Chapter

Indoor Air Quality Monitoring for Enhanced Healthy Buildings

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Abstract

Since most people spend 90% of their time indoors, the indoor environment has a determining influence on human health. In many instances, the air quality parameters are very different from those defined as healthy values. Using real-time monitoring, occupants or the building manager can decide and control behaviors and interventions to improve indoor air quality. The historical database is also useful for assisting doctors to support the medical diagnosis. The continuous technological advancements notably, as regards, networking, sensors, and embedded devices have made it possible to monitor and provide assistance to people in their homes. Smart objects with great capabilities for sensing and connecting could revolutionize the way we are monitoring our environment. This chapter consists of a general overview of several real-time monitoring systems developed and published by the authors. In this chapter, the authors present several new open-source and cost-effective systems that had been developed for monitoring environmental parameters, always with the aim of improving indoor air quality for enhanced healthy buildings.

Keywords: indoor air quality (IAQ), healthy buildings, occupational health, real-time monitoring, Internet of Things (IoT), ambient assisted living (AAL), enhanced living environments

1. Introduction

Indoor environments could be characterized by several pollutant sources. Environmental Protection Agency (EPA) is responsible for environmental air quality index regulation in the United States. This independent agency deliberates that indoor levels of contaminants can be up to 100 times greater than outdoor contaminant level and positioned poor air quality as one of the top five environmental dangers to the community well-being [1]. Thus, indoor air quality (IAQ) is recognized as an essential factor to be controlled for the occupants' health and comfort. Increase in the IAQ is critical as people typically spend more than 90% of their time in indoor environments. The problem of inadequate IAQ is of utmost importance affecting particularly severe form the poorest people in the world who are most vulnerable, presenting itself as a severe problem for world health such as tobacco use, alcoholism or the problem of sexually transmitted diseases [2].

In 1983, the World Health Organization (WHO) used the term "sick building syndrome" (SBS) to the clinical features that we might discover in building residents as a consequence of the poor IAQ [3]. Numerous statements have reported the influence of IAQ in the etiopathogenesis of various generic signs and medical results that illustrate SBS. The scientific representation of this pattern is widespread as it can engage the skin (with xerosis, pruritus), the upper and lower breathing tract (such as, dysphonia, dry cough and asthma), the eyes (ocular pruritus), and the nervous system (for example, headache and difficulty in concentration) [4, 5]. Furthermore, besides the symptoms of this disease, there are syndromes, which could be connected with indoor environments, i.e., Legionnaire's disease, extrinsic allergic alveolitis, asthma, and atopic dermatitis [4, 5]. For example, regarding atopic dermatitis, it is a chronic and inflammatory skin disorder and one of the most usual allergic syndromes in infants. Its occurrence is rising and, while it is related to hereditary influences, there is a considerable suggestion of responsibility for environmental factors, namely indoor air pollutants. This is mainly significant in industrialized nations, where youngsters apply most of their time inside buildings [6]. Including the air contaminants, the volatile organic compounds are connected to the exacerbation of atopic dermatitis, which remain the utmost deliberated usual pollutants of indoor air [5]. Universally acknowledged, in atopic dermatitis, indoor air contaminants could provoke oxidative stress, leading to skin barrier dysfunction or immune dysregulation [6]. Thus, the signs and syndromes related to the "sick buildings" are a problem with emergent significance in public health and have likewise been associated with lower productivity and greater absenteeism. The etiology of the SBS and the building associated disorders might incorporate chemical pollutants (both from outdoor and indoor sources), biological agents, emotional issues, electromagnetic radiation, the deficiency of sunlight, humidity, poor acoustics, deficient ergonomics, and bad ventilation [5]. Although the importance of indoor air quality for public health still exists, there is a lack of interest in the new scientific methods to improve indoor air quality in developed countries [7].

