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A Comprehensive Review of Wireless Sensor Networks Based Air Pollution Monitoring Systems

R. Kingsy Grace[1] · S. Manju[1]

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Abstract
Wireless Sensor Networks (WSN) consists of sensors used for sensing environmental conditions and many more applications in real world. Air pollution is a threat to the life of humans. To control the air pollution it is necessary to monitor the pollutant gases in periodically. Various air pollution monitoring systems using sensor network have been developed, deployed and tested in the literature. This paper presents a comparative study about the literature for air pollution monitoring systems based on the classification such as stationary air pollution monitoring systems, dynamic air pollution monitoring systems and pollution data analysis techniques. These pollution monitoring systems are compared based on the methodologies followed, microcontroller used, communication device used, pollutants analyzed using sensors, evaluation attributes, tested location and performance of the system. This paper also discusses the merits and demerits of the air pollution monitoring systems.

Keywords Air pollution · Sensor network · Air quality

1 Introduction

Air pollution is a major challenge to public health across globe. According to WHO report, in each year 2.4 million people [1, 2] lose their life because of breathing disorders that originate from air pollution. Polluted air might affect human heart, lung, eye, nose, throat and skin, leading to disorders such as breathing trouble, lung cancer, bronchitis and pneumonia. There are number of reasons for air pollution. When the reasons are sorted out, the emission of harmful gases like CO [3] into air rules out. In developing country like India, almost 72% of transportation is based on roadways [4] which highly pollute air. The US Environmental Pollution Agency [US EPA] [5, 6] has listed Ground Level Ozone (O_3), Carbon Monoxide (CO) and Hydrogen Sulfide (H_2S) as the most polluting gases. Some of

✉ R. Kingsy Grace
kingsygrace.r@srec.ac.in

S. Manju
manju.s@srec.ac.in

[1] Department of Computer Science and Engineering, Sri Ramakrishna Engineering College, Coimbatore-22, India

the other gas that affects the environment includesNitrogen Dioxide (NO_2) [7], Particular Matter less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$) [8].

In order to reduce the pollution in the environment, governments have taken lots of efforts for air pollution monitoring and analysis. Also scientists, environmental experts and policy makers are making decisions on improving the quality of living environments. Air pollution is monitored in two ways, either using stationary monitors or vehicular/dynamic pollution monitoring. The former is the conventional pollution monitoring systems. These monitors produce highly reliable and accurate pollution data [3, 4, 9]. Gas chromatograph–mass spectrometers [5] are the devices used for traditional air pollution monitoring. These devices are larger in size, heavy in weight and more expensive [5]. The traditional monitoring devices are used in urban areas and those are location specific. Vehicle emission is a major contributor for air pollution in urban areas worldwide. By 2020, the vehicle ownership will hit to a total count of 2 billion [8]. Unlike stationary pollution monitors, the vehicle pollution monitors are cheaper and can be fixed on vehicles. The pollutant data from the sensors have to be stored on storage devices or on cloud for further processing [3]. The research on pollution data analysis is done in the literature to analyze the polluted data to get the information such as Air Quality Index (AQI).

The remaining part of the paper is organized as follows: Air Quality Management is discussed in Sect. 2. Section 3, presents the necessary facts of environmental monitoring. Section 4 deals with the Stationary Pollution Monitoring Systems. Dynamic/Vehicular Pollution Monitoring Systems is discussed in Sect. 5. Pollution Data Analysis Techniques are elaborated in Sect. 6. Section 7, presents the summary of the Sects. 4, 5 and 6. Section 8 concludes the paper with research directions.

2 Air Quality Management

Air pollution research was started in early 1955s by scientists in California and funded by University of California, Los Angeles (UCLA). The first scientist who identified particles and their photochemical process in Los Angeles was Albert Bush. In 1966, scientist Bush collected air samples from cities in Europe, Africa, Asia, Australia, New Zealand, and Tahiti and build a data base on smog. From then air pollution research was done by many scientists and researchers worldwide. Most of these researches are having social and research perspectives. Nowadays all over the world the cities are integrated to Information and Communication Technology (ICT) and Internet of Things (IoT) technology to promote urban development. The IoT technology is used to manage and improve the city's asserts and services. Across the globe air quality monitoring regulations are framed by each country uniquely to save the humans and environment from harmful gases in the air.

