Internet of Things for Enhanced Smart Cities: A Review, Roadmap and Case Study on Air Quality Sensing

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Abstract. The smart city concept is a strategy to face relevant open issues regarding the socio-economic development requirements that promote people health and well-being. Smart homes are a fundamental element of smart cities and are intended to meet several applications for enhanced living environments and occupational health. Most individuals stay most of their time indoors, and therefore, smart homes are unquestionably an essential place to monitor. Indoor air quality has a meaningful negative influence on occupational health and well-being. Moreover, cities are responsible for a relevant portion of greenhouse emissions, and the outdoor air quality monitoring is relevant to detect adverse air quality situations and design interventions to promote public health. Air quality sensing is a fundamental element of people's daily routine and must be incorporated in smart homes and smart cities to promote health and well-being. Furthermore, this data can be evaluated by health professionals for diagnostics support and to correlate patient symptoms with their living environment but also to support city managers in the intervention planning for enhanced living environments. This paper presents a review and roadmap on air quality sensing and proposes an Internet of Things architecture for air quality supervision. The outcomes are encouraging as the presented system can be used to provide a correct and cost-effective air quality assessment. The proposed method can be used to support city managers to detect possible unhealthy scenarios in smart cities in useful time.

Keywords: Air quality sensing · Ambient assisted living · Enhanced living environments · Indoor environment quality · Internet of Things · Occupational health · Smart cities

1 Introduction

The Internet of Things (IoT) is a ubiquitous behaviour of a variety of entities with intelligence and sensing abilities which can collaborate to achieve shared objectives [1, 2]. IoT technologies offer numerous advantages to several domains such as smart cities, smart homes, healthcare and ambient assisted living (AAL) [3, 4].

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The smart city can be assumed as an approach to embrace modern urban productivity requirements in a general framework and to focus on the role of information and communication technologies (ICTs) on the creation of enhanced living environments [5]. Cities face relevant open issues regarding the socio-economic development requirements to promote people health and well-being [6]. Moreover, the smart city aims to moderate the obstacles caused by the urban population increase and accelerated urbanisation [7]. One of the most consistent open issues regarding smart cities is the no operability between different systems. IoT can present the interoperability to develop a centralised urban-scale ICT framework for enhanced living environments [8]. Is relevant to mention that smart cities will cause several meaningful effects at distinct layers on science, productivity and technology. The smart city will lead to complex challenges in society regarding the ethical and moral context. The smart city must provide correct information access to the right individuals. The security and privacy of that information must be established because that data is accessible at a distinct spatial scale where people can be distinguished [9].

Furthermore, IoT brings numerous opportunities regarding the development of modern daily routine applications and services for smart cities [10]. Several technologies closely related to the smart city context connected with IoT architecture will improve our daily routine and promote health and well-being [11].

Most individuals stay most of their time indoors, and therefore, smart homes are unquestionably an essential domain regarding the smart city context. IoT architectures can provide ubiquitous and pervasive methods for environmental data acquisition and provides wireless communication technologies for enhanced connectivity. Particularly, indoor air quality (IAQ) has a material adverse impact on occupational health and well-being. Therefore, the IAQ supervision is determinant for enhanced living environments and should be a requirement of all buildings and consequently, an integral part of the smart city context. The Environmental Protection Agency (EPA) recognises that IAQ values can be one hundred times higher than outdoor pollutant levels and established air quality on the top five environmental hazards to well-being [12].

Moreover, IAQ affects the most underprivileged people worldwide that remain exposed and therefore, can be compared with other public health problems such as sexually transmitted infections [13]. IAQ supervision must be seen as an effective method for the study and assessment of occupational health and well-being. The IAQ data can be used to detect patterns on the indoor quality and to design interventions plans to promote health. The proliferation of IoT devices and systems makes it possible to create automatic machines with sensing, connection and processing capabilities for enhanced living environments.

Air quality sensing must be an essential element of smart cities and smart homes. On the one hand, the IAQ can be estimated by providing CO_2 supervision system for enhanced public health and well-being. The CO_2 indoor levels can not only be used to evaluate the necessity of fresh air in a room but also can be used as a secondary sign of unusual concentrations of other indoor air pollutants. On the other hand, cities are responsible for a relevant portion of greenhouse emissions. Therefore, CO_2 monitoring must be provided on both indoors and outdoors environments. The concentrations of CO_2 are growing to 400 ppm, achieving further records every time after they started to be analyzed in 1984 [14]. The outdoor CO_2 monitoring can be relevant to plan interventions on traffic and to detect the emission of abnormal amounts of CO_2 in real-time. Moreover, real-time monitoring of CO_2 levels in smart cities at different locations allows the identification of points of interest to plan interventions to decrease the greenhouse gases.

