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A comprehensive review on indoor air quality monitoring systems for enhanced public health

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Abstract

Indoor air pollution (IAP) is a relevant area of concern for most developing countries as it has a direct impact on mortality and morbidity. Around 3 billion people throughout the world use coal and biomass (crop residues, wood, dung, and charcoal) as the primary source of domestic energy. Moreover, humans spend 80–90% of their routine time indoors, so indoor air quality (IAQ) leaves a direct impact on overall health and work efficiency. In this paper, the authors described the relationship between IAP exposure and associated risks. The main idea is to discuss the use of wireless technologies for the development of cyber-physical systems for real-time monitoring. Furthermore, it provides a critical review of microcontrollers used for system designing and challenges in the development of real-time monitoring systems. This paper also presents some new ideas and scopes in the field of IAQ monitoring for the researchers.

Keywords: Developing countries, Environmental health, Indoor air quality monitoring, Indoor air pollution, Public health, Occupational health

Introduction

With the ongoing improvements in quality of life, breathing environment has become an essential area of concern for researchers in the twenty-first century. Many studies confirm that indoor air is more deadly then outdoor air [1]. Nowadays, 90% of the rural households in the most developing countries and around 50% of the world's population make use of unprocessed biomass for open fires and poorly functioning cooking stoves indoors. These deficient methods of cooking are responsible for indoor air pollution (IAP) and poor health of women as well as young children who are often exposed to such a polluted environment [2]. Biomass and coal smoke carry a wide range of harmful pollutants such as Particulate Matter (PM), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Sulphur Oxides, polycyclic organic matter and formaldehyde [3, 4]. Constant exposure to IAP due to the combustion of solid fuels is the common cause of several harmful diseases in developing countries. The list includes chronic obstructive pulmonary disease (COPD), otitis media, acute respiratory infections, tuberculosis, asthma, lung cancer, cancer of larynx and nasopharynx, low birth rate, perinatal conditions and severe eye diseases that can even cause blindness [5, 6].

In the developed countries, the impact of modernization has brought a significant shift in indoor fire and heating systems from biomass fuels such as petroleum products and wood to electricity-based appliances. As per World Energy Outlook 2017 [7], even after several improvements in cooking measures, 1.3 billion people in developing Asia are expected to rely on biomass for cooking by the year 2030. As per current estimates, 2.8 million premature deaths are reported every year due to the use of coal and solid biomass for cooking [7]. The scenario becomes worse with the use of kerosene, candles and other harmful fuels for lighting [7]. Generally, the types of fuels being used for household needs can become cleaner and efficient only if people start moving up on the energy ladder. Note that, animal dung is the lowest level of this ladder, and the successive steps are built with crop residues, wood, charcoal, kerosene, gas, and electricity [8]. People throughout the world tend to move upward on this ladder

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as their socio-economic conditions allow them to improve their lifestyle, but reports reveal that poverty is the principal obstacle in using advanced and cleaner fuels. The slower development cycle in many parts of the world shows that biomass fuels will be utilized by poor households for decades ahead [9]. If we look at the stats provided by The Energy Progress Report 2019 [10], the global access to clean cooking was 58% in the year 2014, and it reached only 59% in the year 2016. The average growth rate was only 0.5% annually; unfortunately, it has been declining since the year 2010. With this annual rate of progress, it is not possible to meet the 2030 target of accessing cleaner fuels on universal level. In order to achieve the set goals, the annual growth rate must accelerate from 0.5 to 3% for the period 2016 to 2030. However, with the present stats, the chances are that almost 2.3 billion people worldwide will not have direct access to clean cooking in 2030. It means the health impacts of IAP will also persist; especially in the areas with inadequate ventilation arrangements [10].

Ventilation plays an essential role in the measurement of indoor air quality (IAQ). In case if proper ventilation arrangement is missing in building structures, the IAQ decreases and buildings become unhealthy to live. Studies reveal that IAP is observed as one of the major causes of increasing health issues associated with poor ventilation. As per a study conducted in few remote villages of Palpa district located in the western part of Nepal, the percentage deficit in ventilation is 80% as compared to the minimal rate suggested by the American Society of Heating, Refrigeration and Air Conditioning Engineers [11]. Another study report that poorly ventilation kitchens in Nepal have 100 times higher concentration of total suspended particles in comparison to the standard prescribed limit and it is due to excessive smoke generation in the premises [12]. Parajuli et al. [11] also monitored the impact of traditional cooking systems and improved cooking systems in the village houses. The estimated reduction of CO concentration and $PM_{2.5}$ concentration was 30 and 39% respectively, with the use of improved cooking systems as compared to traditional cooking systems. Generally, the occupational and educational stats along with housing conditions in urban areas are relatively better when compared to the rural areas. These conditions have a direct relationship with the choice of fuel for household needs and consequently have a significant impact on IAQ.

Reports reveal that poor IAQ is the second major factor for the higher mortality rate in India. It causes around 1.3 million deaths per year in the country. It is observed that out of 70% of the rural population in India [13], almost 80% of the people rely on biomass fuel to fulfill their household requirements [14]. The estimated number of people using harmful fuels for cooking in India is highlighted in Fig. 1 [15]. It means that the largest population of the country lacks access to cleaner and efficient sources of fuel for cooking needs. Kerosene and biomass cooking fuels are also the principal causes of stillbirth in developing countries. Studies reveal that around 12% of stillbirths can be easily prevented by using cleaner cooking fuel for the household needs in India. Similar studies conducted in other developing countries such as Bangladesh, Nepal, Kenya, and Peru show that IAP is causing severe health hazards. Hence it has become necessary to address the challenges, especially for indoor cooking in the rural sectors. Lack of knowledge and understanding of the benefits of cleaner cooking solutions is the principal cause of adverse health consequences. It is essential to design some efficient and affordable household cooking solutions over traditional stoves, and it can be done only after studying behavioral patterns of the low-income population in the country.