According to WHO, Urban Air Pollution (UAP) is a major cause of death due to respiratory illnesses. The older vehicles, poorly maintained vehicles, low quality fuel and poorly maintained roads cause 70–80% of air pollution in developing countries urban areas [10–16]. The pollutants which are responsible for polluting air in mega cities are: (1) NitrogenOxides (NO_X), (2) Sulfur dioxide (SO_2), (3) CO, (4) PM and (5) Volatile Organic Compounds (VOCs). Estarreja is an urban city in Portugal has observed that the urban air quality standards for O3 and PM10 are exceeded [17]. e-UAQMP framework is a standard to forecast air pollution in urban areas which has been proposed by Gokhale and Khare and also suggested ideas for reducing air pollution [18]. In UK, 92% of urban areas have considered Air Quality Management Areas (AQMAs) because of 33% emissions of NO_X and

21% of PM_{10}. Vehicle pollution is a major source in those areas and violates UK's national ambient air quality standards/objectives [19]. The vehicular air pollution from 1990 to 2009 is reduced around 54% in SO_2, 27% in NO_X, 16% in PM_{10} and 21% in $PM_{2.5}$ for European Environment Agency (EEA) countries. But 18% to 49% of people in EEA countries are still in the exceeding the ambient standards for PM_{10} [20].

The Asian countries such as Singapore, Japan and Hong Kong are having increased air pollution near road ways due to the large number of transportation vehicles [21–23]. The PM and NO_2 levels are very high in the developing nations due to the fact of increased urbanization. WHO guidelines for PM and NO_2 levels are increased in the cities like New Delhi, Mumbai, Shanghai, Guangzhou, Chongqing, Calcutta, Beijing, and Bangkok [24]. PM_{10} and NO_2 ambient in Shanghai and Pearl River Delta are six times higher than the developed countries concentrations [25].

AQI is the measurement used for indicating and managing the pollutant concentration in air. It is used for reporting air quality in daily basis. Air quality index values are typically grouped into ranges. AQI ranges from 0 to 500. Above 300 is hazardous and 50, the risk is low.AQI is calculated from five major pollutants in the air indicated by the Clean Air Act. They are namely: (1) ground-level ozone, (2) particle pollution, (3) CO, (4) SO_2, and (5) NO_2. Increased AQI index means higher air pollution and the health concern is also very high. AQI values are spitted intodifferent groups. Each group is assigned with the parameters, namely: (1) a descriptor, (2) a color code, and (3) a standardized public health advisory [26, 27]. The AQI is shown in Table 1.

3 Environmental Monitoring

Environmental monitoring is used to ensure the quality of the environment through some activates and processes. The important process in the environmental monitoring is the systematic sampling of air, water, soil, and biota to observe and study the environment, and to derive knowledge [28–30]. The review of the monitoring will be based on the factors monitored. Air pollutant concentrations are very harmful to the health of the citizens and are monitored with specialized equipment's and analyzed using statistical and algorithmic methods. Usually air quality monitors are handled by researchers, regulatory agencies and citizens. The analysis of monitored air quality is based on spatial and temporal representation of data and the monitored pollutants health effects. Basically clean air is good for health and it is necessary to monitor environment for gathering pollutant concentration in it. One of the applications of Internet of Things (IoT) is environment monitoring [31]. Environment sensors are used for designing the IoT devices to monitor the environment. Environment monitoring is having eight aspects such as monitoring air, monitoring water, monitoring soil, monitoring forests, monitoring for natural disasters, monitoring fisheries, monitoring snowfall levels and monitoring data centers.