This paper presents not only a review and a roadmap on the development of new methods and architectures for the implementation of air quality monitoring systems but also a case study regarding the development of a CO_2 monitoring system based in IoT architecture named **MoniCO$_2$** for enhanced living environments and public health in smart cities. This solution provides a mobile application for CO_2 data analytics and visualisation.

The rest of the document is written as follows: Sect. 2 presents a review on air quality monitoring systems; Sect. 3 is concerned to the application of air quality sensing in the smart city context; Sect. 4 presents the design of a cost-effective monitoring system for air quality assessment; Sect. 5 describes the discussion, and the conclusion is presented in Sect. 6.

2 A Review on Air Quality Monitoring Systems

Several IAQ management systems are presented in state of the art, a review summary is presented in this section. Numerous low-cost IoT methods for air quality management that supports open-source and wireless communication for data collection and transmission but also allow different places supervision at the same time through mobile computing technologies are proposed by [15–22].

An IAQ supervision system based on IoT, which incorporates temperature, humidity and CO2 sensing features developed for the smart city context is proposed by [23]. The data is collected and transmitted from the receiver node and is recorded on a personal computer. The data can be accessed through a LabVIEW and Android application.

An Air quality observation system based on the Arduino UNO microcontroller and low-cost sensors for CO_2 monitoring was proposed by [15]. The nodes receive and send data using ZigBee communication technology. However, this solution does not incorporate mobile computing technologies for data consulting.

The development of a wireless sensor network (WSN) for IAQ management is presented in [24]. This method incorporates temperature, humidity, gas and particulate matter (PM) sensors to determine the environmental health of monitored space. The collected data is used as feedback to control heating, ventilation and air conditioning systems in a smart building.

An IoT method to implement an IAQ management is presented in [25]. The proposed architecture incorporates portable sensors for data collection and implements a low power area network. The collected data is analysed using the cloud. The results presented states the reliability of the air quality sensing data to change behaviour patterns to promote health and well-being.

A cost-effective urban $PM_{2.5}$ supervision system which incorporates mobile sensing features is proposed by [26]. The proposed method incorporates a humidity and temperature sensor, GPS, a dust sensor and a noise sensor. The tests conducted are favourable and can ensure the ability to supervisor air quality at low-cost with reasonable precision.

Air quality sensing is an essential requirement for smart cities and further for global public health. Consequently, the design of cost-effective supervision solutions is a trending and relevant research field. Concerning the quality and appropriate contribution of various actual monitoring solutions [15, 23–26], a shortened comparison study is presented in Table 1.

Table 1. Summarised comparison review table of air quality sensing solutions.

MCU	Architecture	Sensors	Connectivity	Data consulting	Notifications	Ref.
PIC 24F16KA102	IoT	Temperature, humidity and CO_2	nRF24L01	Desktop and mobile	×	[23]
Arduino UNO	WSN	CO_2	ZigBee	×	×	[15]
Waspmote	WSN	CO, CO2, PM, temperature and relative humidity	ZigBee	Desktop	×	[24]
STM 32F103RC	IoT	PM, temperature and humidity	IEEE 802.15.4 k	Web and mobile	×	[25]
Mosaic-Node	StandAlone	GPS, PM2.5, noise, humidity and temperature	×	×	×	[26]

After the review of Table 1, the authors assume that the presented solutions incorporate different microcontroller units based on PIC, Arduino, Waspmote and STMicroelectronics. Moreover, various architectures are used in the development and design of air quality monitoring solutions. The proposed systems can be based on IoT, WSN or be standalone solutions. The most sensors for air quality monitoring are used to measure CO_2. One of the best indicators for air quality is the CO_2 concentration as it is emitted in high amounts and is comparatively effortless measured.

Regarding connectivity, the numerous communication technologies are used, and they are typically wireless. Several methods for data consulting are available such desktop, mobile and web applications. However, the solutions available in the literature does not incorporate notifications and easy installation methods. Notifications can be essential to advise the building or city manager to project arbitrations to improve the air quality on time.

In sum, the literature review presents several automatic systems and projects for air quality sensing, which support the relevance of the IoT architecture and mobile computing technologies as having a significant role in promoting health and well-being.

