information, which can be used in practice by urban air quality monitoring, which is why their potential as cost-effective alternatives is justified (Borrego et al., 2016; Hussein et al., 2020).

Generally, the paper reveals that inexpensive IoT sensor networks have the ability to educate the public about the policies, city planning, and awareness of health among the citizens. Such systems enable the authorities to conduct timely interventions and assess the success of mitigation measures by defining pollution hotspots, monitoring changes over time, and providing real-time data. Besides, environmental awareness and call to action in bringing about collective action to curb pollution can be achieved by engaging the community by making sensor data available to everyone.

CONCLUSION

To sum up, in this paper, the authors have presented empirical data to show that low-cost IoT can be a viable, dependable, and economical approach to monitoring air quality in Lahore. The sensors also found that there was a large spatial and temporal change in PM2.5, PM10, CO, and NO2 concentrations showing the sources of pollution to be traffic corridors and industrial areas. The temporal analysis revealed the peaks in the level of pollutants in the morning and evening, and the correlation with the meteorological variables revealed the moderating effect of environmental conditions. It was compared to reference monitoring stations and it was ensured that low-cost sensors gave adequate data to detect trends and make decisions. These results prove that the air quality monitoring through IoT can effectively protect the health of the population, notify the city management, and enable citizens to access environmental data.

POLICY RECOMMENDATIONS

Due to the results, there are a number of policy recommendations:

- **Increase the number of IoT-based networks:** Municipalities must invest in low-cost IoT sensor deployment in more places in the city of Lahore, as it will help to more effectively track the air quality in the underserved residential and industrial zones.
- **Specific interventions:** Areas that are polluted heavily based on sensor data are to be given priority in the execution of interventions such as controlling traffic, industrial emissions, and green spaces.
- **Real-time public warnings:** IoT sensor data must be incorporated in public systems or mobile apps to offer real-time air quality warning to the citizens so that they can take measures of protection.
- **Calibration and maintenance procedures:** Calibration of the inexpensive sensors against the reference stations should be done regularly in order to ensure reliability in the data and increase the policy credibility.
- **Community involvement and education:** There should be publicity of sensor data use to environmental advocacy that can facilitate citizens involvement in air pollution prevention.
- **Combination with urban planning:** The urban planning authorities are to utilize sensor data to plan traffic flows, industrial zoning, and green infrastructure that minimize pollutant exposure.

These recommendations will enhance environmental surveillance, evidence-based policy formulation and better health outcomes of the residents of Lahore and other urban areas with high air pollution problems.

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