The economic enhancements contribute to reducing IAP caused by various biomass fuels. However, the modern lifestyle is also leading to poor indoor environmental quality. With the improvement in the standard of living, most people are using indoor heating and cooling systems instead of natural ventilation systems [4]. This scenario has increased the cases of Sick Building Syndrome (SBS) somewhere around 30 to 200% [16]. Studies reveal that factors affecting indoor environment include the rate of air exchange, humidity, temperature, ventilation, air movement, biological pollutants, particle pollutants, and gaseous pollutants [17]. Buildings currently constructed are more airtight and make use of advanced insulation materials that help to reduce the loss of energy. However, the air conditioning systems and the latest building envelope also cause a reduction in the circulation of fresh air. Meanwhile, the increasing consumption of chemical products and synthetic materials in indoor environments has increased the presence of several Volatile Organic Compounds (VOC). It is one of the principal causes of hypersensitivity [18]. So, it is fair to say that we are still not safe from hazards associated with IAP.

To deal with the increased mortality and morbidity rate due to IAP, numerous researchers are developing indoor environmental quality monitoring systems. Most of the people spend 80 to 90% of their time indoors either at home or in the offices. Thus, it is necessary to take immediate steps to improve the quality of indoor air. The idea is to create some healthy solutions that can contribute to a comfortable living environment while reducing the chances of the occurrence of severe diseases. This paper puts some light in the direction of efforts made by early researchers to deal with the challenges associated with IAP.

The remaining parts of this review paper are organized below in three different sections, where section of "Indoor

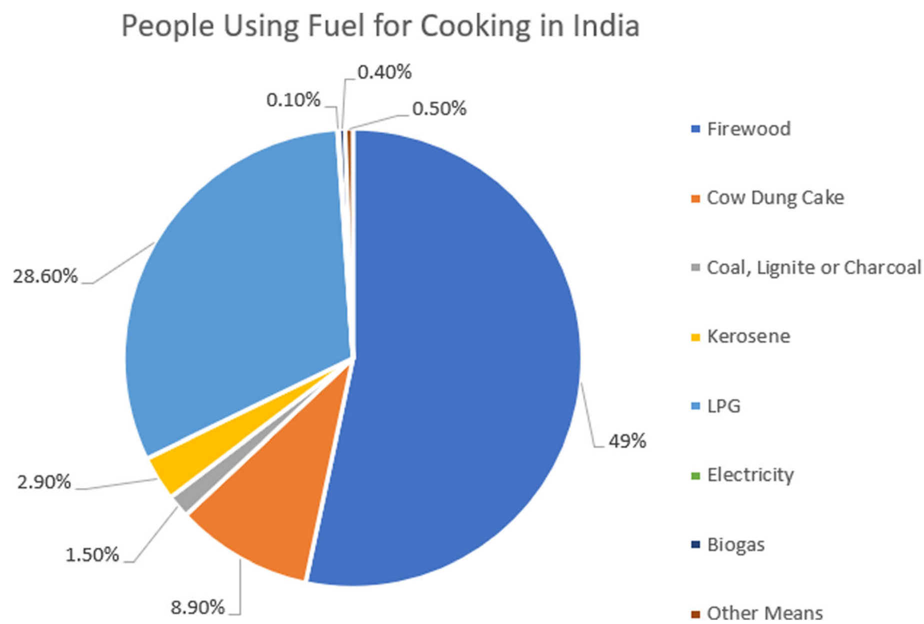

Fig. 1 Stats about people using fuel for cooking in India [15]

air quality and public health" describes the real-time cases of health impacts of IAP in developing countries along with the effect of various pollutants on public health. Section of "indoor air quality monitoring systems" presents an overview of some IAP monitoring systems developed in the past few years. The following section (Results/Discussion) provides a critical analysis of existing systems, along with the advantage and disadvantages of various technologies and sensor networks. Finally, the brief conclusion with future scopes of this study is given in the last section. This paper highlights the background of IAQ, primarily focusing on developing countries along with the potential ideas proposed for monitoring systems by different researchers. It is expected to guide future researchers to focus on new developments by considering the pros and cons of existing systems.

Indoor air quality and public health

IAQ and rural health

Several studies have been reported in India regarding the harmful impacts of IAP. In a nationally representative case-control study published in the year 2010 [19], after adjusting all essential living conditions and demographic factors, excessive exposure to solid fuel increased the number of deaths among children in the age group of 1 to 4. It is because these infants are used to spend more time indoors with their mothers. The prevalence ratio presented in this study for girls was 1.33; 95% Confidence Interval (CI): 1.12–1.58 and for boys: 1.30; 95% CI: 1.08–1.56. Solid fuel was also reported as the most significant reason behind many cases of non-fatal pneumonia with a prevalence ratio of 1.94; 95% CI: 1.13–3.33 for girls and 1.54; 95% CI: 1.01–2.35 for boys [19].