3 Air Quality Sensing for Enhanced Smart Cities

Smart homes are an essential and integral part of smart cities which had been studied for decades [27]. Smart homes are intended to meet several main applications such as the occupant's activity recognition to promote health and well-being, the use of multimedia technologies for monitoring, wherever the information obtained in the context is managed to trigger a notification for the occupant's protection. Additionally, the smart homes which the main propose is to improve energy efficiency using electric devices automation [28]. Numerous technological enhancements had decreased the cost of the implementation and design of smart homes. However, the development of automatic and intelligent systems for smart homes remains a significant challenge. Likewise, it is imperative to develop a system which can be easily installed and configurated both in smart and traditional buildings. In the recent past, the number of sensors and actuators on the smart city context has increased, which lead to the creation of rich datasets for further investigation and data analytics. Smart homes present an effective method for enhanced living environments and improve numerous daily routine activities and provide the digitalisation of people's everyday activities [29]. In general, smart homes are developed for older adults to provide reliable healthcare systems and adequate real-time supervision of the occupant's health and well-being and to deliver feedback to the caregiver. An essential challenge for the smart city and smart home context is the security and privacy of the collected data. Therefore, high-quality research regarding the creation of secure methods to handle sensitive data is demanded [30, 31]. Air quality sensing must be assumed as significant in the smart city context, considering the air quality effects on people's health and well-being. Furthermore, indoor and outdoor air quality must be provided to improve people's health anytime and everywhere.

Nowadays, smartphones support excellent capabilities for data communication and processing, which can be assumed to consult the air quality data in real-time as people carry them in their daily lives. Moreover, buildings support numerous communication technologies and incorporate automation features. The vehicles are also crucial for the mobility of people in smart cities and are an essential source of air pollution. After combining air quality sensing for indoor and outdoor pollution monitoring, the city manager can achieve several benefits for public health and well-being. The gathered data can be used to project arbitrations on the traffic to decrease the pollution levels in the most critical locations of the city.

Additionally, the smart homes must incorporate air quality sensing to detect in useful time unhealthy situations and plan interventions to avoid them to occur. The air quality data must be validated before been stored and should be accessible anytime, anywhere. Furthermore, the data consulting method should be pervasive and ubiquitous and provide enhanced visualisation tools for data analytics. Specialists can analyse this information to assistance patient diagnostics and associate well-being complications with exposure conditions.

Air quality sensing includes several different stages such as data collection, data processing, data imputation, data storage and data analytics to deliver real-time notifications and alerts for enhanced public health (Fig. 1).

Moreover, the air quality data analysis can trigger critical alarms and notifications for the city and building managers using middleware services. The data collected by

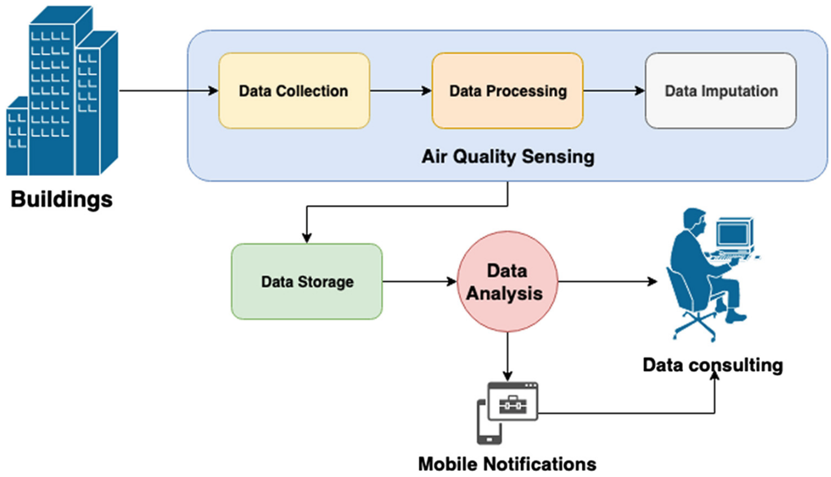

Fig. 1. Schema of an air quality sensing roadmap for enhanced living environments on smart cities.

the air quality monitoring systems are examined before storage. If this data surpasses the established thresholds, a warning should be triggered to support the occupants and city managers to act on time to promote air quality by applying proper air purifying methods inside buildings or by providing different strategies for traffic flow. These real-time alerts offer numerous advantages to achieve various and effective changes because these notifications not only provide measures to improve air quality but also allow the recognition of air quality patterns while repeated harmful situations are identified and to plan interventions to stop them from occurring.