Ventilation is used in buildings to create thermally comfortable environments with acceptable IAQ by regulating indoor air parameters, such as air temperature, relative humidity, airspeed, and chemical species concentrations in the air [8]. An IAQ evaluation system provides an important way to find and enhance the indoor environmental quality. Local and distributed valuation of chemical concentrations is substantial not only for security (gas spills recognition, pollution supervising) and well-being applications but also for efficient temperature regulation, ventilation and air conditioning (HVAC) system for energy efficiency [9]. IAQ monitoring offers an uninterrupted stream of data for centralized regulation of building automation procedures, and delivers a solution for enhanced build management [10]. Real-time supervision of the IAQ is assumed as an essential tool of extreme importance to plan interventions for enhanced occupational health.

In recent past, numerous systems have been created on behalf of environmental supervision, constantly beside the intention to increase the IAQ [11]. The accessibility of cost-effective, energy efficient, and small-scale embedded computers, radios, sensors, and actuators, regularly incorporated on a unique chip, has been conducted for the incorporation of wireless communications to cooperate with the material world for IAQ supervision and enhanced living environments [12].

In this chapter, the authors present several new open-source and cost-effective systems that had been developed for monitoring environmental parameters, always with the aim of improving IAQ for enhanced healthy buildings. The chapter is structured as follows: besides the Introduction (Section 1), Section 2 introduces IoT and AAL themes, and Section 3 is concerned with presenting several IAQ systems for enhanced living environments, and Section 3.2 demonstrates a comparison between the proposed systems, and the conclusions are presented in Section 3.5.

2. IoT and AAL for the enhanced indoor air quality

Ambient assisted living (AAL) is closely related to the necessity of pervasive healthcare supervision, and the main aim is to contribute to the pervasion of the independence and well-being for older adults using Information and Communication Technologies (ICTs) [13].

Nowadays, there are numerous AAL solutions that can be found in literature that incorporate a large number of different types of sensors for biological supervision. These solutions typically incorporate wireless communication technologies for data sharing and collection such as *ZigBee, Bluetooth, Ethernet*, and *Wi-Fi*.

At the second half of this century, 20% of the humankind will be of age 60 or above [14], which is linked with several complex problems for public health. First of all, this will provoke an increase in disorders, healthcare budget, and the scarcity of caretakers, which will conduct to a giant social impact. Another import argument is that people typically choose to remain in their homes even paying the cost of the nursing care [15], which indicate the research of AAL solutions architectures as unquestionably a subject of extraordinary significance taking into account the humankind aging.

AAL researches are planned to encounter the requirements of the elderly population to preserve their independence as long as conceivable. On the one hand, improvements in telecommunications, sensors, and embedded processors conducted to the delivery of real-time supervising and personalized healthcare solutions to entities, which are able to be currently used in their habitats. On the other hand, these incessant scientific developments create the elaboration of smart cyber-physical systems for enhanced living environments and occupational health. Although there is a portion of issues in the creation of an effective AAL ecosystem such as data architecture, interface design, human-computer communication, ergonomics, usability and availability [16], there are also collective and moral difficulties as the recognition by the older people and the privacy and confidentiality that would stand as a prerequisite of the entirely AAL solutions. Indeed, it is likewise crucial to guarantee that technology does not substitute the human care but instead must be an extraordinary compliment.

Internet of Things (IoT) stands as a standard where things are linked to the Internet and incorporate data collection capabilities. The basic idea of the IoT is the pervasive presence of a variety of objects with interaction and cooperation capabilities among them to reach a common objective [17–19]. It is anticipated that the IoT will provoke a considerable effect on numerous characteristics of daily life and this paradigm will be incorporated in several purposes such as domotics, assisted living, e-health and is likewise a perfect emergent knowledge to offer novel evolving data and computational resources on behalf of generating groundbreaking software applications [20]. IoT architectures should incorporate wireless communication technologies. Nowadays, several wireless communication technologies are available such as bluetooth-based technologies, Wi-Fi-based technologies, near-field communication (NFC)-based technologies, and GSM-based technologies.