4 Stationary Air Pollution Monitoring Systems

This section presents the research done on stationary air pollution monitoring systems. Raja Vara et al. [32] have proposed a real time air pollution monitoring system that monitors the calibration level of various gases like CO_2, NO_2, CO, O_2. The system also senses temperature and humidity of the environment. In the system all the gas sensors are integrated

Table 1 AQI [26, 27]

Air quality index (AQI) values	Levels of health concern	Colors	Meaning
0–50	Good	Green	Air quality is considered to be satisfactory; air pollution poses little or no risk
51–100	Moderate	Yellow	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution
101–150	Unhealthy for sensitive groups	Orange	Members of sensitive groups may experience health effects. The general public is not likely to be affected
151–200	Unhealthy	Red	Everyone may begin to experience health effects; Members of sensitive groups may experience more serious health effects
201–300	Very unhealthy	Purple	Health alert: everyone may experience serious health effects
301–500	Hazardous	Maroon	Health warning of emergency conditions. The entire population is more likely to be affected

using wireless sensor motes and deployed in IIT campus Hyderabad and across major cities of Hyderabad. The significance of the work is its live streaming of pollution related data using multi hop data aggregation algorithm. The system has a light weight middle ware and interface to live stream the calibration of pollution level. Various sensors like CO_2 and O_2 gas sensors are integrated into a gas chamber designed with a gas outlet. The test gas is given inside the chamber and the concentration of each gas is measured from which the calibration equation for each gas is derived. The gas chamber is fixed in the environment and the sensed data is live streamed at the server end using the middleware. The system was found to costlier because of the wireless motes and the energy consumption was found high. Hence the use of data compression and modeling algorithms were encouraged.

Kanzheng et al. [33] have introduced a Low Power Wide Area (LPWA) based air quality monitoring system. The architecture of this system is organized into three layers namely sensing, network and application layer. The sensing layer consists of sensor nodes that are placed in wide geographical area. The sensor nodes senses and reports data to the network layer. The network layer comprised of LPWA network provides ubiquitous connectivity between sensor nodes and Access Points (AP). The receivers' sensitivity is improved by implementing Direct Sequenced Spread Spectrum (DSSS). Access Point was developed based on open source software defined radio. The data transmitted from network is process at application layer which is subdivided into two parts. First, is the IoT Cloud in which the AP stores the air quality reports. Second is the client application from which the users can obtain the air quality information. Walter et al. [34] have proposed a Wireless Sensor Network Air Pollution Monitoring System which measures the CO, CO_2 and dust density in air . This system extremely focused on hardware and interface design based on open source and low cost platforms which is economical when compared to other air pollution monitoring systems. The system fixes a node in area to be monitored which has Arduino UNO R3 for processing and sensors for collecting information. Then the data collected is transferred to database which is bridged by C/C++ API. The client side service is provided by using REST web service architecture developed using Eclipse and MySQL. The development process involves scrum with extreme programming which focused on test driven development, incremental design and continuous integration. Testing was done for a period of 1 h at three distinct places like Jipijapa, Castle of Amaguana and Amazon basin. Results obtained were checked with the WHO regulations. It was found that CO content in air exceeded the normal value which was found from statistical processing of two parameters like Confidence Value and Standard Deviation.

Mohammed et al. [35] have proposed a cost effective environmental monitoring system using Raspberry Pi. The system includes various design process like sensing air quality, weather (Temperature, Humidity, Light Level, Earthquake). The Raspberry Pi is connected to air quality detection sensor, temperature, humidity and earthquake prediction sensor. The Raspberry pi collects the information from the sensors, interprets meaningful values and projects it to the client applications through internet. The software part of data processing was developed using open source python libraries. An air pollution monitoring system called Polluino [36] was proposed by Giovanni et al. Polluino is an Arduino based sensor device which collects and transmits air quality data from multiple sensors installed. This system monitors 12 gases like Carbon Monoxide, Carbon Dioxide, Nitrogen Dioxide, Methane, Hydrogen Sulfide, Ozone, Ammonia, Particulate Matter, Benzene, Ethanol, Toluene, Propane contents in air. The Arduino controller is connected to internet via ESP8266-01 wifi module and controls all 12 sensors. Additionally five environmental sensors like temperature, humidity, photo resistor, flames, and rain drop sensors are also connected to Arduino. The communication between sensors and cloud is achieved by

ThingSpeak that uses REST API approach. The data collected from ThinkSpeak was analyzed and visualized by MATLAB applications. When the received value of pollutants in air exceeds threshold values then alerts are generated to respective authorities. In terms of power, cost and performance Polluino system was found to appreciable.