In sum, for all the stated reasons in this section, air quality sensing must be seen as an essential element of people's everyday routine and be incorporated in smart cities to promote health and well-being. This data can be evaluated by professionals to achieve several health benefits that in another way, are impossible to address. Air quality monitoring allows the creation of rich datasets with spatiotemporal behaviour data, which will enable data consulting for city administrators to facilitate accelerated and effective arbitrations to promote public health.

4 Internet of Things Architecture for CO_2 Monitoring System: A Case Study

Taking into account all the requirements of air quality sensing, the authors develop the ***MoniCO$_2$*** solution. In this section, the detailed materials and methods used in the design of the proposed system are presented.

The ***MoniCO$_2$*** is an air quality supervision solution, which incorporates easy installation and configuration. The proposed system uses an ESP8266 which provides built-in wireless networking technologies capabilities and includes an SGP30 Multi-Pixel Gas sensor as a sensing unit. The central goal of the recommended method is to promote health and well-being in smart cities. The proposed method wishes to deliver a mobile computing solution for air quality management to improve public health and safety (Fig. 2). The authors develop a cyber-physical system based on the ESP8266 module, which supports the IEEE 802.11 b/g/n protocol. The data collected is stored in a Microsoft SQL Server database using ASP.NET web services. Mobile computing software has been developed for data consulting using the Swift programming language.

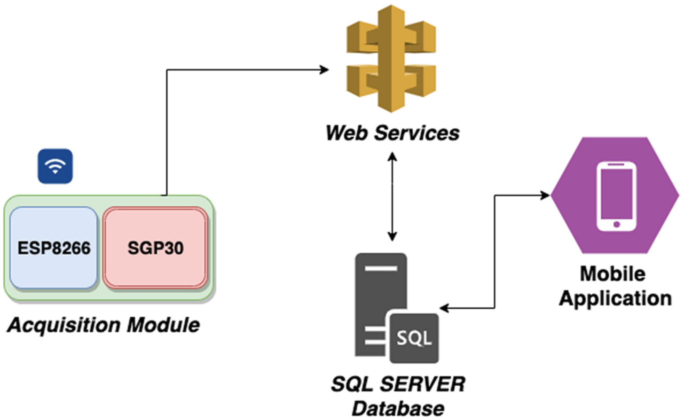

Fig. 2. ***MoniCO*$_2$** system architecture.

Furthermore, the proposed data acquisition module has been developed using on open-source frameworks, and is a cos-effective system, with numerous benefits when associated with actual methods. The acquisition module uses a FireBeetle ESP8266 (*DFRobot*) as a microcontroller, and the SGP30 gas sensor module (*Adafruit*) is connected using the I2C interface. Figure 3 presents the prototype designed by the authors.

The FireBeetle ESP8266 is a wireless board with unified antenna switches, power and low noise amplifiers which is compatible with 802.11 b/g/n protocols. Additionally, this board is WPA/WPA2 compatible and includes a 32-bit MCU and 10-bit ADC. The selected board includes a 16 MB SPI flash memory.

The sensing unit is composed by the SGP30 Multi-Pixel Gas sensor, a metal-oxide gas sensor developed at Sensirion. This sensor provides a calibrated output with 15% of accuracy and provides an I2C connection for data communication [32]. The sensor range for eCO_2 and TVOC concentration is 400–60,000 ppm and 0 to 60,000 ppb, respectively. The eCO_2 output is based on a hydrogen measurement. The sensor sampling rate is 1 s, and the average current consumption is 48 mA.

The proposed method offers a history of the variations of the indoor situation to support the home or city administrator to deliver an accurate examination of the environment. The data collected can likewise to be employed to assist decision-making on potential arbitrations for enhanced public health and well-being. The acquisition module firmware is executed employing the Arduino Core, which is an open-source framework

