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Review

Indoor Air Quality Monitoring Systems for Enhanced Living Environments: A Review toward Sustainable Smart Cities

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Abstract: Smart cities follow different strategies to face public health challenges associated with socio-economic objectives. Buildings play a crucial role in smart cities and are closely related to people's health. Moreover, they are equally essential to meet sustainable objectives. People spend most of their time indoors. Therefore, indoor air quality has a critical impact on health and well-being. With the increasing population of elders, ambient-assisted living systems are required to promote occupational health and well-being. Furthermore, living environments must incorporate monitoring systems to detect unfavorable indoor quality scenarios in useful time. This paper reviews the current state of the art on indoor air quality monitoring systems based on Internet of Things and wireless sensor networks in the last five years (2014–2019). This document focuses on the architecture, microcontrollers, connectivity, and sensors used by these systems. The main contribution is to synthesize the existing body of knowledge and identify common threads and gaps that open up new significant and challenging future research directions. The results show that 57% of the indoor air quality monitoring systems are based on Arduino, 53% of the systems use Internet of Things, and WSN architectures represent 33%. The CO_2 and PM monitoring sensors are the most monitored parameters in the analyzed literature, corresponding to 67% and 29%, respectively.

Keywords: ambient assisted living; enhanced living environments; health informatics; indoor air quality; smart cities

1. Introduction

The concept of Internet of Things can be better defined as the ubiquitous presence of cyber-physical systems with advanced communication and sensing capabilities [1]. Ambient-Assisted Living is known as a multidisciplinary field that helps to enhance the overall quality of life for individuals, especially for older adults. This field is closely associated with the ecosystem of new-age technologies that promote personal healthcare monitoring with ubiquitous computing [2,3]. Enhanced Living Environments is another relevant term that is also related to the Ambient-Assisted Living area. The idea is supported by Information and Communications Technologies [4]. In general, Enhanced Living Environments include all the Information and Communications Technologies-based achievements to improve the field of Ambient-Assisted Living [5]. Enhanced Living Environments focus on numerous Information and Communications Technologies-powered solutions designed with unique algorithms, systems, and platforms [6]. These innovative applications and flexible services ensure an independent, reliable, and autonomous living [7]. Furthermore, Enhanced Living Environments make use of advancements in the field of the Internet of Things to present Information and Communications Technologies-based solutions for enhanced health and overall well-being [8]. A healthcare system has two main components: Hardware and software. They work together to provide numbers of healthcare applications and services to individuals for promoting overall health and well-being in a pervasive manner [9,10]. Enhanced Living Environments and Ambient-Assisted Living are two significant technologies contributing to the development of advanced healthcare systems [11,12]. Ambient-Assisted Living offers vast potential to address several healthcare challenges when powered with Information and Communications Technologies [13,14]. On the other hand, Enhanced Living Environments make use of medical sensors, wireless communication technologies, microcontrollers, and open-source software platforms for data analytics and visualization in advanced healthcare systems. Ambient Assisted Living technology promise ambient intelligence for Enhanced Living Environments-based healthcare systems. It enables 24/7 monitoring and enhanced control of the environment [15,16]. These advanced healthcare systems provide direct or indirect assistance for maintaining patient health within home environments without moving them to institutionalized environments [17]. Moreover, these systems promise independent movements to the patients while facilitating quality treatments [18]. The new-age healthcare systems incorporate advanced technologies to monitor human health, physiological status, and various environmental parameters. The real-time updates for such measurements are possible with wireless communication technologies such as Wi-Fi, Ethernet, Bluetooth, 3G, and ZigBee [19].

Indoor Air Quality (IAQ) is one of the primary environmental health risks [20]. Therefore, in order to maintain the desired level of comfort, it is essential to perform IAQ monitoring in all buildings [21]. As human beings spend more than 90% of their time inside buildings, it is crucial to monitor IAQ on a real-time basis for Enhanced Living Environments and improved occupational health. IAQ measurement and assessment help in reliable decision-making on possible interventions so that the productivity of individuals can be enhanced. Healthy living environments can also promote better health and well-being [22,23].

The smart city must be addressed considering its major role in the design of Enhanced Living Environments to support and promote citizens' health [24]. A sustainable approach must be taken when making policies and interventions in cities, and that is also closely related to the building architectures [25]. Furthermore, the smart cities must take into consideration the indoor quality of their buildings [26]. IAQ is affected by outdoor conditions, but buildings assume a crucial role acting as a shield for residents. Therefore, it is essential to design efficient and cost-effective architectures for indoor quality monitoring [27]. However, the operability between different systems is a critical challenge for smart cities. Internet of Things can fulfill the requirements regarding the interoperability of heterogeneous architectures [28]. Moreover, the security and privacy of the citizens must be guaranteed since these systems can handle sensible data associated with people's daily routines [29].

This paper reviews the current state of the art on IAQ monitoring systems based on the Internet of Things and wireless sensor networks (WSN) in the last five years (2014–2019). The main objective is to present a comprehensive literature review of the architecture, microcontrollers, connectivity, and sensors used by these analyzed studies. The main contribution is to synthesize the existing body of knowledge and identify common threads and gaps that open up new significant and challenging future research directions. This paper provides a comprehensive analysis of existing IAQ monitoring systems and highlights the materials and methods used and intends to summarize the primary outcomes and limitations in the analyzed studies.

The rest of this paper is structured as follows: Section 2 presents an overview of the impact of air pollutants in public health on air quality monitoring systems. Section 3 is concerned with the architectures and algorithms used in the IAQ monitoring systems. Section 4 presents the results and discussion of the analyzed literature, and Section 5 presents the main conclusions.

2. Indoor Air Quality and Enhanced Living Environments

People usually spend most of their time inside residential or commercial buildings. Therefore, real-time monitoring of indoor environmental quality (IEQ) for enhanced occupational health and overall well-being is essential [30]. The assessment of IEQ is typically based on specific parameters, such as light, sound, thermal comfort, and air quality conditions [31].