Another case study [20] reveals that routine exposure to fuel other than liquid petroleum gas is directly linked to acute infections in the lower respiratory tract. The adjusted Odds Ratio = 4.73; 95% CI: 1.67–13.45, and these stats were obtained even after adjusting the rest of the risk factors. According to this study, out of the total number of children affected with acute lower respiratory tract infection; almost 24.8% were affected by pneumonia, 45.5% suffered from severe pneumonia whereas, the other 29.7% were observed to have a severe disease [20]. Furthermore, biomass fuel usage in India is also associated with prolonged nasal mucociliary clearance time. It was recorded to be 766 ± 378 s, whereas this time is reported to be 545 ± 216 s in the case of clean fuel users [21]. If we look at 2018 Environmental Performance Index Results, India ranked 177th among 180 countries; whereas, other developing countries like Nepal and Bangladesh ranked 176th and 179th respectively [22]. These stats reveal that some serious efforts are required to improve building health in most developing countries.

IAQ and potential pollutants

IAQ is determined by the concentration of several pollutants such as particle matter, primary, and secondary gaseous pollutants. Studies reveal that a higher number of PM in the urban indoor environment is observed to be of ultra-fine size. Typically, smaller than 0.1 μm, whereas the particles with a size larger than 0.1 μm are observed to be present in a short amount, somewhere below the 10% concentration level [23, 24].

The list of primary gaseous pollutants includes radon, O_3, Nitric oxides (NOx), Sulphur dioxide (SO_2), CO, Diatomic carbon, and VOCs. Within the past few years, the usage of chemical products in indoor environments has been increased drastically. These chemical materials generate several hazardous chemical pollutants under room temperature including VOCs. These compounds can cause several health issues with symptoms such as nausea, headache, dizziness, tiredness, nose, eye, and throat irritations [25]. Ground-level ozone is a colorless gas that acts as an integral component of the atmosphere and is the leading cause of several health diseases related to the respiratory system [25]. Common symptoms of CO poisoning include vomiting, nausea, weakness, dizziness, headache, and loss of consciousness. SO_2 is a highly reactive and colorless gas that plays an essential role in the atmosphere. It is harmful to human health and the patients that are already suffering from lung disease, older people, children, as well as those who face regular exposure to SO, are at higher risks of developing lung diseases and skin related problems. Nitrogen oxide is the leading cause of several infections associated with the respiratory system. Some of the most commonly observed symptoms of NO_2 toxicity include wheezing, coughing, bronchospasm, fever, diaphoresis, chest pain, dyspnea, headache, throat irritations, and pulmonary edema [26]. CO_2 is a by-product of combustion and is also produced by the metabolic process of living organisms. Several studies reveal that a moderate concentration of CO_2 in indoor air can cause fatigue and headaches, whereas higher levels lead to vomiting, dizziness, and nausea. Loss of concentration can also occur at too high levels of CO_2 [27].

Higher concentration of VOCs in buildings can irritate skin, throat, nose, and eyes. Medical health experts also report a broader set of illnesses due to VOCs, such as headaches, respiratory symptoms, fatigue and SBS [28].

The mixture of various pollutants present in the indoor air can cause a chain of chemical reactions, and it further generates secondary pollutants in the environment. Studies reveal that these secondary pollutants are more harmful when compared to the primary ones [29, 30]. Indoor secondary pollutants (such as ozone, NO_2, sulphur trioxide) are observed to cause significant discomfort and a harmful impact on human health. Moreover, they are challenging to measure and predict due to the complexities involved in their composition [27]. Volatile, non-volatile, and non-biological agents cause a harmful impact on indoor air while degrading the overall quality of the environment. The list of biological organisms includes dust mites, pollen, mildew, fungi, molds, bacteria, and many insects, animal dander, anthropoid, infectious agents, pollen, mycotoxins, infectious agents, and animal saliva. The dangerous combination of several indoor air allergens with specific outdoor allergens such as molds, grass pollen, animal allergens, cockroaches, and smoking cause risks of allergic sensitization, asthma and many other respiratory diseases [31]. The list of major indoor air pollutants, sources of emission, and associated medical health consequences is shown in Table 1.

Indoor air quality monitoring (IAQM) systems

Currently, the increasing health issues due to IAP are an essential matter of discussion for researchers worldwide. Some professionals utilized advanced sensor networks and communication technologies to propose IAQ monitoring systems for the enhanced living environment. As researchers are actively working in this field to improve building health, it is difficult to review all existing and proposed IAQ monitoring systems in this paper. Nonetheless, this section includes studies based on the most prominent IAP parameters. As automatic alert systems are need of the hour in our busy schedules, we have preferably picked monitoring systems that propose online access to recorded environmental factors or generate SMS based alerts. Although several techniques have been invented for real-time monitoring, the preference to be reviewed was given to Wireless Sensor Network (WSN) and Internet of Things (IoT) based models due to their rising scope in the Industry 4.0 revolution.

Alhmiedat and Samara [32] developed a low-cost ZigBee sensor network architecture to monitor IAQ in real-time. It is possible to install four sensor nodes in the indoor environment and collect data for more than four weeks. The environmental data were further transferred for analysis via a ZigBee communication protocol. Authors of this paper analyzed CO_2, benzene, NOx, and ammonia for IAQ assessment at the time of cooking in the kitchen, while other sensors collected desired input from the bedroom, living room and office area. It provides real-time monitoring of all factors contributing to indoor air; however, few developments to this system can be still made by reducing power consumption and improving the accuracy of monitored parameters.