IoT solutions must stand pervasive, be context aware, and allow environment intelligence skills that are directly connected to AAL. IoT is an appropriate method to construct well-being solutions. Scientific developments turn possible to create novel and innovative instruments to empower real-time healthcare supervising solutions for decision-making in the management of several syndromes.

Nowadays, several IoT architectures had been implemented for clinical monitoring that claim IoT as a reliable platform to develop personalized healthcare systems. Due to Bluetooth technology, the use of wearables for data collection and smartphones for data transmission is now possible to provide physiological parameter supervision [20]. In 2009, several research initiatives for remote healthcare was been developed using IoT. Furthermore, IoT can increase the knowledge of data collection, which support IoT solutions in the medical area [21]. On behalf of the potential of the IoT concept for wellbeing solutions nowadays several challenges to be overcome still subsist.

The influence and impact of the IoT in the today's market is not clearly known, as well as the acceptance of pervasive and ubiquitous IoT products. Although the scientific advancements that turn IoT healthcare systems currently are feasible, the timing might be too early [22].

The "smart city" conception has lately presented as a tactical strategy to face contemporary municipal manufacture features in a mutual framework and, in specific, to focus the significance of ICT in the previous 20 years for increasing the economical profile of a city as suggested by [23]. Currently, cities have fascinating challenges and complications to gather socioeconomic progress and quality of life intents. The "smart cities" are related to react to these problems [24]. The smart city is also straightly connected to an emergent approach to decrease the difficulties produced by the urban population progress and quick urbanization [25]. The highest significant challenge in smart cities is the interoperability of the diverse technologies. IoT might be able to offer the interoperability to develop an integrated urban-scale ICT architecture for smart cities [26]. The smart city execution will produce effects at diverse stages such as effects on science, effects on technology and competitiveness, and effects on culture; however, this will likewise provoke ethical concerns as the smart city requires to offer accurate data access as it becomes fundamental, once such data are accessible at a fine spatial scale where people can be recognized [27]. IoT has an important potential to build novel real-life solutions and services for the smart city background [28].

3. Indoor air quality monitoring systems

Several solutions have been developed to improve the occupational health, aiming to provide real-time monitoring of indoor environments for enhanced living environments and occupational health. These solutions could revolutionize the indoor environments contributing to enhanced healthy buildings and to decrease the SBS problem. Some systems developed by the authors are described below.

3.1 *iAQ system*

iAQ system [29] is an automatic low-cost indoor air quality monitoring wireless sensor network system, developed using *Arduino*, *XBee* modules, and microsensors. This solution can be accessed by the building supervisor to identify a diversity of factors as temperature, humidity, luminosity, carbon dioxide (CO_2), and carbon monoxide (CO), in real time. Other parameters can be analyzed for particular contaminants as other sensors might be added for data collection.

The *iAQ Sensor* is responsible for the environmental data collection and to transmit these data to the *iAQ Gateway*. The *iAQ Gateway* uses Web services to provide data transmission and storage in a *MySQL* database. The Web services was been developed in PHP (**Figure 1**).

The iAQ system can incorporate one or more iAQ Sensors (**Figure 2**). The *iAQ Sensors* not only collect data from the environment but also send these data to the *iAQ Gateway* and can be placed in different locations. The *iAQ Gateway*, which is