IEQ in buildings presents a composition of IAQ, thermal comfort, acoustics, and lighting [32]. It is widely understood that poor IEQ leaves a negative impact on occupational health, especially on older adults and infants. It is observed that Internet of Things has a considerable impact on the everyday life of the current generation. This concept will be further used in several applications, including assisted living, domotics, and e-health. It is also referred to as an ideal solution for creating revolutionary software applications with efficient data and computational resources [33]. One of the most critical applications of Internet of Things in human life is the monitoring of IAQ [34]. The considerable growth in the field of Information and Communications Technologies, along with the advancements in Internet of Things leads to significant opportunities for the development of flexible healthcare information systems. However, researchers need to deal with the challenges associated with security, safety, and privacy associated with healthcare systems [35,36].

Human physiological status monitoring assists in the perception of the medical state of an individual. It is more critical for individuals that are at high risk, such as older adults, respiratory health patients, and newborns, as symptoms can be detected ahead of time [37,38]. The environmental conditions in the living spaces are closely associated with overall health and well-being. The real-time monitoring can help to detect and prevent critical health problems on time. However, the monitored physiological and environmental data can be further analyzed and processed by experienced doctors to advise appropriate clinical diagnostics [39,40].

Poor IAQ levels beyond specific threshold levels cause adverse health effects. Some of the most common symptoms include difficulty breathing, dizziness, headaches, restlessness, coma, elevated blood pressure, increase heart rate, and asphyxia [41–43]. Continuous monitoring of IEQ can deliver details about the on-going patterns of the IAQ. This information can be further utilized to plan interventions for Enhanced Living Environments [44,45]. With the advancements in the field of Internet of Things technologies, smart homes must be equipped with real-time environment monitoring solutions. It can be made possible by using open source technologies for data collection, transmission, and analysis. Furthermore, microsensors can be utilized for various monitoring activities, such as noise monitoring, activity recognition, and assessment of light and thermal comfort in the buildings [46,47]. Furthermore, poor IAQ is recognized as a potential issue for people that are already suffering from the issue of sexually transmitted diseases or are addicted to tobacco use [48]. Environmental Protection Agency (EPA) is responsible for regulating indoor and outdoor air in the United States. The recent reports presented by EPA ranked poor IAQ as one of the five most prominent environmental risks to public health [49].

Particulate Matter (PM) is determined as a multifaceted combination of liquefied and solid biological, as well as mineral material, particles that are suspended in the air. Several researchers have recognized it as one of the potential pollutants that has a direct relation to individual health and well-being [50,51]. PM usually includes dirt, dust, soot, smoke, and liquid droplets that can penetrate the lower airways in the human body. As a result, they cause potential adverse health effects. In developing countries, repeated exposure to PM in the indoor environment is determined as the primary cause behind increasing cases of acute lower respiratory infections. It is further associated with mortality among young children, chronic obstructive pulmonary disease, cardiovascular disease, and lung cancer among adults. Strong similarities are found between the airborne PM levels sampled from the populated cities in developed countries all over the world [52].

As per the stats gathered from the year 1987, National Ambient Air Quality Standard (NAAQS) for particles having a diameter lower than 10 microns (PM10) was redefined by US EPA [53]. Tobacco smoke is observed as a significant contributor to indoor air pollution and repeated exposure to harmful particles [54]. The World Health Organization (WHO) determines 25–50 $\mu g \cdot m^{-3}$ (24-h mean) or 10–20 $\mu g \cdot m^{-3}$ (annual mean) for PM2.5 and PM10, respectively [55]. Numerous studies also relate higher PM levels to adverse cardiovascular health effects. Some researchers also present a pathophysiological interconnection of PM exposure with cardiopulmonary morbidity and mortality [56,57].

The rising carbon dioxide (CO_2) levels is another significant issue for the classrooms in the schools [58–61]. However, by using a real-time monitoring system for data collection, it is possible to detect and manage occupational health risk situations. Proper IAQ levels contribute to better health, enhanced comfort and productivity with decreased pollution load in living spaces, even if the ventilation arrangements remain unchanged [62].

Studies reveal that non-industrial IAQ has been identified as the leading cause of public health concerns within the past 150 years [63]. Unfortunately, the scientific communities in the developed countries are still not actively involved in IAQ management tasks. In fact, with the latest technologies, it is now possible to improve IAQ levels. We need to be aware of that and use system innovations [64]. In order to deal with the challenges associated with reduced IAQ levels, occupational health municipal authorities, as well as government agencies, need to implement the real-time IAQ supervision systems. These monitoring units can detect unhealthy situations for Enhanced Living Environments while contributing to better occupational health, especially in public places, such as schools and hospitals. It is observed that a few simple interventions conducted by the homeowners and building operators can ensure considerable positive impacts on IAQ levels. People can take some steps to avoid smoking indoors or switch to natural ventilation whenever needed. However, in order to create Enhanced Living Environments, the very first step is to set up real-time monitoring systems. They can detect unhealthy behavior on the premises so that occupants can think of correct ventilation arrangements and adequate use of heating and air conditioning (HVAC) systems. Furthermore, the Internet of Things brings numerous opportunities regarding the development of modern daily routine applications and services for smart cities [65]. Several technologies closely related to the smart city context connected with Internet of Things architecture will improve our daily routine and promote health and well-being [66].

Due to a clear connection between IAQ and public health, the theme is now included in a few specific disciplines in the university courses. However, it is crucial to bring awareness about IAQ consequences among children right from the beginning [67]. Indoor living environments are not limited to apartments and homes. Preferably, they include several types of premises, including workplaces as well. The focus for IAQ management must be extended to hospitals, offices, public service centers, libraries, schools, leisure spaces, and also the vehicle cabins [68]. Schools must be the main focus of IAQ monitoring. Typically, it is not just about the availability of pollutants but also to focus on the number of occupants and the number of hours they spend indoors. These details can help to design more efficient automatic supervision systems so that teachers, students, and the remaining school staff can have a healthful and productive workplace [69].