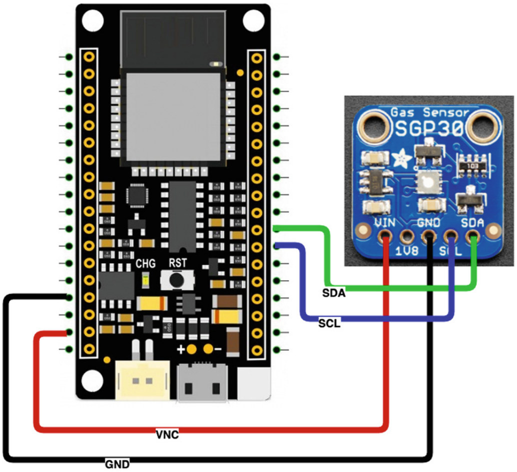

Fig. 3. Acquisition module connection diagram.

that intends to facilitate the use of regular Arduino libraries on the ESP8266 board without an external Arduino board. The proposed system cost is presented in Table 2. The choice of the sensor unit has been made according to the cost of the module as the principal intention was to study the functional design of the proposed method. The ***MoniCO$_2$*** is a low-cost system for air quality management, which costs an estimated 38.04 USD (Table 1).

Table 2. Amount value of the components used to design the proposed method.

Component	Amount (USD)
FireBeetle ESP8266	7.50
Adafruit SGP30 module	19.95
Cables and box	10.59
Overall cost	38.04

The proposed system offers a relevant function that delivers an easy configuration of the wireless network. The system is configured as a Wi-Fi client however if it is incapable of connecting to the wireless network or if no Wi-Fi networks are ready, the proposed system turn to hotspot mode and start a wireless network. At this time, this hotspot can be used to configure the Wi-Fi network to which the system will be connected through the introduction of the network access credentials.

The iOS application, denominated ***MoniCO$_2$Mobile,*** has been established using Swift in Xcode. The developed application has iOS 12 as minimum application requirements (Fig. 4). This mobile application includes numerous essential features, such as real-time data consulting using numeric tables and charts. Using the mobile application, people can inquire about the environmental data after authentication. Consequently, people can hold the parameters of chronicle records for additional examination. The introduced method is a decision-making tool to project arbitrations sustained by the data obtained for enhanced public health.

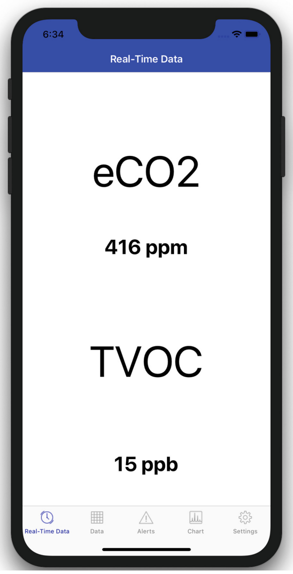

Fig. 4. ***MoniCO₂Mobile*** application: last collected data.

5 Current Status and Discussion

The proposed system was installed and tested inside a controlled laboratory environment. The system was tested continually for two months, and several experiments had been conducted with induced simulations. The module is powered using a 230 V-5 V AC-DC 2A power supply. The experiments indicate that the proposed air quality monitoring system can be used to detect unhealthy scenarios based on the CO_2 and TVOC data at low-cost. The data is collected every 30 s, but this value can be changed according to the needs of the installation. The ***MoniCO$_2$Mobile*** offers information checking as graphical or statistical modes. An example of the data gathered by the system is represented in Fig. 5. The graphs present the results gathered in the physical environment, including provoked simulations of smoke. The results are promising the proposed IoT architecture can provide accurate CO_2 monitoring in real-time and demonstrate a fast response on significative CO_2 variation.

The chart view available on the mobile application provides an improved inspection of observed parameters behaviours when compared with the statistical presentation. First, mobile software presents quick and straightforward access to the obtained data and allows further accurate investigation of air quality progression. Consequently, this method is a relevant instrument for air quality surveillance and to assist decision making on potential interventions to improve performance but also to detect exposure risk scenarios. Second, this IoT architecture offers chronological data evolution for improved air quality assessment, which is particularly appropriate to identify unhealthy scenarios and project interferences to improve health and well-being. Moreover, the mobile application provides a configuration are for the alerts, and the user can easily change that values according to the requirement of the monitored space.