Umesh et al. [37] have proposed a pollution monitoring system where the sensors are kept mobile and polluted area is identified using Global Positioning System (GPS). Three sensors were used to measure the levels of CO, NO and SO_x. The data collected are analyzed using association rule mining. Using Apriori algorithm the frequent term sets are identified. The support degree and confidence value of the strong associations are calculated and checked against the threshold values of support degree and confidence value. Balasubramaniyan and Manivannan [38] have proposed an IoT Enabled Air Quality Monitoring System (AQMS) using Raspberry Pi. The system consists of sensor motes connected to processing power Raspberry Pi which has a local SQL database. The data collected from sensors are transferred from processing power to the Thing Speak cloud services using wifi module through the network router. The data stored at cloud services are analyzed through MATLAB code. The results of data analytics are given as alerts to the user devices.

Lamling et al. [39] has come up with a deep literature comparison and calibration of all the gas sensors widely used in the market for three gases like O_2, CO and CO_2. Calibration is the process of converting the electric signals obtained from sensors into numeric values that could be understood by human. In this system Mass Flow Controller (MFC) was used to analyze the concentration of test gases. Then the sensors were analyzed based on the three parameters like Noise level, Sensitivity and Response time. For Calibration of CO sensors like Alphasense CO-BX, CO-AX and CO-D4 and Transducer Technology RCO100F and 3CO1ET1500, synthetic air was used. Calibration of CO_2 gas sensor TSG4161 was done with Nitrogen and Argon gas. For the calibration of Figaro KE-25 Oxygen Sensor, oxygen from oxygen generator and Argon gas was used. Further calibration to be considered based on humidity and temperature. Gary et al. have proposed a new technique called On-Road Heavy-Duty Vehicle Emissions Monitoring System (OHMS) was proposed. The OHMS is composed of three systems, an exhaust collection system, vehicle monitoring equipment and a suite of gas and particle analysis instruments. The exhaust collection system is an extra-large event tent that allows a heavy duty truck to pass safely underneath. The exhaust collection system has a pipe which collects sample from the vehicles which pass underneath the tent. The vehicles inside the tent are identified using Vehicle Identification Number (VIN). The gaseous emission analyzer system holds a Horiba AIA-240CO and CO_2 non dispersive IR analyzer and two Horiba FCA-240 Total Hydrocarbon (THC)/NO or total NO_x analyzers. The system used only one analyzer to measure the THC. The OHMS was experimented for 5 days to measure the quality of vehicle emitted gases [40].

5 Dynamic/Vehicular Air Pollution Monitoring Systems

There are many research works have been implemented on dynamic and vehicular monitoring systems. Some of them are discussed in this section. Jamil et al. [41] have proposed a new model of cluster based sensor deployment to monitor the pollution caused by smoke, dust and CO_2 across the major cities. The traditional system of WSN deployment includes a sensor node or intermediate to collect information and a sink node for processing the data. This transfer of data from sensor node to sink node required efficient routing algorithms that could route information in a short span. The proposed model forms a cluster of sensor nodes with a sink node at each cluster. The metro buses are installed with pollution monitoring devices and allowed to roam through the city. There also exist some stationary nodes which when comes in contact with sensor nodes of metro buses transfers' information. The data collection across the cities used stationary zigbee network that consumes low power. Data collected from metro buses and stationary pollution nodes across the cities are loaded into the cloud a central storage for analytics. Thus the proposed system has reduced the utilization of power by reducing the unwanted number of handovers between nodes.

Souvik Mana et al. [42] have proposed a RFID based vehicular pollution monitoring system in which the vehicles that causes rise in pollution level can be easily identified. The system verified the pollution level of two gases like CO and SO_2. In this system, the RFID readers and sensor nodes are placed across the road to gather information. The vehicles are installed with passive RFID tags that run across cities. When the vehicles cross the road where the sensor node is deployed, the sensor node senses the pollution levels emitted by the vehicle. When the threshold of pollution level exceeds, then the roadside RFID reader identifies the vehicle id by its RFID tag. Then that particular vehicle is listed as the reason for increase in pollution level in server using GPRS modem. After which the concerned authorities may take necessary actions on the respective vehicles. Ramagiri et al. [43] have proposed Vehicular pollution monitoring system in which vehicles that cause air pollution are identified using RFID. The system installs a RFID reader in a location where pollution level has to be monitored and RFID tag in vehicles. The location is also installed with sensors to check the air quality index of two gases namely CO_2 and SO_x. When the vehicle installed with RFID tag crosses the location (where RFID readers and Sensors are installed) the reader reads the vehicle's id and identifies the vehicle crossing the location. Meanwhile the sensors installed starts sensing the pollution level and records the sensed data. The data collected is referred with the nominal values that are stored in database. If the level exceeds then the threshold value then alarms are sent to vehicle owners for consideration.