In sum, IAQ is a critical matter ranked in the top five public challenges worldwide (Figure 1). People typically spend 90% of their time inside buildings. On the one hand, PM is a critical air pollutant of indoor environments and must be monitored in real-time for Enhanced Living Environments. On the other hand, CO_2 is a relevant parameter to be controlled [39,70]. CO_2 results from human metabolism and the indoor concentrations indicate the overall degradation of the air quality as a whole [71–73].

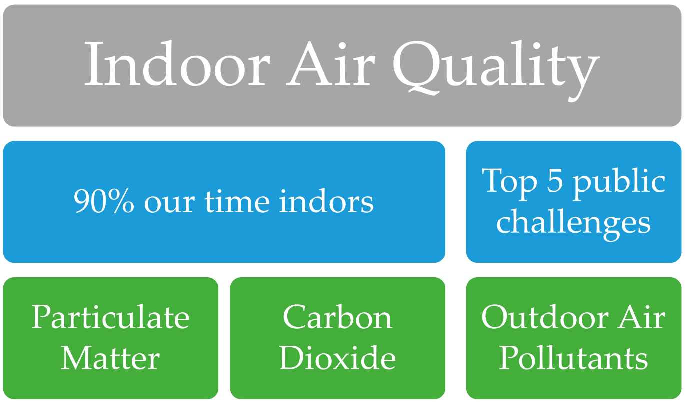

Figure 1. Indoor Air Quality (IAQ) a critical public challenge.

3. Indoor Air Quality Monitoring: Architectures, Algorithms, and Systems

The combination of Internet of Things and Ambient-Assisted Living technologies creates a consistent approach for the development of Enhanced Living Environments to improve productivity in the day to day activities, as well as for the overall well-being. With new technologies, it is possible to design intelligent cyber-physical systems for easy installation at regular buildings.

In order to improve the quality of occupational health, it is essential to monitor the majority of living environments on a real-time basis. It can be done by utilizing the latest approaches and technologies for data access. Alerts can be sent to the users to take appropriate steps for handling poor ambient air quality. It is essential to mention that a large population in the developing countries spends most of their time indoors. In such situations, IAQ monitoring plays an essential role in creating Enhanced Living Environments with better occupational health. Moreover, the world population is aging with time. It is now essential to make efforts to improve the quality of life for the elderly while minimizing the cost of caregivers.

Numerous Internet of Things-based projects designed for monitoring IAQ levels make use of open source technologies for processing, as well as transmission of data. Furthermore, microsensors are utilized for data acquisition. They provide easy access to the data obtained from different locations with mobile computing. These technology-inspired projects have been applied to the multidisciplinary research fields, such as agriculture [74–78], noise pollution supervision [79–81], indoor quality monitoring [82,83], and other numerous applications for Enhanced Living Environments and occupational health.

From the past few years, numerous researchers have contributed to this field. However, it is not possible to include all those studies in this paper. This section provides highlights from 21 studies conducted on IAQ monitoring in recent years. The research studies are selected by following these four criteria: (1) Use low-cost sensors for IAQ supervision, (2) incorporate various open-source technologies, (3) the connectivity and architecture, (4) present the practical implementation of the system and provide experimental results, and (5) published in recent five years (2014–2019). These studies have been collected for multiple research databases such as IEEE, ScienceDirect, Web of Science, Springer, and ReserachGate.

A WSN based real-time system IAQ monitoring at smart cities works on many essential parameters, such as relative humidity, ambient temperature, acoustic levels, and dust particle concentrations in the air [84]. The main idea behind using WSN systems is to monitor the quality of air in large-scale indoor space. These systems make use of wireless signals for transmitting data updates. With this, it becomes easier to identify the patterns for indoor environment assessment. This information can be used to optimize the allocation of air terminals in the buildings to supply healthy air as per the identified patterns of temperature distribution.

Another system to monitor humidity, temperature, particulate matter, ozone, carbon monoxide, volatile organic compounds (VOC), sulphur dioxide, nitrogen oxides, and CO_2 was proposed by [85]. This system works with a smoothing algorithm that prevents temporary sensor errors. Furthermore, an aggregation algorithm helps to reduce the traffic on the network leading to lesser power consumption. Researchers used the Raspberry Pi module for designing this prototype sensor module.

A WSN-based system for IAQ supervision was developed by [86,87] using Arduino, microsensors, and XBee modules. It was focused around the monitoring of temperature, humidity, CO_2, carbon monoxide, and luminosity. Researchers also designed a web portal and an Android mobile application for storage and access to monitoring data on a real-time basis. This system consists of one gateway and multiple sensor nodes. The gateway collects data from different sensor nodes connected in the network using the ZigBee protocol. The data communication in the next stage is done through Ethernet and web services for enhanced occupational health. The main idea behind this IAQ monitoring system was to reduce the burden of reduced health symptoms and diseases within sick buildings. However, the system had complex installation architecture regarding coordinator configuration and the sensor nodes.

An Internet of Things architecture-based IAQ monitoring hardware prototype was designed by [88] for ambient data collection. It provided updates via web and smartphone software. This system was centered around open-source technologies where collected data were stored on the ThingSpeak, a widely known cloud Internet of Things analytics platform.

A low-cost Arduino-based sensor network was designed by [89] using WSN and ZigBee technologies for efficient IAQ monitoring. The focused parameters for IAQ monitoring were VOC, CO_2, temperature, and humidity. However, the same as the previous IAQ monitoring system [88], this prototype was also restricted to monitoring applications only. It does not provide any mobile computing solution for further analysis and evaluation of collected data.

An Ambient-Assisted Living-based IAQ supervision system was proposed by [90]. This model was based on a hybrid Internet of Things/WSN architecture that promises real-time monitoring of luminosity, temperature, humidity, $CO_{2,}$ and carbon monoxide. It was also powered by two leading open-source technologies: Arduino and ZigBee. For data communication, the gateway of this model was further connected wirelessly to the Internet via the ESP8266 module.

