SCALING AIR QUALITY IN SMART CITIES: AN INTEGRATED INTERNET OF THINGS AND MOBILE COMPUTING PERSPECTIVE

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Abstract

Monitoring air quality in modern cities has become a major issue for planning and decision making of enhanced living environments. Industrial and domestic sources and, predominantly, automobiles are accountable for pollutant exhausts that decisively disturb healthy lifestyle in urban areas. Consequently, quality of air must be estimated in real-time to deliver a spatiotemporal database for improved data processing and visualization. Conventional air quality monitoring systems in smart cities have been fabricated on sparse regulatory monitoring, improved with satellite data and prediction techniques. However, technologies related to Industry 4.0 like Internet of Things (IoT), big data, machine learning, artificial intelligence, and computing platforms are reforming smart cities globally. Smart cities can harness these technologies combined with conventional approaches for effective air quality monitoring and to provide enhanced living environments. In order to integrate technical implications of pollutants and prevailing IoT-based mobile computing frameworks for monitoring air pollution, we review several cutting-edge researches found in the literature. This study presents a perspective regarding the existing opportunities in addressing the issues related to air quality monitoring in smart cities. We discuss the reimbursements of integrating mobile computing and IoT technologies in monitoring and evaluating environmental quality in smart cities. Also, we describe the challenges and future directions in leveraging these technologies to estimate air pollution levels and risks.

Keywords: air pollution, air quality index; IoT, mobile computing, smart cities.

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1. Introduction

Quality of air continues to deteriorate every year due to the rapid urbanization and industrialization as well as elevated discharges of air pollutants from automobiles. Albeit air is a vital source for life, individuals are indifferent to the rigorousness of air pollution or have only understood the severity of the problem in recent times [1, 2]. Amid different kinds of pollutions like thermal, water, noise, and soil, air pollution is the most severe and hazardous, instigating lethal diseases and climate change. Several researchers have demonstrated that the air pollution has a direct relation to public health and comfort [3, 4]. Air quality monitoring (AQM) frameworks can be employed to deliver real-time data in both indoor and outdoor living atmospheres to scheme policies for improving public health and productivity. Furthermore, these data can be accessed by city administrators and medical professionals to relate ecological status with health signs for improved public safety and health.

Poor air quality is leading to severe health issues, since breathing contaminated air raises the risk of devastating and deadly diseases including stroke, lung cancer, asthma, ischemic heart disease, chronic bronchitis, and sinusitis. Besides, air contaminants have an ill-effect on individuals as well as the earth’s ecology such as Ozone layer depletion, acid rain, photochemical smog, and climate changes [5]. These glitches create severe undesirable effects on urban citizens. Hence, monitoring air quality is decisive process and should be embedded as an indispensable part in sustainable smart cities to enhance inhabitants’ comfort and well-being [6]. The data collected from air quality monitoring system is important not only to increase the sustainability of the smart city but also to create extensive database that comprises of spatiotemporal data to help city administrators make decision for better living environments.

Based on the statistical report released from WHO (World Health Organization), 90% of the inhabitants now breathe contaminated air, and it kills 7 million individuals yearly [7]. Air pollution deteriorates the quality of life by instigating disease and premature death. It decreases global economy by triggering a loss of productivity. According to World Bank report, early deaths owing to air pollution cost the global economy around $5.11 trillion in welfare losses and around $225 billion in lost labor work days, a cost that is approximately equal to the gross domestic product of Japan. For India alone, the projection for welfare losses $505 billion and for lost labor work days was $55 billion [8]. This report revealed that air pollution leads to not only a health hazard but also a financial burden. Therefore, monitoring air quality becomes quintessential topic for innumerable community-based initiatives and research studies.

Of late, several industrial and scientific organizations have adopted and applied the concepts of IoT and mobile computing technologies as effective techniques to measure air pollution levels and related risks in smart cities. Generally, these technologies enable devices to estimates classical air pollutants like particulate matter (PM) equal or less than 2.5 µm and 10 µm in aerodynamic diameter ($PM_{2.5}$, and PM_{10} and correspondingly), carbon dioxide (CO_2), ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) [9 - 11]. PM is mainly engendered by wood and biomass fuel combustion in various fields, such as households, transport, industry, energy, and agriculture. It is measured as a complex mixture of solid and liquefied substances that are suspended in the atmosphere. Both $PM_{2.5}$ and PM_{10} can enter the lungs but $PM_{2.5}$ is capable of penetrating deep into the veins, mainly causing cardiac and respirational problems, and also distressing other body parts [12].