Wu et al. [33] worked on mobile microscopy and machine learning methods to perform accurate quantification and impact analysis of PM. The authors demonstrated a cost-effective and portable PM imaging, quantification and sizing model named C-Air, and the results were displayed on a mobile-based app. A remote server was used for automated processing of essential digital holographic microscope images that ensues accurate PM measurements. This system was capable of providing valuable statistics about density distribution and particle size with the sizing accuracy of approximately 93%. C-Air can be customized to detect specific air particles such as mold and

Table 1 Major pollutants affecting the quality of indoor air and the common sources of emission

Pollutants	Major Sources of Emission	Associated Medical Health Consequences
SO_2	Fossil fuel combustion such as oil, coal and natural gas, outdoor air	Acute exposure leads to bronchial activity.
CO	Tobacco smoke, stoves, boilers, kerosene or gas heaters, fuel burning	Low birth weight, Increase in perinatal deaths
CO_2	Combustion activities, metabolic activity and motor vehicle in garages	Headaches, sleepiness, Poor concentration, Loss of attention
Fungal Spores	Internal surfaces, foodstuffs, plants and soil	Asthma episodes, Allergic reactions, Eye, throat and nose irritation, Sinus and other respiratory problems
Radon	Soil Building concentration materials such as stone and concrete	Risk of lung cancer, Breathing problems
Asbestos	Insulation, fire retardant materials	Cancers such as mesothelioma, Pleural thickening, Pleural plaques and asbestosis
NO_2	Motor vehicles in garages, fuel burning and outdoor air	Exacerbation of asthma and wheezing, Reduced lung function in kids, Respiratory infections
Pollens and allergens	Outdoor air, plants, weeds, grass, trees, insects, domestic animals, and house dust	Trigger symptoms of allergy
Particles (small particles < 10 μm; and < 2.5 μm aerodynamic diameter)	Tobacco smoke, re-suspension, combustion products	Exacerbation of Asthma, Wheezing, Respiratory infections, Exacerbation of COPD, Chronic bronchitis and COPD
Ozone	Photochemical reactions	Airway irritation, Permanent lung damage, Pneumonia and bronchitis, Aggravate asthma
Lead	Paints, firearms, lead bullets, dust, soil, radiators, consumer products	Memory loss, Hearing loss, Damage to the nervous system in new-borns, High blood pressure, Kidney & heart disease, Reduced fertility, Hyperactivity or loss of consciousness
VOCs	Burning of gas, wood, and kerosene, cleaning agents, paints, hair spray, perfumes and tobacco smoke	Allergic skin reactions, Visual disorders and memory impairments, Damage to the central nervous system, kidney, and liver, Decline in serum, cholinesterase levels, SBS

pollens. The performance of C-Air was tested for indoor as well as outdoor air environments.

Zampolli et al. [34] developed a low-cost model with an electronic nose based solid-state sensor array for monitoring IAQ. By using a combination of advanced pattern recognition techniques and optimized gas sensor array, researchers targeted the quantification of NOx, CO, along with VOCs and relative humidity (RH). The performance of the electronic nose was analyzed in real operating conditions where NO_2 concentrations at 20 ppb and CO at 5 ppm were monitored continuously for at least 45 d. This approach helped to identify the presence of individual pollutants along with the mixture of different contaminants in the test environment. This system was found feasible enough to detect NO_2 and CO levels in indoor air, and these results were further used to manage the appropriate usage of heating, ventilation, and air conditioning (HVAC) systems in the indoor environment without disturbing the air quality.

Kim et al. [35] focused on seven gases (CO_2, VOCs, SO_2, NOx, CO, PM, and ozone) to test IAQ in real-time. The experiments were conducted in three different settings: big church, medium size classroom, and small size living room to test the impact of different factors on IAQ. Researchers concluded that so many factors contribute to altering the quality of indoor air. Some of these are wind, location, airflow, the density of people and room size. However, it was found that gas sensors consume lots of power, so it is important to apply critical thinking for the selection of appropriate sensor nodes. Future researchers are also advised to work on environmental settings and sensor characteristics to ensure reliable calibration of the system to obtain accurate results.

Yu and Lin [36] constructed an intelligent wireless sensing and control system to deal with health issues caused by IAP. The system is made up of three different parts: 1) Data acquisition that helps in obtaining values about environmental indicators such as CO_2 concentration, RH, and temperature through polling mechanism; 2) Data analysis, responsible for collecting data and interfacing with the AutoRegressive Integrated Moving Average (ARIMA) prediction model to analyze air quality trends in the premises; and 3) Data feedback to trigger necessary actions based on fuzzy results. It may send a warning message or may control the speed of the fan automatically. Each sensor node in this hardware architecture is powered by the IEEE1451.4 standard, and the communication channel is established by ZigBee technology. The software architecture is precisely separated into three different sections where 1) Data monitoring agent creates a bridge between software and hardware,

2) Air quality analyzing agent takes care of air quality trends and triggers relevant actions for higher pollution levels; and 3) Application agent provides services for data display automatic control and alerts. The final ARIMA prediction model based IAQ monitoring system was deployed in the real-time environment at nine different areas of Taiwan. It included Environmental Protection Administration, university, and elementary schools. The performance of the system was further tested using two tests: Validation of the accuracy of the prediction model and validation of energy-saving performance. The system used to make useful decisions about ventilation equipment in the premises depending upon the threshold level of air quality parameters.

Pillai et al. [37] implemented a sensor network for IAQ monitoring using the Controller Area Network (CAN) interface. In order to run the experiment on a real-time basis, the sensors were distributed in a specific area, and a serial standard bus communication network was used for information exchange between them. CAN is a specially designed high integrity serial bus protocol that works on high speed by supporting information exchange rate between 20 kbit s^{-1} to 1 Mbit s^{-1}. Using CAN, researchers were able to develop a highly reliable, efficient, and economical communication link between display nodes and sensor nodes. The hardware tests provided highly accurate monitoring for IAQ with short processing time.