In order to measure PM in the indoor environment, the authors of [91] proposed iDust as a real-time monitoring system. It contributes to efficient decision-making with Internet of Things architecture so that building health can be improved. This system was designed using a few low-cost sensors and open source technologies. The researchers also created a web portal for reliable data evaluation and to generate instant alerts so that building managers can take necessary steps for enhanced IAQ.

Furthermore, a health informatics system for IAQ measurement was proposed by [92], which incorporates advanced mobile computing technologies. The parameters focused for measurement with this IAQ monitoring system are temperature, humidity, CO_2 carbon monoxide (CO), and light. Another Internet of Things-based indoor monitoring and control architecture was proposed by [93]. This system used Arduino along with a few low-cost sensors to ensure reliable data collection for temperature, humidity, light, and flame detection. The monitored data were further accessible via web, desktop, and mobile applications.

A context-aware mobile sensing solution was proposed by [94] for IAQ monitoring. This system also made use of the Arduino platform along with humidity, temperature, CO, and CO_2 sensors. The collected data from target sites were uploaded to the dedicated server using Wi-Fi communication technologies. This data were also accessible on mobile phones via Bluetooth Low Energy (BLE) connection.

In order to measure occupant comfort, as well as essential energy parameters inside buildings, [95] proposed an autonomous mobile indoor robot. This system used TurtleBot for navigation, however, the target parameters for measurement were temperature, humidity, light, CO_2, airspeed, occupancy levels, and electricity consumption.

Another indoor autonomous mobile robot system with sensor-rich navigation capabilities was designed for monitoring environmental quality of the indoor space [96]. The proposed model includes CO_2, light, VOC, and temperature sensors, and the data transfer to the server was managed through Wi-Fi communication technology.

An IAQ monitoring system by combining WSN and Internet of Things architecture is presented in [97]. This sensor system was designed to measure CO_2 variations on the premises and send IAQ information to a remote server for further data evaluation and visualization.

The "open-source smart lamp" designed a smart object for IAQ management using the Arduino platform [98]. It was capable enough to measure essential IAQ parameters, such as temperature, humidity, light, and CO_2. This advanced solution was expected to control indoor thermal comfort, lighting quality, and IAQ as well.

A system containing mobile robots for environmental supervision was proposed by [99]. It was connected to the cloud server wirelessly. The master robot was designed to work as a base station unit. However, the rest of the modules were configured to work as sensor nodes. The nodes were responsible for the collection and transmission of data to the base station. After receiving data from the individual nodes, the base station was used to upload it to the dedicated cloud server for further analytics and visualization.

An assistive robot for indoor air quality monitoring based on the Internet of Things, which can communicate with occupants and triggers alerts automatically using social networks is presented in [100]. The collected data can be consulted by the healthcare giver and the proposed architecture presents relevant results. This study is a cross-domain application combining the Ambient-Assisted Living, Internet of Things, WSN, social networks, and IAQ research fields. The proposed WSN architecture uses sensor nodes developed by Sun Microsystems, which is compatible with ZigBee wireless communication technology and incorporates a liquefied petroleum gas (LPG) sensor as a sensing unit.

A real-time mobile IAQ system for CO_2, CO, PM10, NO_2, temperature, and humidity supervision is proposed by the authors of [101]. The proposed method uses open source technologies and incorporates a GP2Y1010AU, MH-Z14, MICS-4514, and DHT22 miniaturized sensors and an ESP32 as a microcontroller unit. The system is connected to the internet using Wi-Fi communication technology and the collected data are stored in a cloud server. The system provides a mobile computing technology for data consulting.

A low-cost system to address IAQ issues by using a distributed Internet of Things architecture in buildings that uses CO_2, VOCs, atmospheric pressure, humidity, and temperature is presented in [102]. The proposed system uses two Arduino microcontrollers for data collection and pre-processing. These data are transmitted to the Raspberry Pi microcontroller, which is the master unit. The Arduino microcontrollers are connected to the Raspberry Pi through serial communication. The collected data can be consulted using a mobile application.

An IAQ monitoring system, which includes an MQ135 for relative air quality assessment and an MQ7 sensor for CO supervision, is proposed by [103]. This sensor includes an Arduino Uno microcontroller and an ESP8266 for Wi-Fi compatibility. The data are stored in the ThingSpeak Platform. Moreover, the ThingSpeak Cloud service is also used for data visualization.

An Arduino-based system for IAQ, which incorporates a miniaturized sensor to detect temperature, CO_2, and VOC, is presented in [104]. Moreover, this system incorporates Bluetooth communication technology to transmit the data collected to a smartphone. The main purpose of this system is to notify the user of the abnormal increase in the monitored parameters. The proposed method incorporates a 12 volts solar panel as the power source.

4. Results and Discussion

Numerous technology-inspired solutions were presented in Section 3 for IAQ supervision. Most of them make use of open-source technologies for data collection, processing, and transmission. Furthermore, they use mobile computing architectures to provide real-time data access through web servers or mobile apps. It is crucial to emphasize that IAQ monitoring is a trending topic, and numerous researchers are working in this direction to design open-source, low-cost, and efficient monitoring systems.

Figure 2 presents the location of the authors involved in the analyzed studies included in the analysis done in this paper.