Yajie et al. [44] have developed a distributed infrastructure based on wireless sensors and grid to monitor the pollution level in air called as Mobile Discovery Net (MoDisNet). The architecture of MoDisNet consists of both Mobile Sensor Nodes (MSN) and Static Sensor Nodes (SSN) installed with GUSTO sensors. The MSN's are installed in vehicles that go around the cities to collect information related to air pollutants. MSN's preprocess the collected data and send the processed information to the SSN via multiple Sensor Gateways (SG) for further processing and analysis. Then the information is transferred from SSN to grid service e-Science using in a multi-hop fashion where the information is stored in data warehouse. Further air pollution monitoring and control are done through patterns obtained by applying data mining techniques. Kim et al. [45] have proposed an air pollution monitoring system to monitor the Pollutants NOx, CO, and TX (Toluene, and Xylenes) across the road side of Bangkok. This monitoring system analyses the air pollutants by categorizing the vehicles into eight fleets namely motorcycle (gasoline), three-wheeler, private car, taxi, van, bus, truck etc., in an hourly basis. Operational Street Pollution Model (OSPM) was used to analyze the emission of pollutants from different vehicles using back calculation method. In addition to pollution monitoring wind data like wind speed and wind direction were also monitored from speed meter installed on buildings.

6 Pollution Data Analysis Techniques

Different air pollution data analysis techniques in the literature are discussed in this section. Ruiyun et al. [46] have proposed a random forest approach to predict the air quality (RAQ) in urban sensing systems. The RAQ algorithm uses data which has been collected from the urban areas that includes Metrological Data (MD), Traffic Data (TCS), Road Information (RI), Point of Interest (POI), and air monitoring station data i.e. Air Quality Index (AQI) in an interval of an hour. The area under study is divided into grids where one grid provides data real time data from AQI while other grids provides just the prediction value. The difference in the AQI of two grids is given as difference in AQI levels from which the prediction could be accessed. In [47] Ghaemi et al. have proposed an air pollution prediction system to predict the air pollutants 1 day in advance. The system uses an online algorithm called LaSVM for classification and prediction based on SVM approach. Since the data to be handled for prediction will be highly voluminous higher computational power was used. Such a highly voluminous large scale data is handled by distributed computing in Hadoop framework of multi-processing system. Parallel processing and analysis of data is done through Map Reduce techniques. The performance of the algorithm was verified across three parameters like accuracy, RMSE, Rsquered that holds 0.7, 0.6 and 0.8 which could be further improved.

Ojeda et al. [48] have proposed an Automatic Environmental Monitoring Network (AEMN) deployed across Cruz RojaNativitas DIF in Salamanca, the most polluted Mexican city. The system AEMN monitors the toxic gases like SO_2, PM_{10}, and O_3 along with the other environmental parameters like temperature, humidity, and wind direction and speed. The system AEMN has both fixed stations and mobile stations to analyze the air pollutants. The collected information is validated by Institute of Ecology. The information collected from three stations is collectively analyzed using a Possibilistic Fuzzy C Means Clustering algorithm. The algorithm works by clustering the data into subgroups where the members of same group have higher similarities while the members of different groups have higher dissimilarities. The correlation analysis was done based on various parameters to find the pollutant concentrations in air. Senay et al. have proposed a new scheme to reduce the number of monitoring stations in air pollution. The work aims at reducing the operational cost of monitoring systems. The monitoring stations that emit same pollution level data are grouped into classes by using Principal Component Analysis (PCA) and Fuzzy C-Means (FCM). Classification was also done based on analysis method of pollution data and pollutants [49]. Time series analysis technique [50] was used by Salcedo et al. to find the air pollution environmental levels. The proposed technique is used to find the concentrations of: (1) Strong Acidity (SA) and (2) Black Smoke (BS) in daily basis in the Oporto area. The SA concentration is affected by industry activity and the BS concentration is related with the road traffic. The period chosen for analysis is week middle days and weekends. The concentration on week middle days on peeks and weekends are troughs. The BS observed is related with vehicle traffic and is less during weekends.