The increasing CO_2 level is one more important problem in smart cities [13]. Source of CO_2 pollution are production of cement and combustion of fossil fuels. Contact to CO_2 will affects the range from physiologic (e.g. ventilatory stimulation), to toxic (e.g. cardiovascular arrests and arrhythmias), anaesthetic (considerably depressed CNS action), and deadly (severe anoxia and acidosis) [14]. But, the impact of CO_2 on the people health is based on lifestyle, physical activities, age, and occupation. Ozone layer is produced by photochemical action of sunlight on the pollutants like volatile organic compounds (VOC) and nitrogen oxides. It is ruined by reactions with NO_2 and it is dropped to the earth. Fossil fuel combustion and chemical solvent are the primary sources of O_3 layer. Contact to O_3 for a few hours will cause chest agony, decreases activity of the lung, coughing as well as asthmatics. SO_2 is toxic in nature. It can produce sulphuric acid by dissolving with water which is the leading constituent of acid rain. SO_2 is usually emitted from the petroleum refineries, medicinal waste, solid waste that comprises of perilous, and industries that burn high sulphur coal. Research studies reveal that contact to acid rain leads to asthma, bronchitis, and skin cancer. NO_2 is the most reactive gas pollutants. It is discharged from the combustion of fossil fuels. Emissions from automobiles and static sources including industrial boilers and electric utilities are the main sources of NO_2 in the atmosphere [15]. Long-term contact to NO_2 causes influenza and decreases lung activities of the individuals [16].

Generally, the proliferation of IoT technology allows us to gather innumerable environmental data and implement numerous applications to exploit these data in smart cities. Similarly, mobile computing adds social interactivity and portability to those applications to provide real-time data to inhabitants for improved knowledge integration. IoT is a network of devices where identifiable physical things or objects (e.g., sensors, wearable devices, smart cars, industrial and utility components, etc.) are seamlessly incorporated as part of network (usually the Internet). These smart things are reinforced with data analytic tools that are considerably transforming the way we live and work. Actually, the things can communicate with each other and the environment without any human intervention to provide omnipresent applications [17].

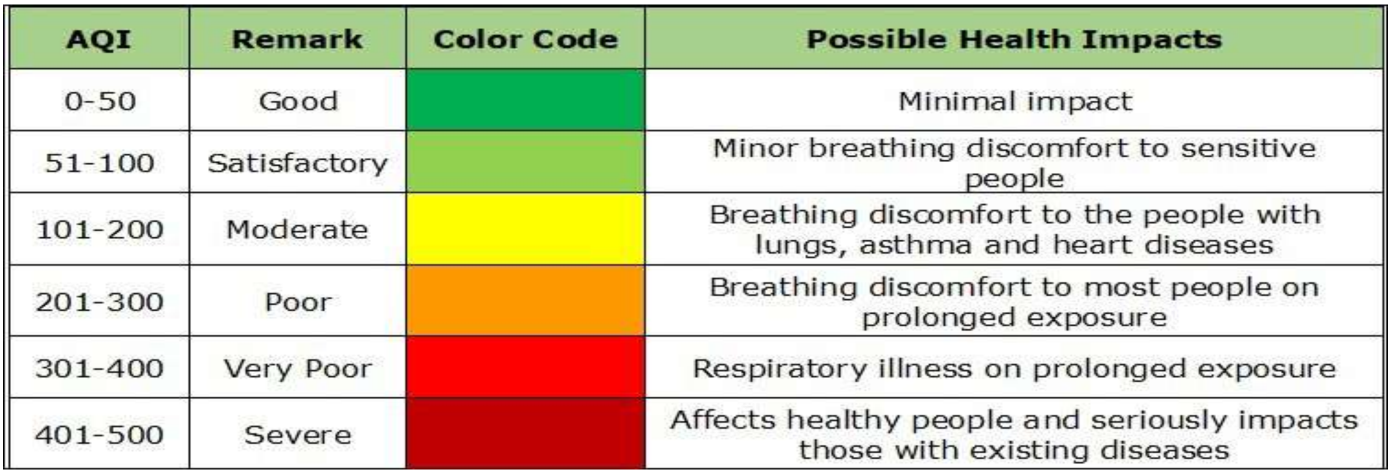
IoT employs sensors, RFID, (radiofrequency identification), QR (quick response) codes, as well as wireless communication technology to facilitate interaction among objects. IoT enables smart objects to ingest, store, exchange, and analyze data and take actions accordingly. Hence, IoT could demonstrate useful in managing air quality in smart cities. It enables inexpensive yet effective solution by monitoring the level of air quality in real-time; allowing precautionary steps like shuttering thermal power plants and steel mills, keeping automobiles out of some selected regions in the cities, building infrastructure for cycle bikes, repositioning polluting industries out of cities, etc. to be implemented. Moreover, an IoT-based air quality scaling model can collect substantial information, which will show helpful in classifying parameters and understanding patterns that influence the status of air quality, and providing advanced ways for increasing quality of air.