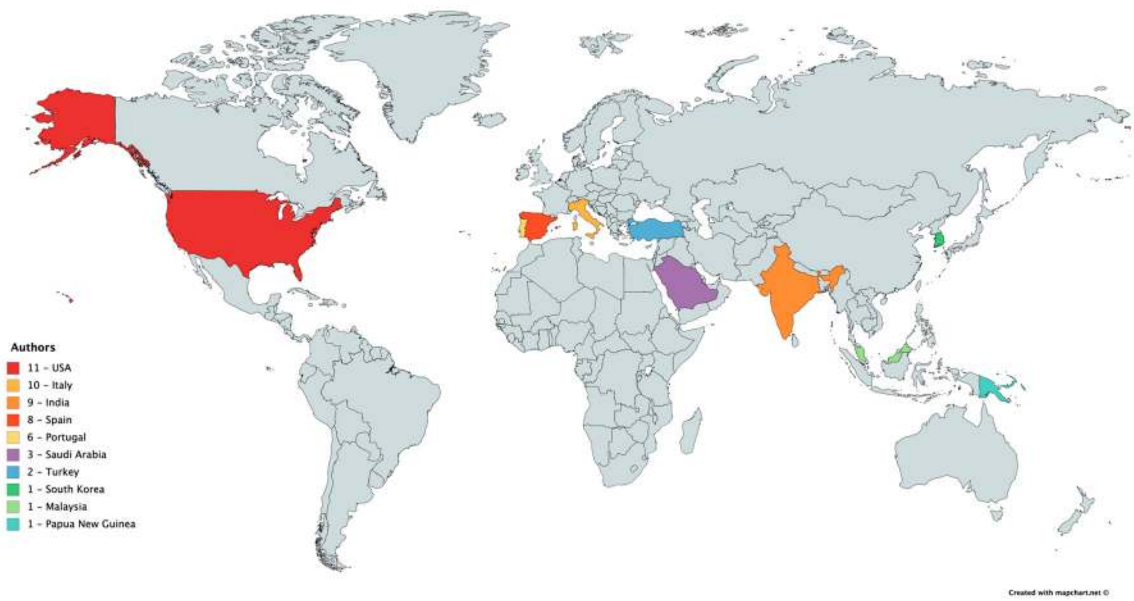

Figure 2. Location of the authors involved in the analyzed research papers.

The analyzed literature involves authors from several locations, such as the USA, Italy, India, Spain, Portugal, Saudi Arabia, Turkey, South Korea, Malaysia, and Papua New Guinea. In total, the analyzed studies include 52 different authors. The majority of the authors are located in the USA and Italy, representing 21% and 19%, respectively. Furthermore, IAQ is a topic of relevance in India, Spain, and Portugal. In total, eleven authors have conducted research in the USA, ten in Italy, eight in Spain, six in Portugal, and three individuals are working in Saudi Arabia. Finally, two authors are located in Turkey and South Korea. Malaysia and Papua New Guinea are also working on IAQ monitoring systems involving one author from each country.

Figure 3 shows the distribution of the percentage of the analyzed studies according to the publication year. Most of the papers considered in this work were conducted in 2019, representing 28.57%. In total, three studies were conducted in 2014, two studies correspond to the year of 2015 and 2018, four papers were published in 2016 and 2017, and six research papers were published in 2019.

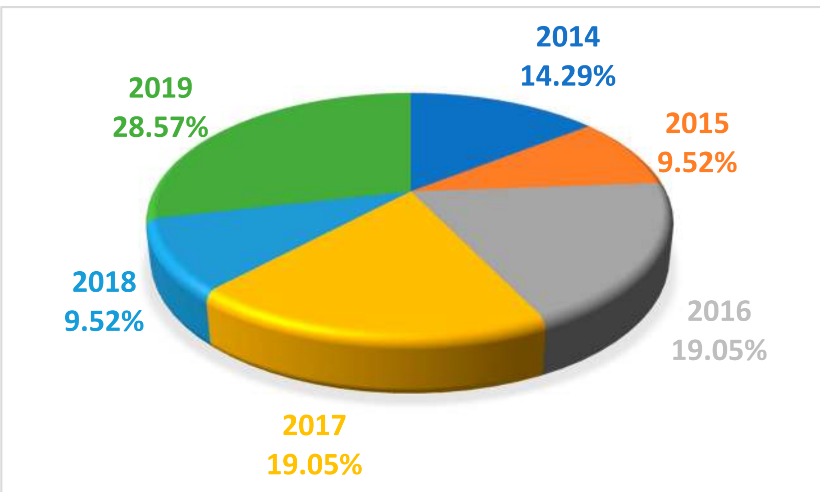

Figure 3. Distribution of the analyzed literature according to the year of publication.

Table 1 presents the study correspondence with the publication year and the total number of studies in each year.

Table 1. Distribution of the analyzed literature according to the year of publication.

Year	Ref	Total of Studies
2014	[85,89,99]	3
2015	[84,95]	2
2016	[86,90,94,97]	4
2017	[87,88,93,98]	4
2018	[91,96]	2
2019	[92,100–104]	6

This work has analyzed several studies from different research databases. Table 2 presents the distribution of the analyzed literature according to the respective database. Most of the reviewed literature is from Web of Science and IEEE research databases, representing 38% and 29% of the analyzed studies, respectively. In total, three studies have been retrieved from Springer, and two papers have been selected for ScienceDirect and ResearchGate databases.

Table 2. Distribution of the analyzed literature according to the year of publication.

Database	Ref	Total of Studies
IEEE	[84–86,93,94,99]	6
Springer	[87,88,92]	3
ScienceDirect	[89,96]	2
Web of Science	[90,91,98,100–104]	8
ResearchGate	[95,97]	2

The successful implementation of the IAQ monitoring systems depends on several factors, such as system architecture, the microcontroller used for the development of the system (MCU), the communication technology used for data transmission, and the sensors used. Table 3 presents the distribution of the analyzed solutions regarding the connectivity used for data communication and the MCU used for the systems development.

Table 3. Communication technologies used on IAQ monitoring systems regarding the microcontroller (MCU).