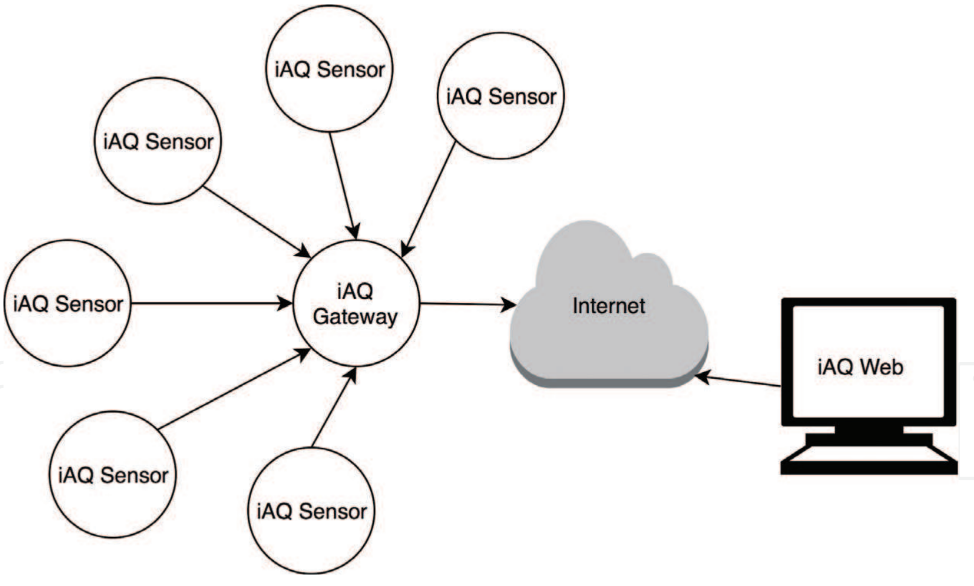

Figure 1.
iAQ WSN architecture, from [29].

Figure 2.
iAQ Sensor hardware, from [29].

linked to the Internet through an *Arduino* Ethernet Shield, is responsible for the data storage.

The Web portal *iAQ Web* was been developed in PHP and supports authentication. This Web portal is responsible for the availability of the data to the end user. Accessing the *iAQ Web* is possible to analyze the environmental quality. The data can be analyzed as numeric values or in chart form. The *iAQ Web* is prepared with a notification manager that notifies the user in case a particular parameter overdoes the maximum value. This portal additionally acknowledges the user to retain the parameters' history. Offering a history of changes, this system provides an evaluation platform to accurately analyze the IAQ behavior. Furthermore, it is possible to take actions in the environment to increase the air quality in the building in real time.

The wireless communication features are created with the *ZigBee* networking protocol. Several *XBee* modules are used to implement the *IEEE 802.15.4* radio standard [30]. This standard identifies the physical and medium access control layers for low data-rate personal networks. *ZigBee* is a cost-effective, energy efficient, support mesh networks standard and was develop upon 802.15.4. Radio waves are transmitted from *iAQ Sensor* to the base station *iAQ Gateway*.

3.2 *iAQ mobile system*

Currently, smartphones incorporate high processing specifications aside from a diversity of sensors appropriated to the research and development of AAL systems. Sensors such as global position system (*GPS*), bluetooth low energy (*BLE*), camera, microphone, luminosity, accelerometer, gyroscope, and near-field communication (NFC).

As for the importance of the smartphone's role in human life, *iAQ* solution has been updated with an *Android* application [31, 32]. This mobile application was designed to provide quick and easy access to *iAQ system* to allow the end user to keep all the relevant information of *iAQ system* in your pocket.

This application provides data authentication and protection mechanisms for information visualizations and allows one to view system data in detail and receive notifications when any of the values exceed normal values.

This mobile application was developed for the android mobile operating system. The *integrated development environment* (IDE) *Android Studio* was used to build the application. The minimum requirement is the *application programming interface* (API) 15: *Android* 4.0.3 Ice Cream Sandwich. According to the IDE, this mobile app is compatible with 96.2% of active devices in the *Google play store* (information collected on January 22, 2016).

Figure 3 represents the mobile application features. The left image represents the login screen of the application that guarantees the authentication before data access. The right image represents the ability to select one of the monitored

Figure 3.
Android app, from [33].

locations that correspond to a specific *iAQ Sensor* node. The user can access to the current humidity, temperature, carbon dioxide, carbon monoxide, and light values.

Using the mobile app, the user can likewise rapidly access to the alerts generated when the monitored parameters exceed the minimum or the maximum values.