Mathematical modeling of environmental data is introduced by Warsono et al. There are two motives in this proposed work [51]. They are: (1) log-logistics distribution is introduced to model polluted data (2) Apply the model to the polluted data to check the quality of the data. Experimental results shows that GLL(mr, mz) performs better than log-normal, GLL (l, l), GLL(l, m), and GLL (m, m) distributions, and slightly better than the GLL (m, 1) distribution. Wang et al. [52] proposed an automated identification and integration method to analyze the air pollution emitted by vehicles. The analysis was done on real time environment in Canada roads for gases NO_x, CO, particle number, black carbon, Benzene, Toluene, Ethylbenzene, Xylenes and Methanol. The pollution concentration is measured for each vehicle plume Igor Pro 6.34. Based on the analysis vehicles were categorized as high emitters.

Asghari et al. [53] proposed a neural network based hybrid method for air pollution prediction in Tehran considering particulate matter less than 10 microns(PM_{10}). The proposed work hybrids Artificial Neural Network with Back Propagation (BP) with Genetic Algorithm (GA). Prediction was done with Microsoft Excel and Matlab 2013 which exhibited higher accuracy and performance when compared to the basic Artificial Neural Networks along with (BP) [54]. Kingsy et al. proposed enhanced K-Means clustering algorithm to analyze the air pollution data of O_3, SO, NO_x, PM_{10}, CO, and SO_2 as well as environmental variables such as wind speed and wind direction. The proposed enhanced K-Means clustering algorithm gives AQI value in higher accuracy of 40% with less execution time compared with Possibilistic Fuzzy C-Means (PFCM) clustering algorithm in terms of accuracy and execution time [27].

7 Summary

This section, presents the summary of various air pollution monitoring and analysis strategies followed across the world. The review was done based on various following aspects such as:

- Static pollution monitoring system,
- Dynamic pollution monitoring system.
- Pollution analysis using various classification and clustering algorithms.

Tables 2 and 3 presents the summary of various static air pollution monitoring systems based on static and dynamic nature of the implementations. Table 4 describes the summary of various dynamic air pollution analysis systems along various parameters like gases taken into study are, evaluation attributes, micro controllers used, pollutants analyzed using sensors, test location and performance.

The air pollution monitoring systems are evaluated based on reliability, agile methodologies, having additional capabilities such as earthquake detection, low power, low cost and high performance pollution monitoring system, provides pollution information to the users and particulate emission measurement from vehicles. The important components of air pollution monitoring systems are the sensors used for analyzing pollutants in the air. Gas Concentration-PPM Level and AQI are the two important evaluation parameters in the air pollution monitoring systems. Most of the air pollution monitoring systems followed the methodologies such as: Muti-hop data aggregation algorithm, Software Defined Radio prototyping, REST, SCRUM, Association rule mining—Apriori algorithm and GSTWH. The gases which are sensed are CO_2, NO_2, CO, O_2, temperature, humidity, Methane, Hydrogen Sulfide, Ozone, Ammonia, PM, Benzene, Ethanol, Toluene, Propane and Dust. In Dynamic/Vehicular Air Pollution Monitoring Systems uses the methodologies such as, RFID, distributed data mining algorithm, clustering back calculation method. The methodologies used in on Air Pollution Data Analysis are LaSVM, RAQ–A Random