MCU/ Connectivity	Arduino	TI MSP430	Raspberry Pi	Waspmote	ESP8266	ESP32	Sun SPOT
Wi-Fi	[88,90,92,96,99,103]	-	[97,102]	-	[85,88,90,92,94,103]	[101]	-
Bluetooth	[94,99,104]	-	-	-	-	-	-
Ethernet	[86,87,93]	-	-	-	-	-	-
ZigBee	[86,87,89,90,98]	[85]	[85]	[84]	-	-	[100]

From the analyses of Table 3, it is possible to identify that the most used communication technologies are ZigBee and Wi-Fi. Moreover, the less used communication technologies are Bluetooth and Ethernet. Considering the IAQ monitoring systems which use Wi-Fi, most of them are based on ESP8266 MCU, as this microcontroller supports built-in Wi-Fi compatibility. On the one hand, most IAQ monitoring systems are based on Arduino (57%), followed by ESP8266 (29%). On the other hand, the least used microcontrollers are the Sun SPOT, ESP32, and Waspmote, which are only used by one study each. The methods proposed by the author of [85,88,90,92,94,103] implement different processing units since the ESP8266 is included only to provide Wi-Fi internet connection.

Table 4 presents a review summary of the distribution of the analyzed studies regarding the architecture used. In total, 53% of the systems use Internet of Things and WSN architectures represent

33%. Finally, 14% of the systems are designed using hybrid Internet of Things/WSN architectures. On the one hand, most of the analyzed studies based on hybrid or Internet of Things architectures use Wi-Fi communication technologies. On the other hand, most of the WSN architectures use ZigBee.

Table 4. Communication technologies used on IAQ monitoring systems regarding the architecture.

Architecture/Connectivity	WSN	Internet of Things	WSN/Internet of Things
Wi-Fi	[89]	[88,91,92,94–96,101–103]	[90,97,99]
Bluetooth	-	[94,104]	[99]
Ethernet	[86,87]	[93]	-
ZigBee	[84–87,89,98,100]	-	[90]

Table 5 presents the distribution of the analyzed studies regarding their architecture and MCU. Based on the results, the authors found that the hybrid WSN/Internet of Things architectures are developed using the Raspberry Pi and Arduino platform. Moreover, Arduino is the most used platform for Internet of Things and WSN architecture. This is related to the opportunities and the extensive support provided by this open-source platform considering the different communication technologies available in state of the art.

Table 5. The architecture used on IAQ monitoring systems regarding the MCU.

MCU/Architecture	Arduino	TI MSP430	Raspberry Pi	Waspmote	ESP8266	ESP32	Sun SPOT
WSN	[86,87,89,90,98]	[85]	[85]	[84]	[90]	-	[100]
Internet of Things	[88,93,94,96,103,104]	-	[102]	-	-	[101]	-
WSN/Internet of Things	[99]	-	[97]	-	-	-	-

The distribution of sensors used in the analyzed studies is presented in Table 6. The most used sensors incorporated by these systems are temperature and CO_2, followed by humidity and light. Numerous researchers have worked on CO_2 as it is comparatively easier to measure. Moreover, there are more sources of CO_2 in our surroundings as it is produced by people, as well as combustion equipment. Hence, it is considered as a prime indicator for the presence of other pollutants, and therefore, of the IAQ levels. PM is used by six IAQ monitoring systems considering the health effect of particle pullulation on global public health. The least used sensors in the analyzed IAQ monitoring systems are the O_3, SO_2, LPG, and air quality index that are only used in one study.

Table 6. Sensors used by the analyzed studies.

Sensors	Studies Distribution	Total of Studies
Temperature	[84,86–90,92–94,96,99,101,102,104]	14
CO_2	[85–88,90,92,94–96,98,99,101,102,104]	14
Humidity	[84,86–90,92–94,99,101,102]	12
Light	[86–88,90,92,93,95,96]	8
PM	[84,85,88,91,92,101]	6
CO	[85–87,90,101,103]	6
VOC	[85,89,96,102,104]	4
NO_2	[85,101]	2
O_3	[85]	1
SO_2	[85]	1
Sound	[84]	1
Flame sensor	[93]	1
GPS	[84]	1
LPG	[100]	1
Pressure	[102]	1
Air Quality Index	[103]	1

This work involves 52 different researchers from multiple such as the USA, Italy, India, Spain, Portugal, Saudi Arabia, Turkey, South Korea, Malaysia and Papua New Guinea. Air quality is a critical challenge worldwide. However, the referred countries have studied and proposed different methods for IAQ monitoring. In total, 57% of the IAQ monitoring systems are based on Arduino and, 83% of the proposed methods are based on Internet of Things and WSN architectures. Furthermore, CO_2 and PM monitoring sensors are the most monitored parameters in the analyzed literature included in 67% and 29% of the proposed methods, respectively.

Without any doubt, new-age healthcare systems play an essential role in providing global access to medical information and treatment facilities. The technological advancements promise trustworthy solutions for the aging population while making it easier to distribute and process medical data [105]. Even after several advantages associated with the healthcare systems, a critical matter of concern for the medical health community is to maintain the confidentiality and safety of the patients' data [106,107]. Other than this, researchers need to work on normalization, business models, network setup, data security, and QoS as referred by [108]. Efficient evaluation of IAQ on a real-time basis helps in enhanced decision-making for improved occupational health.

Furthermore, local and distributed assessment of all essential chemical concentrations promotes safety (e.g., pollution monitoring and gas spills detection) and security applications. At the same time, it contributes to improved ventilation, HVAC systems leading to higher energy efficiency [109].

The continuous IAQ measurements in the building environment generate a consistent stream of data for enhanced management of building health with informed decision-making [110]. In most cases, when homeowners and building administrators can get continuous updates about air quality, they can take positive interventions for enhanced thermal comfort and well-being. For example, they may avoid smoking inside or switch to natural ventilation practices whenever necessary.

Currently, buildings include wireless communication technologies, such as Wi-Fi, and can provide effective methods for Internet connectivity. IAQ depends on outdoor activities, such as vehicles, and industry activities assume a high impact on the overall outdoor air quality. Therefore, monitoring air quality using cost-effective methods can provide a continuous flow of relevant data for decision-making on possible interventions, such as for traffic control, to decrease air pollution levels for sustainable smart cities.