Mobile computing integrates high performance computing and effective communication systems. Modern mobile phones consist of many sensing elements for environmental data collection, including microphone, camera, accelerometer, gyroscope, proximity sensor, and global positioning system (GPS). Furthermore, smartphones support appropriate communication protocols like

Bluetooth low energy (BLE) and near field communication (NFC). Mobile devices are employed for numerous applications related to recognition and analysis of physical activities [18, 19]. Modern mobile phones include both short-range communication technologies (e.g., Wi-Fi and Bluetooth) and long-range communication technologies (e.g., 5G/4G technology, GPRS, etc.) [20]. Moreover, there is an exponential growth in the usage of smartphone worldwide and people usually spend more time using mobile phones related to other gadgets, like tablets and laptops [21]. Smartphones support our daily routine and allow as implementing heterogeneous applications like data communication, analytics, and visualization [22]. Smartphones enable a ubiquitous link to the Internet, and these expedients fetched numerous innovations in people’s day-to-day activities [23].

Several researchers developed different mobile applications to alert the public by sending the status of air quality along with GPS coordinates through existing location services. The portable and inexpensive sensors combined with Internet connection offers an optimal solution to construct an air pollution monitoring model that can be used to form a group with commuters that gather and exchange the status of air quality. These extensive open source data are useful to notify the concerned authorities and enable them take necessary steps to decrease the negative impacts of the pollutants. Besides, these data can be employed to find out the trends and levels of air quality in each city, to classify non-attainment cities, and other policy purposes. These data also aid the investigators to determine the source, features, formation, and impact of pollutants in climate change since the inaccurate estimation of pollutants are playing important roles in creation of a smart city. Simulation studies exploit these data to evaluate and enhance the monitoring system.

Air quality index (AQI) is an indicator number for recording the daily or hourly air quality in vicinity concerning its impacts on the public health [24]. AQI integrates various contaminants levels to derive a single number using numerical calculations to indicate the status of air quality. The key objective of defining AQI is to secure public health, particularly the health of delicate people like the asthmatics, children, and elderly. According to AQI, a region can be classified as severe, very poor, poor, moderate, satisfactory, and good [25]. The level of contaminants varies with areas in smart cities. It hinges on the natures of industrial and other activities and causes different health risks. Recently, the Indian government propelled a National Air Quality Index (NAQI) notification mechanism to inform the people about the levels of air pollution and related health impacts as given in Figure 1. Subsequently, the Natural Resources Defense Council and the Public Health Foundation of India headed a discussion with top authorities to examine the health menaces of air pollution and the necessity of augmented interactions. With technical alliance and administration, India is well poised to take necessary actions towards increasing the quality of air.



AQI	Remark	Color Code	Possible Health Impacts
0-50	Good	🟩	Minimal impact
51-100	Satisfactory	🟩	Minor breathing discomfort to sensitive people
101-200	Moderate	🟨	Breathing discomfort to the people with lungs, asthma and heart diseases
201-300	Poor	🟧	Breathing discomfort to most people on prolonged exposure
301-400	Very Poor	🟥	Respiratory illness on prolonged exposure
401-500	Severe	🟥	Affects healthy people and seriously impacts those with existing diseases