Abraham and Li [38] proposed a cost-effective WSN system for monitoring IAQ. The system was designed using low-cost micro gas sensors (CO, VOC, and CO_2) and use the Arduino microcontroller as the processing unit. The mesh network for this monitoring system was developed using the ZigBee module that promised low power, low cost and wireless solution for communication. Data calibration for micro gas sensor networks was further performed using Least-Square Method. It helped researchers to study the current status of IAQ while collecting valuable data for the long-term impacts of bad air quality on human health. The proposed system was also compared with standard GrayWolf System, and it was observed to be independent of humidity and temperature variations.

Cheng et al. [39] developed AirCloud that is a cloud-based air quality monitoring system designed to serve low cost personal and pervasive needs. The authors worked on two types of Internet-connected PM monitors (focused around $PM_{2.5}$ levels) that were named as mini air quality monitoring (AQM) and AQM. The monitoring process was based entirely upon the mechanical structures that were designed for maintaining optimal airflow. On the cloud side, the authors created an air quality analytics engine to learn and develop models of measured air quality with the help of sensors. This cloud-based engine helped in the calibration of mini AQMs and AQMs on a real-time basis while inferring $PM_{2.5}$ concentrations. This system provided relevant accuracies at lower cost ensuring dense coverage ability.

Kang and Hwang [40] introduced an air quality monitoring system to test the relevance of the Comprehensive Air Quality Index for accurate IAQ assessment. The authors also proposed a real-time Comprehensive Indoor Air Quality Indicator (CIAQI) system that can work effectively against all dynamic changes and is quite efficient in processing ability along with memory overhead. In order to develop the experimental setup for realistic indoor air environment monitoring, the authors used VOC, PM_{10}, CO, temperature and humidity sensors. The authors also compared the proposed system performance with absolute concentration of all considered pollutants used for ambient air quality index (AQI) with Simple Moving Average scheme and observed that the proposed CIAQI system is more adaptive to real-time changes in the IAQ. Also, this system utilized small memory; therefore, it was considered as an economical solution for the IoT based air quality monitoring.

Bhattacharya et al. [41] developed a wireless system for monitoring IAQ by working on a few essential parameters such as humidity, temperature, gaseous pollutants, and PM. This system determines indoor environment health in terms of the AQI and at the same time gives real-time inputs to control HVAC systems. In order to serve the smart building applications, authors have also developed a toolkit that measures live air quality data in the form of graphs and numbers.

Ahn et al. [42] designed a microchip by utilizing six atmospheric sensors: VOCs, light quantity, humidity, temperature, fine dust, and CO_2. The atmospheric changes were estimated using deep learning models. Performance of the proposed Gated Recurrent Network (GRU) model was also compared with other models such as Long Short-Term Memory (LSTM) networks and linear regression, where the proposed system presented better performance with higher accuracy of 85% over a variety of parameter settings.

Pitarma et al. [43] developed a low-cost IAQ monitoring unit using a WSN system in combination with microsensors, XBee modules, and Arduino. They worked on five major IAP parameters: luminosity, CO_2, CO, humidity and air temperature while performing real-time monitoring on a web portal. The wireless communication network between sensors and gateway was established with the XBee module utilizing ZigBee networking protocol and IEEE802.15.4 radio standards. Sensors involved in real-time measurement were sensor SHT10 for RH and temperature; MQ7 for CO, T6615 sensor for CO_2 measurement and LDR5 mm for light detection. The web interface was designed using MySQL database and Personal

Home Page (PHP). The prime goal to design this system was to help users get instant updates about exposure risks in the living environment.

Benammar et al. [44] designed an end to end IAQM system using WSN technology. It was focused around the measurement of RH, ambient temperature, Cl_2, O_3, NO_2, SO_2, CO, and CO_2. The sensor nodes were made to communicate to the gateway via XBee PRO radio modules. The sensor nodes in this study include a set of calibrated sensor units, a data storage unit named Waspmote, and sensor interface board known as Gas Pro sensor board. The prime role of the gateway in this study was to process the IAQ data collected from target sites and perform reliable dissemination via a web server. This system was adapted to open source IoT web server platform, named Emoncms to ensure long-term storage as well as live monitoring of IAQM data. Seamless integration of smart mobile standards, WSN, and many other sensing technologies is performed to design the ultimate scalable smart system to monitor IAP. In order to meet the power requirements of the system, authors also designed separate battery units for the sensor network.

Saad et al. [45] created a system to monitor various environmental parameters that are directly related to air quality. They focused on RH, temperature, PM, and gaseous pollutants that have a direct impact on human health. A WSN was used to measure data from the target location, and it was transferred to the base station via the WSN node. A self-developed server program on the computer system used to access and process this data to analyze IAQ on a real-time basis.

Tiele et al. [46] focused on the design and development of a portable and low-cost indoor environment monitoring system. This study was performed on a few essential parameters of indoor air such as sound levels, illuminance, CO, CO_2, VOCs, PM_{10}, $PM_{2.5}$, RH, and temperature. The experiments were conducted in both indoor work environments and outdoors. The authors defined an Indoor Environment Quality (IEQ) index to estimate the overall percentage of IEQ.

Moreno-Rangel et al. [47] presented a study to assess usability, accuracy, and the precision of low-cost IAQ monitor within a residential building. After analyzing the cost and complexity related issues associated with existing scientific solutions for IAQ monitoring, the authors proposed a reliable and low-cost system for households. They focused on a few essential parameters, such as $PM_{2.5}$, CO_2, VOCs, RH, and temperature. All sensors were calibrated before installation to ensure an adequate measurement. The collected data was analyzed using FOOBOT monitors based on the percentage of time the pollutant levels crossed the threshold levels set by World Health Organization. In order to enhance the accuracy of the measurement, authors in this study used IBM SPSS Statistics to perform statistical analysis.