The 5G networks are currently being installed around the world, and this relevant advanced mobile communication technology will play a critical role in the digital transformation [111,112]. In particular, 5G will bring several outcomes for sensorial procedures and the development of enhanced IAQ systems, which cannot be implemented with similar technologies [113]. This technology will promote flexibility and provide support for a massive number of sensorial systems for IAQ and fulfill the most ambitious speed, bandwidth, and quality of service requirements [114]. Furthermore, 5G will support critical communications with the most rigorous performance requirements by providing reliability and low latency to support the implementation of a massive number of IAQ monitoring systems for enhanced living environments and smart cities [115]. The high number of IAQ monitoring systems will collect, gather, analyze, share, and transmit data in real-time, and consequently, produce a substantially large set of structured, unstructured, or semi-structured data, also called Big Data [116]. Analyzing these large amounts of data will allow the identification of trends, patterns, and correlations that lead to new information and knowledge to support the decision-making on possible interventions for enhanced public health and well-being [117,118].

Mobile devices include smartphones, tablets, and smartwatches, which are frequently used by most people in their daily routines [119]. Therefore, IAQ monitoring systems should include software compatibility for mobile devices [120]. These mobile applications should include several essential features for data analytics, visualization, and notifications [121]. On the one hand, mobile applications can be used to trigger notifications in real-time when specific air quality conditions are verified [122]. In this way, it will be possible to detect unhealthy living conditions on time and plan interventions to avoid them from occurring. Consequently, these mobile applications are an effective and efficient method to ensure good IAQ conditions for enhanced living environments and occupational health [123]. On the other hand, mobile devices currently support considerable computational capabilities and multiple long-range and short-range communication protocols. Therefore, these devices should be considered as a relevant instrument for data consulting and analysis.

The reviewed studies incorporate different technologies used in the processing and communications units. The technologies used for the processing unit are Arduino, TI MSP430, Raspberry Pi, Waspmote, ESP8266, ESP32, and Sun SPOT, whereas the communication technologies used are Wi-Fi, Ethernet, Bluetooth, and ZigBee communication. The microcontroller platforms are widely on different real-world applications and provide Integrated Development Environments (IDEs) to support code development and the integration of a high array of sensors and actuators. Most of the studies incorporate Arduino Uno as the microcontroller. This microcontroller has several advantages related to the high availability of documentation and sensor support. The processing unit incorporates a 16 MHz CPU and does not incorporate built-in communication support. Therefore, the communication capabilities are provided using shields for Wi-Fi, Ethernet, Bluetooth, and ZigBee compatibility. The TI MSP430 incorporates a low power RISC mixed-signal microprocessor from Texas Instruments. The MSP430 CPU speed is 25 MHz, however, has a low support for sensors and applications when compared with the Arduino platform. The Raspberry Pi support built-in communication capabilities for Ethernet, Wi-Fi, and Bluetooth. Moreover, the Raspberry Pi integrates the most powerful CPU unit. The CPU processing power ranges from 700 MHz to 1.4 GHz and this microcontroller has high RAM specifications that range from 256 MB to 4 GB, according to the version. Nevertheless, this microcontroller does not include a built-in analog to digital converter (ADC) for sensor connection which is included in the other microcontrollers. Therefore, it is needed to interface external ADC to connect analog sensors. The ESP32 and ESP8266 are Wi-Fi modules microcontrollers that are specifically designed for the Internet of Things. These microcontrollers incorporate 32-bit processors. The ESP32 is dual-core 160 MHz to 240 MHz CPU and the ESP8266 is a single-core processor that runs at 80 MHz. The most significant advantage of these microcontrollers is the built-in wireless communication technologies when compared with Arduino. The ESP8266 has Wi-Fi compatibility and the ESP32 has Wi-Fi and Bluetooth. Furthermore, these sensors support a high array of different protocols for sensor interfacing and are affordable. Finally, the Sun SPOT is a miniaturized microcontroller unit designed by Sun Microsystems for WSN applications. This microcontroller is programmed in Java and uses Java VM running on the hardware. Moreover, this microcontroller supports ZigBee compatibility and a built-in rechargeable battery. The Sun SPOT includes a 32-bit ARM9 CPU, 512 K memory and 2 Mb flash storage. This microcontroller also has integrated temperature and light sensors, two push buttons, two momentary switches and a 3-axis accelerometer. However, the solution is currently not supported and has a higher cost than the other analyzed microcontrollers.

The current study has identified some limitations of the proposed methods. One of the limitations is related to the protocols used for the Internet connection. Most of the systems only support one communication technology. Therefore, it is essential to design novel methods that support several communication technologies in the same system. These methods should support short-range technologies, such as Wi-Fi and BLE, but also long-range mobile network protocols, such as GSM, 2G, 3G, and 4G. Another significant limitation is regarding processing capabilities and system energy consumption. Solving these two limitations is a considerable challenge since if the method includes more processing power, it will increase energy consumption as a result. Consequently, it is essential to design architectures that make the correct balance between these two relevant factors.

The sensors' accuracy is also another crucial challenge for future research since some of the used low-cost sensors frequently require calibration procedures and also need maintenance. Therefore, the development of new sensors that provide accurate output data with low energy consumption is also required for enhanced IAQ monitoring systems.

The IAQ monitoring systems include multiple stages since data acquisition, processing, storage, and analytics. The data acquisition phase is conducted at the hardware level using physical sensors.

The processing phase is performed in the hardware and software level since the data are acquired and sent to the remote server for storage and/or processing. The software is responsible for triggering the notifications and also to provide data consulting methods for enhanced data analytics and visualization.

The conceptual architecture of an IAQ monitoring system is proposed in Figure 4 and intends to provide a comprehensive overview of the possibilities and limitations identified in this paper.