Table 2 Comparison on static air pollution monitoring systems

S. no.	Air pollution monitoring systems	Methodologies followed	Microcontroller used	Pollutants analyzed using sensors	Evaluation attributes	Tested location	Performance
1.	Real time wireless Air pollution monitoring system [32]	Muti-hop data aggregation algorithm	WASP Libelium motes	CO_2, NO_2, CO, O_2, temperature, humidity	Gas concentration-PPM Level	IIT Hyderabad campus, Hyderabad City	Reliable source of real time fine-grain pollution data
2.	LPWA-based air quality monitoring system [33]	Software defined radio prototyping	ARM 32 bit Cortex M3	Dust	AQI	Not mentioned	Reliable
3.	Distributed system as Internet of Things for a new low-cost, air pollution wireless monitoring on real time [34]	REST, SCRUM	Arduino UNO R3	CO, CO_2, dust density	Confidence level, standard deviation, coefficient of variation	Cities of Quito, Amaguana and Tena	Low cost system as a result of agile methods
4.	Smart environmental monitoring using Raspberry-Pi computer [35]	Not mentioned	Raspberry Pi	CO, temperature, humidity, light level	Gas concentration-PPM level	Not mentioned	Includes earthquake detection capability using seismic sensors
5.	Cloud based management of Iot devices for air quality monitoring [36]	REST	Arduino	CO,CO_2, NO_2, methane, hydrogen sulfide, ozone, ammonia, PM, benzene, ethanol, toluene, propane	Gas concentration-PPM Level	Not mentioned	Low power, low cost and high performance pollution monitoring system
6.	Air pollution monitoring and tracking system using mobile sensors and analysis of data using data mining [37]	Association rule mining a priori algorithm	Not mentioned	CO, NO_x, SO_x	Support degree and confidence value	Not mentioned	Acquire air pollutants levels in large city area

Table 2 (continued)

S. no.	Air pollution monitoring systems	Methodologies followed	Microcontroller used	Pollutants analyzed using sensors	Evaluation attributes	Tested location	Performance
7.	IoT enabled air quality monitoring system (AQMS) using Raspberry Pi [38]	GSTWH	Raspberry Pi, with Gove Pi	CO, CO_2, NH_3, NO_x	Gas concentration-PPM Level	Not mentioned	Alert and low cost systems
8.	Sensor module for real-time pollution monitoring [39]	Not mentioned	PIC 18F14K50	CO_2, O_2, CO	Gas concentration-PPM level, deviation from mean (ADC reading), response time, power spectral density, frequency (Hz)	Not mentioned	Fine-grain gas pollution information to the users
9.	On-road heavy-duty vehicle emissions monitoring system (OHMS) [40]	Not mentioned	Not mentioned	NO, CO_2, CO	Gas concentration-PPM level, gBC/kg, gPM/kg	Los Angeles	Particulate emission measurement from vehicles

Table 3 Comparison on dynamic/vehicular air pollution monitoring systems

S. no.	Air pollution monitoring systems	Methodologies followed	Microcontroller used/ communication device	Pollutants analyzed using sensors	Evaluation attributes	Tested location	Performance
1.	Smart environment monitoring system by employing wireless sensor networks on vehicles [41]	Not mentioned	Zigbee based wireless sensor network	Smoke, dust	Not mentioned	Pakistan	Low cost and more efficient system for M2M devices
2.	Vehicular pollution monitoring using IoT [42]	RFID	Arduino Uno	Carbon monoxide, sulphur dioxide, nitrogen dioxide, methane	Pollution concentration	Road side	To find the pollution emission concentration of individual vehicles
3.	IoT based vehicular pollution monitoring system [43]	RFID	Arduino Uno, ATmega328 microcontroller	CO_2, SOx	Pollution concentration	Road side	Pollutant levels of vehicles
4.	Air pollution monitoring and mining based on sensor grid in London [44]	Distributed data mining algorithm clustering	Zigbee	NO, NO_2, O_3, SO_2	Average percentage membership match (APMM)	East London	High performance
5.	On-road vehicle emission factor using integrated monitoring and modeling approach [45]	Back calculation method	Not mentioned	NO, CO, toluene, M,P-Xylenes, O, O Xylene	Correlation coefficient, pollution concentration	Bangkok	To generate necessary data for the traffic emission inventory in a city