Idrees et al. [48] closely observed the challenges associated with IAP and developed an Arduino based platform for real-time IAQ monitoring systems. They initiated steps toward the detailed investigation of factors such as computational complexity, infrastructure, issues, and procedures for efficient designing. The prototype for the proposed real-time IAQ monitoring system was designed using the IBM Watson IoT platform and Arduino board. The authors worked on eight parameters that have a considerable impact on human health in the building environment. The list includes RH, temperature, O_3, SO_2, NO_2, CO, $PM_{2.5}$, and PM_{10}. The significant advantage of this system was its ability to reduce the computational burden of the sensing nodes by almost 70%, leading to longer battery life. In order to ensure higher accuracy for measurements, authors used standard calibration procedures on sensor networks, and a data transmission strategy was used to minimize the power consumption along with redundant network traffic. The three most essential layers of the proposed monitoring system were sensing layer, edge computing layer, and application layer. This model reported a reduction of 23% in the overall power consumption, and the performance was validated by setting the system in different environments.

Sivasankari et al. [49] proposed an IoT based system to monitor IAQ, and the analysis was performed using a Raspberry Pi model. The parameters included in this study were RH, temperature, NO_2, CO, and concentrations of smoke. The measurements were done using MQ series sensors, Mics 2714 NO_2 sensor, LM-35, and DHT11 sensor. An analog to digital converter was also added to the system so that sensors can be directly interfaced with the Raspberry pi module via eight different channels. This system was used to generate an alarm for indicating a high concentration of emissions, such as a warning for the air pollution rate in the premises.

Arroyo et al. [50] presented an air quality measurement system made of a distributed sensor network and cloud-based WSN system. Low power ZigBee motes were used for collecting field data, and an optimized cloud computing system was implemented for processing, monitoring, storing, and visualizing received data. This laboratory study was based on the measurement of VOCs, including xylene, ethylbenzene, toluene, and benzene. Multilayer perceptron, principle component analysis, support vector machine, and backpropagation learning algorithm were used at the data processing stage.

This section summarizes the review of IAP monitoring systems that are proposed by early researchers from different countries in the past few years. The main idea is to discuss potential techniques, architectures, and configurations that are already used by researchers. Reliable and efficient monitoring systems can be used in urban as well as rural areas to monitor the IAP and its impact on residents. It is believed that instant alerts can guide people to make proper ventilation arrangements by opening windows or doors in the kitchen; such systems are more useful in homes having traditional cooking systems, and inadequate ventilation arrangements. The results and discussion section further provide a detailed analysis of these studies while covering the strengths, weaknesses of the existing IAQ monitoring systems along with future scopes to guide future researchers.

Results and discussion

WSN based systems

The trends in the development of the IAQ monitoring system reveal that most of the researchers in the past few years have worked on WSN based designs with ZigBee as the most reliable communication protocol. The ATmega microcontroller manages the real-time data collection; however, Raspberry Pi is another common choice for setting up a sensor network in the target environment. WSN is an Ad Hoc Network, where sensor networks consume immense energy while transmitting data in multiple hops. The time taken by sensors to send a signal to the monitoring unit was observed to be considerably high. In such situations, researchers needed to work on battery power management to improve overall system performance. However, only a few researchers, such as Yu and Lin [36] were successful in implementing energy-saving and cost-saving monitoring systems using WSN architecture. Trends reveal that most of the WSN based IAQ monitoring systems use web servers as data access platforms; it demands additional efforts to generate real-time alerts on user smartphones to prevent hazardous conditions. Table 2 highlights the summary of WSN based IAQ monitoring systems.

IoT based systems

Considering the battery life expectancy and reliable single-hop communication abilities, IoT monitoring systems are believed to be the most reliable solutions for IAQ measurement. With lower latencies and lesser power consumption, these systems also demand lesser efforts for maintenance. IoT based real-time monitoring systems are known as smart systems; consequently, most of the researchers and industrial manufacturers are more attracted to this architecture. Experts reveal that the IoT system can monitor a large number of parameters, even without compromising system performance. Studies carried by Idrees et al. [48] and Sivasankari et al. [49] gave a new edge to the IAQ monitoring systems with impactful IoT architecture design. However, very few researchers in the past few years have worked on prediction systems in the field of IAQ monitoring. Studies reveal that it is much easier to combine IoT monitoring systems to machine learning and deep learning networks to initiate reliable prediction decisions. It is a significant area of work for new age researchers. Table 3 presents a summary of IoT based IAQ monitoring systems.

Other technologies

Some researchers also worked on architectures other than WSN and IoT, but few parameters reveal the low performance of such systems as compared to the potential of IoT systems for real-time monitoring. The most significant disadvantage of the C-Air platform presented by Wu et al. [33] was that this study was limited to PM levels only; but in the real world, IAQ is affected by many other pollutants as well. Zampolli et al. [34] tried working on multiple pollutants, but the study was limited to the simulation environment only; the practical implementation of such systems is the real challenge. Moreover, these researchers worked on low-cost sensors where calibration is a significant challenge, and it leads to a lack of performance for the overall design. Similar constraints were found with the approach followed by Pillai et al. [37], where the system was studied on breadboards in a controlled lab environment only. Cheng et al. [39] tried to implement a prediction model with CAN interface, but the study was again limited to PM levels only; the impact of other pollutants was not considered in this study. Moreno-Rangel et al. [47] presented a valuable study with FOOBOT monitors, and they considered multiple IAQ parameters for the real-time analysis, but the sensor calibration was again a relevant challenge to ensure desired performance. Table 4 presents a summary of IAQ monitoring systems based on architectures other than WSN and IoT.