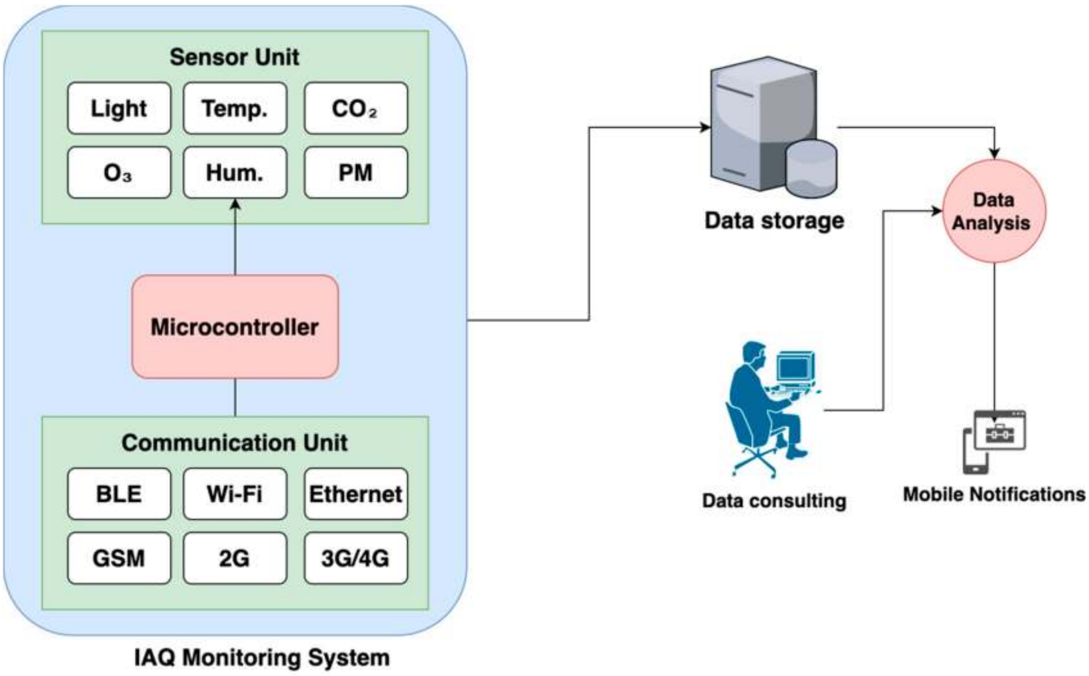

Figure 4. Conceptual architecture of an IAQ monitoring system.

Air quality monitoring is a critical and public health challenge and must be incorporated as an essential element for sustainable smart cities to promote citizens' health and well-being. The air quality information is significant not only for the correct management of a sustainable city but also to allow the conception of significant datasets that includes spatiotemporal information to support city managers in the decision making on effective interventions for Enhanced Living Environments.

The healthy IAQ requirements and energy-efficient buildings are a strictly related challenge studied by several researchers [124–129]. IAQ monitoring and assessment should be considered as an efficient and effective method to support decision making while designing enhanced living environments in energy-efficient buildings [130]. The increase of IAQ monitoring systems leads to the development of potential energy-efficient methods to promote IAQ. The collected real-time tempo-spatial data will support the development of systematic methods to analyze the impact on energy consumption to ensure good IAQ conditions [131]. The building airtightness is designed to prevent infiltrations and heat losses to promote energy efficiency [132]. Moreover, the building infiltration properties directly influence the air exchange rate and reduce the ventilation of the indoor environment, which leads to bad IAQ conditions [133]. Therefore, the IAQ monitoring systems are an essential solution to ensure the correct balance between energy efficiency in buildings and providing the correct ventilation rates to ensure healthy IAQ conditions for enhanced health and well-being of the occupants [126]. Furthermore, HVAC systems play a major role in the total building energy consumption, and in numerous cases, they are not efficiently used [134]. The data collected by IAQ monitoring systems can be efficiently used to adapt the energy load of HVAC systems according to the real-time parameters of the indoor environments. Sustainable buildings do not certainly ensure good IAQ conditions since certification schemes present ineffectual considerations to promote IAQ levels [135]. Indeed, some sustainable approaches and green products could decrease IAQ levels [127,136]. Since people spend more of their time indoors IAQ quality monitoring systems can support the application of enhanced sustainable building programs and ensure good IAQ conditions at the same times [127].

5. Conclusions and Future Scope

This paper has presented a status on the current state of the art on IAQ monitoring systems, considering the last five years (2014–2019). In total, ten different countries are involved in the analysis done in this paper. The majority of the authors of the analyzed studies belong to the USA and Italy, representing 21% and 19%, respectively. Moreover, most IAQ monitoring systems are based on Arduino (57%), followed by ESP8266 (29%). The results show that 53% of the systems use the Internet of Things, and WSN architectures represent 33%. Finally, 14% of the systems are designed using hybrid Internet of Things/WSN architectures. Wi-Fi communication technology is the most used for the Internet connection. Temperature, humidity, and light sensors are incorporated by the majority for the methods for enhanced thermal and luminous comfort. On the one hand, the CO_2 and PM sensors are the most used for air quality assessment, but several solutions also provide VOC and CO monitoring. On the other hand, O_3, SO_2, LPG are only used by one monitoring system. Nevertheless, these parameters have a high impact on public health.

Nevertheless, the current state of the art has several limitations. The authors found that most solutions do not incorporate notification systems to trigger warnings in reduced air quality scenarios. Furthermore, there are critical limitations regarding the processing capabilities, the sensors' accuracy, the communication technologies used, and energy consumption. Therefore, further research initiatives are needed to address these critical challenges to create novel and more efficient methods for IAQ monitoring and assessment.

The air quality data can be evaluated by health professionals to support the decision process on medical diagnostics. Moreover, it will be possible to associate patient diseases with their environmental conditions. The incorporation of notifications using mobile devices is essential to alert the building occupations or city managers on time.

This current study has identified several limitations, however, the main results are significant, and future research on IAQ monitoring systems will promote Enhanced Living Environments and sustainable smart cities. Similarly there are other studies where wireless sensor networks and IoT are used for precision agriculture and home applications as like air quality respectively [137,138]. In future, same study can be applied to monitor the air quality in agriculture fields and area's near to different industries.

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