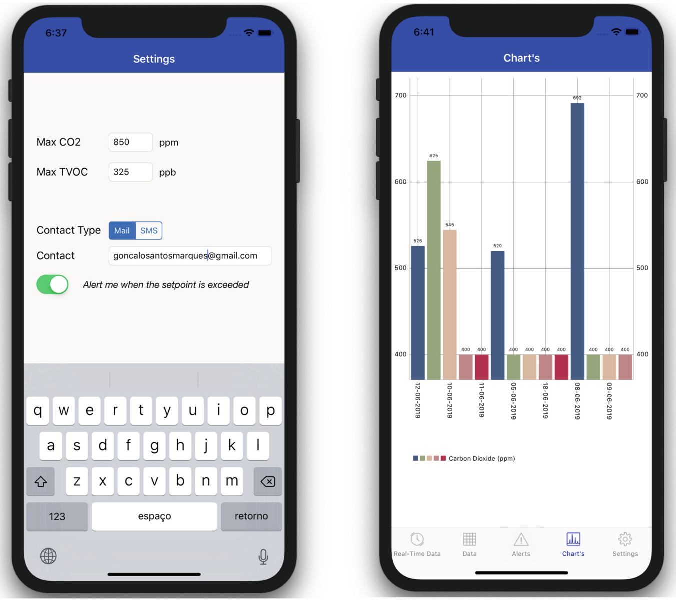

Fig. 5. ***MoniCO₂Mobile*** application: settings and chart view.

The mobile software provides fast and intuitive access to the collected data as mobile phones have today high performance and storage capacities, and most people use them every day. In this way, the building or city manager can transport the air quality data of their environment for further analysis.

Currently, most air quality monitoring systems are high-priced and are established on random sampling. Therefore, these methods are limited by offering data associated with a particular sample without temporal association. Right to be told, the professional systems available on the market are accurate and developed for industrial activities. Further, some solutions are portable and compact. However, these solutions do not support real-time information accessibility for city authorities or build managers. These real-time alerts are essential to facilitate accelerated and decisive interference to promote health and safety. The existing industrial products offer data history constricted to the system memory and required special software for data downloading and administration. The design and development of innovative air quality sensing systems based on the literature which support real-time data consulting for examination and visualisation must be assumed as an essential enhancement regarding the smart city objectives.

Compared with the systems presented in Table 1, the proposed solution provides adaptability and precision of analysis in real-time, providing a meaningful progression of the actual air quality monitoring systems. The results are promising as the proposed system can be used to provide a correct air quality assessment at low-cost. The proposed method can be used to support city managers to detect possible unhealthy scenarios in smart cities in useful time. Another essential benefit of the presented method is the scalability related with the modularity of the solution. The installation can be done through one module, but other modules can be added in the future regarding the requirements of the environment.

IoT is a standard that intends to increase the quality of personal experience. IoT architectures and AAL will reciprocally provide systematic improvements leading to the design of automated and intelligent systems to promote health and well-being. IoT is as a meaningful concept to improve daily routine actions in numerous fields such as buildings, manufacturing, healthcare, smart homes and smart cities. Shortly, innovative methods will improve the number of intelligent solutions established in traditional people houses.

The authors consider that soon, most of the residences will be controlled in real-time and implement warnings to inform the homeowner in the occurrence of inadequate ambient quality. Our living environments will support monitoring features, and the data gathered will be distributed with the therapeutic specialist to compare wellness complications among inadequate practices of the patients and assist clinical assessment.

6 Conclusion

The smart city concept is an approach to embrace current urban production in a mutual context as cities face relevant open issues regarding the socio-economic development requirements and to improve people well-being. IoT will be able to offer the operability between different systems to develop a centralised urban-scale framework for enhanced smart cities.

Smart homes are an essential and integral part of smart cities and are intended to meet several applications to promote health and well-being. Most individuals stay most of their time indoors, and therefore, smart homes are unquestionably an extraordinary place to monitor. Moreover, IoT architectures can provide ubiquitous and pervasive methods for environmental data acquisition and provide connectivity for data transmission. Particularly, IAQ has a material adverse impact on occupational health and well-being. Therefore, air quality sensing must be seen as an integral part of society's everyday activities and must be incorporated in smart cities to promote health and well-being.

Moreover, this data can be evaluated by health professionals for diagnostics support and to correlate patient problems with their living environment. Nevertheless, the air monitoring solutions available in the literature does not incorporate notifications and easy installation methods. Notifications can be essential to advise the building or city manager in real-time to design mediations to promote the air quality in useful time. Therefore, this manuscript had performed a review and roadmap for air quality sensing and proposed an IoT architecture for air quality supervision. The results are encouraging as the suggested system can be used to provide proper air quality assessment. The proposed method can be used to support city managers to detect possible unhealthy scenarios in smart cities early. Furthermore, mobile software provides fast and intuitive access to the collected data, as actually, most people use mobile phones.

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