Figure 1: Air quality index breakpoints and definitions

IOT in air quality monitoring

By digitizing the corporeal world, IoT technology provides significant benefits to the society and immeasurably increases the opportunity of real-time monitoring frameworks. The innumerable potentials that arise from the ability to monitor and control objects in the physical realm electronically have stimulated a surge of innovation and interest. Of late, the wide application of IoT-enabled frameworks has intensified the explosion of real-time monitoring systems for different domains including manufacturing, environmental monitoring, energy management, security, home automation, and medical industry [26]. In smart city environments, IoT brings innovations and pushing forward our cognizance of the logistics of smart cities. There are already a projected 35.82 billion connected objects in use and 75.44 billion IoTs are anticipated by 2025 [27]. Numerous IoT-based air quality monitoring systems have been described in the literature. These studies embrace low-cost IoT systems to measure various contaminants in the air through static or mobile sensors. Wonohardjo and Kusuma proposed a real-time IoT-based pollution monitoring system to measure the level of carbon monoxide [28]. Toma et al. developed a real-time IoT-based pollution tracking framework to alleviate serious problems and to promote cognizance about the impacts of pollution exposure [29]. Sai et al. proposed an indoor air quality scaling framework, which consists of an air quality sensor (i.e., MQ135 sensor) to monitor harmful gases and a semiconductor gas sensor (i.e., MQ7 sensor) to measure the level of CO in the atmosphere [30]. This system contains an Arduino Uno microcontroller and an ESP8266 for communication. The collected data are warehoused in the cloud computing platform for processing and data visualization.

Zakaria et al. proposed an IoT-based architecture for air quality monitoring which consists of lucrative sensors for scaling air pollutants, humidity, and temperature [31]. The proposed model incorporates a Raspberry Pi 2 microcontroller and a cloud storage system. This model provides instantaneous AQI value, e-mail alert services, and web connectivity for data retrieval. Benammar et al. developed an IoT-enabled model to realize real-time end-to-end air quality tracking [32]. The proposed system measures O_3, CO, CO_2, SO_2, NO_2, chlorine (Cl_2), temperature, and humidity. The measured statistics are kept in an non-proprietary IoT platform (i.e., the EMONCMS) for real-time monitoring and long-standing storage. It employs a cohesive IoT/wireless sensor network architecture and includes Waspmote microcontroller and Raspberry Pi. Parmar el al. developed a model for monitoring ambient air pollution by scaling the levels of the most important toxin gases [33]. The system employs air quality scaling devices which contain inexpensive gas sensors and Wi-Fi units. It estimates level of different gases including CO, CO_2, SO_2, and NO_2 through appropriate sensors. These sensors collect several ecological statistics and transfer it to the nearby access point. Firdhous et al. proposed an IoT- enabled air quality tracking model for scaling the level of O_3 near a high volume photocopier machine [34]. The proposed unit has been automated to gather and transfer data at a regular interval over Bluetooth link to a gateway node that consequently connects with the computing element through a Wi-Fi module.

Jo et al. proposed an IoT-enabled air quality tracking system, comprising of an air quality tacking device known as “Smart-Air” and a web server. Smart-Air also depends on cloud technology to collect the data anytime and anywhere. This system proficiently tracks the quality of air by scaling the level of aerosol, VOC, CO_2, CO, temperature, and humidity. It transmits the measured values to a web server using Long Term Evolution (LTE) technology. Also, the system contains appropriate sensors, a microcontroller, and LTE modem. Alshamsi et al. proposed an IoT-based model that eatimates air pollution by sensing instantaneous data in a particular location. Then, this data is tested against a predefined value. The measured data is transmitted to the concerned authorities to enable them to take the required actions in case of any defilement. Moreover, if the measured value surpasses the threshold value, a notification mechanism is activated to alert the nearby people. The abovementioned works have proved that IoT is an appropriate technology for air pollution monitoring in smart cities as it sense and compatible with other expedients, connected by networks. On the other hand, it is frequently challenging to reproduce such systems as adequate software and hardware details are not usually delivered in study methodology. We observed that most of the systems do not include alert mechanisms to generate notification in poor air quality scenarios. The integration of alerts using mobile phones is needed to inform the city managers and building occupations on time.

Mobile computing and urban informatics

Mobile technology is defined as a form of human–machine communication where the machine is a portable computer. The technological advancement over the last decade has developed pervasive computing that enables trillions of citizens to access information, services, and people for better knowledge integration using their mobile devices (e.g., cellular phones, wearable sensors, smart cars, tablets, portable computers, etc.). With the germination in both number of users and cellular technologies, mobile phones are shifting from dedicated and personalized systems to influential computing platforms.