Discussion and critical analysis

The primary requirement at present is to perform real-time monitoring of IAQ parameters and generate alerts to the building occupants to avoid hazardous conditions. The IoT approach has great potential in this direction to ensure lesser power consumption, negligible time delays, and has a better ability to interact with the physical world.

One of the prime concerns in the development of IAQ systems is the higher cost and massive power consumption of sensor nodes. If we consider the real-time applications of IAQ systems, the sensor units are usually installed in an industrial environment, inside homes, offices, and outdoor areas as well. However, in all these cases, the design of the sensor unit demands more focus on size, design cost, power consumption, communication protocol, and performance dependence on temperature and humidity variations. Sensor calibration is currently the main

Table 2 Summary of IAQ monitoring systems based on WSN

Sr. No.	References	Year	Parameters Considered	Architecture	Communication Interface	MCU	Data Access	Remarks
1.	Alhmiedat and Samara [32]	2017	CO_2, benzene, NO_x and ammonia	WSN	ZigBee	ATtiny85 microcontroller	Simulation environment	A sleep state algorithm and interface circuit used to minimize power consumption
2.	Kim et al. [35]	2014	CO_2, VOCs, SO_2, NO_x, CO, PM and O_3	WSN	ZigBee	Raspberry Pi	Web server and Mobile	Experiments conducted in three different settings: big church, medium size classroom and small size living room; Real-time monitoring alert
3.	Yu and Lin [36]	2015	CO_2, RH, temperature	WSN	ZigBee	Not available	Web Pages and Mobile App	Use of ARIMA Model for prediction, System provided 55% reduction to the sensor network energy consumption with Fuzzy Log-c based decision model
4.	Abraham and Li [38]	2014	CO, VOC and CO_2, O_3, RH, temperature,	WSN	ZigBee module	Arduino Uno microcontroller	Web Server	Micro gas sensors were calibrated using least square estimation-based method
5.	Bhattacharya et al. [41]	2012	RH, temperature, gaseous pollutants and PM	WSN	ZigBee module	ATmega1281 (Waspmote)	HVAC control application, SMS and email-based alerts can be generated on subscription.	Context-Aware Framework was designed to connect sensors with applications.
6.	Ahn et al. [42]	2017	VOC, light quantity, RH, temperature, fine dust, CO_2	WSN	UART/I2C, ESP8266 Wi-Fi Module	ATmega328P	Linux Server	Comparative prediction models were designed using LSTM and GRU networks
7.	Pitarma et al. [43]	2016	Luminosity, CO_2, CO, RH and air temperature	WSN	ZigBee module	Arduino	Web portal	A dedicated web portal named as iAQ was designed using PHP to access system data
8.	Benammar et al. [44]	2018	RH, ambient temperature, Cl_2, O_3, NO_2, SO_2, CO, CO_2	WSN	ZigBee Pro radio module	ATmega 1281 (Waspmote), Raspberry Pi2 for core gateway	Open-source IoT web server platform	–
9.	Saad et al. [45]	2013	RH, temperature, PM and gaseous pollutants	WSN	AT86RF230 radio frequency front end IC for ZigBee standard	ATmega1281 low power MCU	Web InterfacThe s	Study was carried within the Lab environment.
10.	Tiele et al. [46]	2018	Sound levels, illuminance, CO, CO_2, total VOCs, PM_{10}, $PM_{2.5}$, RH and temperature	WSN	I2C/UART	Feather M0	OLED Display, MicroSD Card	Made use of eNose for data collection, Custom low-cost sensor module was designed using Altium Designer
11.	Arroyo et al. [50]	2019	Toluene, ethylbenzene, benzene, and xylene	WSN	ZigBee	Not available	Cloud server	Laboratoy based case study

challenge in front of future researchers to ensure accurate real-time monitoring. Although Metal Oxide Semiconductor sensors are cheaper when compared to the optical and electromechanical sensors (some examples are TGS 2442 and TGS416), they work on the resistive heating; hence, consume loads of energy from limited battery unit of wireless motes. As a result, it reduces the overall lifetime of the network. A considerable solution to solve this problem is placing motes (a specific type of sensor node that can collect, process information and can communicate with other nodes in the network) in sleep mode when they are not working actively in the system. Some studies also reveal that a high-quality micro gas sensor can perform better in variable humidity and temperature conditions. One advanced solution to air quality monitoring is Mobile Sensing System for IAQ – personalized mobile sensing system that is gaining popularity due to the portable, energy-efficient and inexpensive design. Most of the researchers have used ZigBee to establish a communication network between sensor nodes and

Table 3 Summary of IAQ monitoring systems based on IoT

Sr. No.	References	Year	Parameters considered	Architecture	Communication Interface	MCU	Data Access	Remarks
1.	Kang and Hwang [40]	2016	VOC, PM_{10}, CO, temperature and RH	IoT	Bluetooth, Wi-Fi and RF communication module	TI MSP430	Wb server	Comprehensive Real-Time Indoor Air-Quality Level Indicator was designed
2.	Idrees et al. [48]	2018	RH, temperature, O_3, SO_2, NO_2, CO, $PM_{2.5}$ and PM_{10}	IoT	ZigBee and Wi-Fi ESP8266	ATmega328P	Web-based IBM Watson IoT platform, Mobile App	Automatic calibration system was developed fothe r sensor system, performed detailed power consumption and computational cost analysis
3.	Sivasankari et al. [49]	2018	RH, temperature, NO_2, CO and concentrations of smoke	IoT	UART	Raspberry Pi	IP Address on Web	Data can be monitored from anywhere by logging into IP address.