Table 4 Comparison on Air Pollution Data Analysis

S. no.	Air pollution monitoring and analysis systems	Methodologies followed	Pollutants analyzed using sensors	Evaluation attributes	Tested location	Performance
1.	Hadoop-based distributed system for online prediction of air pollution [46]	LaSVM	NO_2, CO, SO_2, PM_{10}, O_3	Accuracy, RMSC, RSquered	Iran	The accuracy of 0.7, RMSE of 0.6 and R squared of 0.8 proved the feasibility of the online algorithm
2.	RAQ–A random forest approach for predicting air quality in urban sensing systems [47]	RAQ–A random forest approach	CO, NO_2, SO_2, O_3, PM_{10}, $PM_{2.5}$	AQI	Sanhao street of Shenya, China	Overall precision is 81%
3.	Air pollution analysis with a PFCM clustering algorithm [48]	PFCM clustering algorithm	SO_2, PM_{10}, O_3	Combined measure, correlation coefficient	Mexico	Significance correlation between pollutant concentrations and environmental variables
4.	Principal component analysis and fuzzy C-means clustering [49]	PCA	SO_2, PM_{10}	AQI along each cluster	Marmara	Reduces the operational cost of monitoring systems
5.	Time-series analysis of air pollution data [50]	Time-series	Strong acidity (SA), black smoke (BS)	Not mentioned	Oporto	Not mentioned
6.	Plume-based analysis of vehicle fleet air pollutant emissions and the contribution from high emitters [52]	Not mentioned	NO, CO, particle number, black carbon, benzene, toluene, ethylbenzene, xylenes and methanol	Mean AT and mean fleet EFs	Canada	Analysis of individual vehicle pollution emission
7.	Predicting air pollution in Tehran: genetic algorithm and back propagation neural network [53]	Genetic algorithm	PM	Mean square error, root mean square error, mean absolute error	Tehran	Higher accuracy and performance when compared to the basic artificial neural networks along with (BP)
8.	Air pollution analysis using enhanced K-means clustering algorithm for real time sensor [54]	Enhanced K-means clustering algorithm	O_3, SO, NO_x, PM, CO, and SO_2	AQI	Not mentioned	Higher accuracy of 40% with less execution time

Forest Approach, PFCM Clustering Algorithm, PCA, Time-Series, Genetic algorithm and Enhanced K-Means Clustering Algorithm.

Most of the air pollution monitoring systems are implemented and tested in real time scenario. In static air pollution monitoring systems the microcontrollers such as WASP Libelium motes, ARM 32 bit Cortex M3, Arduino UNO R3, Raspberry Pi, Arduino, Raspberry Pi and PIC 18F14K50 are used to collect the pollutant data through sensors. Whereas in dynamic air pollution monitoring systems the microcontrollers and the transmission techniques used are: Zigbee based Wireless Sensor Network, Arduino Uno with wifi and ATmega328 microcontroller.

8 Conclusion and Future work

Air Pollution being the giant problem threatens human health in all aspects. In a vision to avert the consequences of air pollution this work aims at analyzing the air pollution monitoring systems and finding a best way to sort out the problem in future. This paper has presented a detailed performance comparison of various air pollution monitoring systems using sensors adapted around the world. The study was an analysis about the gases which are sensed using sensors, methodologies, communication mode, calibrating sensor values and air quality index calculation. This paper has done a deep study on air pollution monitoring with an aim to propose a robust air pollution monitoring system.

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R. Kingsy Grace is currently working as Associate Professor in the Department of Computer Science and Engineering, Sri Ramakrishna Engineering College, Coimbatore, India. She has completed her Ph.D. under Anna University. She is the alumnus of Noorul Islam College of Engineering, India and Karunya Institute of Technology, Coimbatore, India. Her area of interest includes Grid and cloud Computing, High Performance Computing, Air Pollution Monitoring and Analysis and IoT.

S. Manju is currently working as Assistant Professor in Department of Computer Science and Engineering, Sri Ramakrishna Engineering College, Coimbatore, India. She has completed her Master of Engineering in Computer Science and Engineering from Sri Krishna College of Engineering and Technology in 2016 and Bachelor of Engineering in Computer Science and Engineering from Dr. Mahalingam College of Engineering and Technology in 2014. Her area of interests includes Wireless Networking and High Performance Computing.