By utilizing data collected from sensors and a comprehensive computing system, we can develop computing infrastructure for urban planning. With limited network bandwidth and battery power, processing resources provided by this technology are not as dependable as the other technologies such as cloud and edge computing. However, modern mobile devices are portable and capable of collecting and processing data where edge and cloud computing technologies are absent. Mobile computing plays a vital role in traffic and transport controlling, energy and utilities management, public safety and security, environmental protection and sustainability. As Wong et al. revealed in their assessments, techniques have been proposed and applied to enable customers to collect real-time energy performance views on their plans and decisions of building models, like the location of construction and thermal enactment, using mobile applications (i.e., applications based on smartphone/iPad). In chorus, smartphones deliver volunteered geographic information (VGI) to measure environmental parameters in near-real-time. For instance, Koukoutsidis employed a mobile-based participatory sensing approach to measure the average temperature in a linear region that shows the impact of urban heat island.

Integration of IOT and mobile computing in air quality monitoring

A distinctive integration of air pollution sensors, mobile computing technologies deliver a platform to develop a mobile social networking of individuals who are concerned about air pollution levels and transferring the data to other individuals with similar interest to support them to evade harmful risks. Several state-of-the-art approaches proposed by prevailing works in the literature for air quality monitoring include lucrative sensing elements for data aggregation and appropriate mobile applications to access data anytime and anywhere. Alabdullah et al. developed an Arduino-based air quality tracking method, which contains small sensors to estimate VOC, CO_2, and temperature. Additionally, this model includes Bluetooth link to send the collected data to a mobile phone. The key objective of this model is to inform the user about the deviation in the observed data. Rathore et al. proposed a real-time city microclimate assessment model that integrates smartphones, IoT and cloud technologies.

Marques and Pitarma proposed a real-time IoT-based air quality tracking system, called iAir. This system consists of an ESP8266 microcontroller to process the aggregated data and to enable communication. Also, this system includes a semiconductor sensor (i.e., MICS-6814) to measure CO, NO_2, ethanol, methane, and propane and a mobile application for accessing data. An instantaneous alert system is developed using open-source platforms. The data procurement module is connected to the Internet using a Wi-Fi module and offers simple installation procedures. In another work, the authors proposed a real-time system for monitoring environmental quality which combines mobile computing technology for data processing and alert system. The sensing module is consists of a PMS5003ST sensor to measure PM, formaldehyde (CH_2O), humidity, and temperature. Additionally, it includes a Wi-Fi module and mobile application for data analytics and visualization. The key objective of this work is to deliver a well-organized database to increase productivity and public health. Furthermore, these data can be stored with corresponding health signs of the residents and their circumstances.

Hasenfratz et al. developed a smartphone-based air pollution monitoring platform, named GasMobile, to calculate O_3 levels through an affordable sensor. A similar project, implemented by Intel and UC Berkeley, known as N-SMARTS which employs GPS-based mobile devices with appropriate sensing nodes to collect air pollution data. The UCLA Personal Environmental Impact Report (PEIR) project exploits the sensing competence of smart phones to realize a model that monitor user’s activities to assess ecological impact on public health of contact to carbon discharges. Nazelle et al. demonstrated that the utilization and significance of the CalFit technology to monitor person-level time, geographical location, and pattern of physical actions for achieving better-quality air pollution analysis. Specifically some CalFit-fortified mobile phones are employed to monitor physical tasks and geographical location. Mapping instantaneous air quality through mobile devices promotes greater spatial coverage related to stationary stations to monitor air quality. The stationary stations have significant restrictions as the measured data do not deliver an unceasing time-series of estimation.