controller unit, but the prime disadvantages of ZigBee modules are short communication range and low network stability with high maintenance cost. The highly efficient IoT systems bring new scope to this field. By using IoT architecture and the Raspberry Pi microcontroller, which has in-built Wi-Fi communication features ensure fast data transfer. Note that the most used Arduino boards do not offer direct network connectivity. Therefore, users need to use additional modules for internet accessibility. One commonly used Wi-Fi module for Arduino boards is ESP8266 chip, but it needs an external converter for 5–3 logic shifting since most Arduino microcontrollers use 5 V operating voltage. Moreover, it leads to additional cost and energy consumption. Furthermore, Raspberry Pi 3 has more processing power than Arduino Uno as the clock speed for the former is 1.2 GHz, whereas later works on 16 MHz.

Several methods for real-time IAQ monitoring are available in the literature. Furthermore, the presented methods provide practical solutions to improve occupational health and contribute to enhanced living environments considering numerous technical challenges. However, few improvements in the system performance are still required to ensure a reliable solution. By using an IAQ monitoring system, the manager can understand the IAQ behavior of the environment and plan interventions to avoid unhealthy situations. Therefore, the development of enhanced IAQ monitoring systems will address critical health challenges in today's world.

This section describes the weaknesses and strengths of the existing monitoring systems while describing the potential of available technologies and architectures. This in-depth review can guide new researchers to pick the most relevant topics for research in the future so that the quality of the living environment can be improved by inventing new methods and techniques.

Conclusions

In this review, the authors provide details about how various factors such as VOCs, PM_{10}, $PM_{2.5}$, CO, SO_2,

Table 4 Summary of IAQ monitoring systems based on other architectures

Sr. No.	References	Year	Parameters considered	Architecture	Communication Interface	MCU	Data Access	Remarks
1.	Wu et al. [33]	2017	PM	C-Air platform	Not available	Raspberry Pi A+	Mobile app	Machine learning algorithm was used for particle detection and sizing
2.	Zampolli et al. [34]	2004	NO_x, CO, VOCs and RH	eNose architecture based solid-state sensor array	Custom-made electronic interface	ST52T301P	Simulation environment	Fuzzy pattern recognition algorithm was used
3.	Pillai et al. [37]	2010	VOCs, CO, hydrogen	C-N based sensor network	CAN	AT89C51CC03	LED DisplaThe e	Experiment was performed on breadboards in a lab environment
4.	Cheng et al. [39]	2014	$PM_{2.5}$ levels	Cloud-based engine	Bluetooth 0.4, 3G mobile data connection and Wi-Fi	Raspberry Pi	Mobile Apps, WeThe p	Prediction model was designed using Artificial Neural Network
5.	Moreno-Rangel et al. [47]	2018	Fine $PM_{2.5}$, CO_2, VOCs, RH and temperature	Foobot FBT0002100	Wi-Fi	Not available	Cloud System, Tablet	–

NO, O_3, temperature, and RH affect IAQ. Furthermore, authors have highlighted the technical aspects of the studies performed by early researchers in this field. Trends reveal that most of the researchers till now have worked upon WSN and IoT architectures to study associated factors with IAQ and provide mobile computing software for data consulting.

Instead of working within a controlled laboratory environment or on simulation systems, researchers need to implement real-time IAQ monitoring systems in real scenarios. The development of prediction systems is another primary concern for future studies because it is easier to control the adverse impact of indoor air pollutants when we are aware of future happenings. Deep learning models such as LSTM and GRU can be utilized to design the prediction systems, and the instant alerts about variation in indoor pollutant levels above the threshold limit must be sent via SMS or email to the smartphones. Note that, LSTM is the enhanced strategy to traditional Recurrent Neural Network, whereas GRU is the further extension to LSTM with forget and update gates. These models work with parameterized functions that have a direct impact on ideal parameters of the data; hence lead to better prediction. Mobile app-based systems analysis is also an essential part of the design. This field has considerable scope for development, and future researchers need to work on in-depth design solutions by combining IoT and deep learning models to come up with cost-effective, accurate, and reliable IAQ management systems. However, the research should not be limited to the industrial environment and cities. Only slightly suitable systems must be designed for the village areas where people suffer more due to their excessive exposure to solid fuels. The development of such systems can lead to an incredible contribution to the medical health department as well.

The main areas of work for future researchers can be summarized as:

– Developing an IAQ monitoring system that can work efficiently in real-time conditions, instead of simulated or laboratory-based environments.
– Consider specific requirements of rural areas and design a cost-effective IAQ monitoring system to provide a safe solution for enhanced living environments.
– Work on IAQ prediction systems so that appropriate preventive measures can be followed on time.
– Designing a power-efficient and robust system for severe monitoring conditions in the urban as well as rural areas.
– Developing more efficient systems that can generate instant alerts to the users via email and SMS whenever IAP crosses certain threshold levels.
– Develop mobile app-based monitoring systems that can be operated by non-tech savvy people as well.
– Developing quick alert systems with possible preventive measures like switch on/off air conditioner, open/close windows, and check gas leakage to guide people towards healthy solutions with a variety of specific pollutants in the living environment.

In conclusion, the monitoring solutions/architectures proposed to address the IAQ should incorporate artificial intelligence to predict unhealthy situations for the enhanced living environment and occupational health.

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