Challenges related to IOT and mobile computing integration

- **Big data handling:** In general, air quality information is collected from different sources such as in-situ sensing, remote sensing, IoT sensing, social sensing, and simulation. The composed data deliver an inclusive understanding of the air pollution in smart cities. On the other hand, the measurements and simulation generate huge volume of data that far beyond the memory capacity of user's mobile devices. Effectively hoarding such a massive data is a perplexing task. In the interim, with the proliferation of cutting-edge technologies, data are generated in extraordinary velocity continuously. The high speed data demands data streaming and assessment methodologies for executing applications in near-real-time. Besides, the heterogeneous data are logged in different file formats, like text, image, audio, or video and brings several difficulties in managing big data using conventional database system.
- **Compute intensive processing:** Since a smart city is a complex environment in which huge data are ingested, effective methods are developed to provide smart services. Mostly, these methods depend on intricate data models and analytics. Data models denote things or real-time scenario, and a digital model creates scientific assessment. Data analytics is a vital constituent of the big data realm. Nonetheless, it comes after data ingestion, completion, deduplication, collection, synchronization, filtering, and contextualization. These elements are indispensable to allow analytic models to obtain valuable insights. A number of resources need to be allocated for diverse computing elements. For instance, transferring fractional computing resources to data aggregation locations to clean the measured data can decrease the data volume transmitted to the analytics system, leads to an improved analysis speed and reduced bandwidth cost.
- **Data Security and Privacy:** Security and privacy concerns are the key issues in urban informatics owing to the security problems related to various computing layers and the identification information in the data. Usually, most of the measured data may cover sensitive or confidential information associated with governments or public. Hence, processing such data should be secured against illegal access. For example, a phone number denotes an individual and makes day-to-day tasks of peoples noticeable, which may reveal the personal activities of individuals. At the same time, in smart city applications, data transfer over several processing layers using Internet, some of which may not be secured. Generally, mobile nodes require Wi-Fi connection to send data to any processing systems. At the same time, utilization of unlicensed Wi-Fi may fetch security risks to the system. In addition to communication network, distributed as well as non-proprietary big data platforms (e.g., Hadoop) is progressively famous for distributed processing and storage; but, related to proprietary platforms, these systems lack adequate security assurances.
- **Efficiency:** A trend in air pollution management applications in smart city is to retrieve information from big data environment, and therefore, poor performance creates a bottleneck of most data processing applications. Generally, the applications differ in intricacy levels and need diverse response times. Effective communication requires direct ideal route selection approach according to current traffic data. Albeit several non-proprietary big data platforms, (e.g., Apache Spark, Strom and Hadoop) are established and implemented in different fields, they are not intended to handle spatiotemporal data.

Performance hitches are inevitable while utilizing these systems to handle spatiotemporal data without applying any tuning methods. The implementation of an effective spatiotemporal data processing system is still in an early stage; how to exploit and enhance big data processing system to realize effective applications in smart cities remains a challenging endeavor.

Implementing an IoT-based mobile application in a smart city needs initial investigation on the elements and the communication network among them to realize the proofs of concept and attain substantiated models. This process includes several elements including IoT devices, communications network, software services, and data storage devices. Therefore, creating prototype models of an IoT-enabled device with appropriate sensing elements for an urban area that satisfies particular demands is impossible through empirical trials. Simulation and modeling are alternate methods to develop, analyze, and evaluate the IoT applications. We observed that these methods are appropriate in modelling wireless sensor network. The benefits of utilizing the simulation are the minimization of risks, the saving of costs, and the acceleration of the tests. Thus, it is possible to perform a scalability assessment, identify the types of sensing elements, or define the control variables. In spite of these developments, selection of appropriate simulation tool for an IoT application is important research topics. Though we have reviewed some simulator and modelling concepts defined in the literature, the end-to-end validation of the simulators is still in an early stage.

2. Conclusions and future directions

This study has explored a status on the present state-of-the-art on air quality scaling systems using integrated IoT and mobile computing solutions. Also, it shows that there is growing interest from people, city managers and supervisory body in the air quality within cities, there is also much better cognizance of the costs and adverse effect of air pollutants. Improvements in processing power, the IoT combined with emergent mobile computing technologies, create opportunities for smart cities to design efficient systems for scaling air pollutants. However, it reveals lack of standard approach to relate the air quality in cities that follow diverse directives. From this study, we observed that the PM and CO_2 sensors are widely employed to assess the state of the air quality, but some other solutions also provide CO and VOC monitoring. In chorus, sensors for SO_2 and O_3 monitoring are rarely employed by the researchers. However, the current state-of-the-art has some restrictions.

We observed that most of the proposed approaches do not include alert mechanism to generate notification in poor air quality states. Besides, there are serious restrictions in terms of the computing power, the accuracy of the sensing devices, the performance of communication network used, and power dissipation of the system. Hence, innovative research studies are required to explore these perilous challenges to propose new and more effective techniques for tracking and analysis of air quality. The air quality data can be assessed by medical authorities to aid the decision making on disease diagnostics. Furthermore, it is feasible to relate diseases with patient's circumstances. Future research on air quality monitoring models will support improved living atmospheres and sustainable smart cities. In future, similar research can be carried out to measure the air quality in farming grounds and area's adjoining to various industries.

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