3.3 *iAQ IoT system*

iAQ solution has also been updated to adopt an IoT architecture using the *ESP8266* and be a fully wireless solution for IAQ. *iAQ IoT Gateway* [33] has replaced the *Arduino* by a *Wemos Mini D1 (Wemos Electronics)* as a processing unit. The processing unit is a miniaturized *Wi-Fi* board based on *ESP-8266EX*. This board incorporates 11digital input pins and 1 digital output pin, and 1 analogue input pin. The interface used for programming and power is micro-USB. *Wemos Mini D1* can be programmed using the *Arduino* IDE and incorporate 32 bits CPU with an 80/160 MHz clock speed, which works at 3.3 V, 4 Mb flash, and has 34.2 × 25.6 mm size and a weight of 10 g.

A majority of the IAQ supervision solutions currently available on the market are especially expensive and only permit the collection of arbitrary values from the environment. *iAQ* IoT is an IAQ solution developed on top of the IoT concept that integrates in its assembly Arduino, *ESP8266*, and *XBee* technologies for data processing and transmission and sensors for data collection.

iAQ IoT Gateway incorporates only wireless communication technologies to interact with the nodes as well as for Internet accessibility. It collects data from *iAQ Sensor* using an *XBee* module and then uses Wi-Fi to provide data storage to a *MySQL* database using Web services. The schematic and connections used in *iAQ Gateway* are described in **Figure 4**.

3.4 *iAQ Wi-Fi system*

iAQ Wi-Fi [34] is a real-time indoor air quality monitoring solution that is capable of measuring temperature, humidity, PM10, CO_2, and luminosity in real time. This solution is based on the IoT concept and is fully wireless. The access to the Internet in order to provide data storage of the monitored parameters is developed using the *ESP8266* chip, which implements the *IEEE 802.11 b/g/n* networking protocol and supports radio transmission within the 2.4 GHz band.

This solution incorporates open-source technologies, using an *Arduino UNO* as a microcontroller as processing unit and an *ESP8266* module as the communication unit. The monitored data are uploaded to the *ThingSpeak* platform. *ThingSpeak* is an

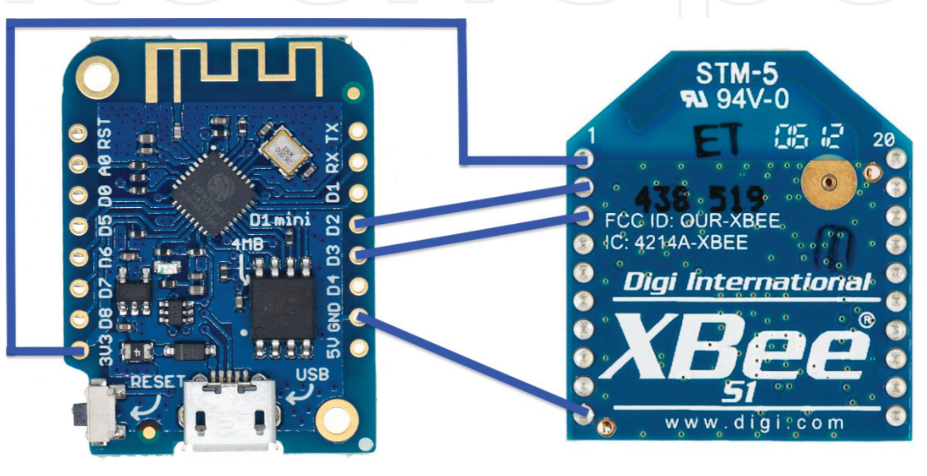

Figure 4.
iAQ IoT Gateway, from [33].

open-source IoT platform that offers *APIs* for storing and retrieving data from sensors and devices using *HTTP* [12]. *iAQ Wi-Fi* prototype is represented in **Figure 5**.

The end user can access the data from the Web page provided by *ThingSpeak* platform or can use the smartphone app developed in *SWIFT*, an open-source programming language with *XCODE* IDE created for iOS operating system. *iAQ Wi-Fi* system architecture is based on IoT. **Figure 6** represents the system architecture used by the authors.

The *Arduino UNO* incorporates sensors that are responsible for the data collection and send that information to the *ESP8266* by serial communication. The

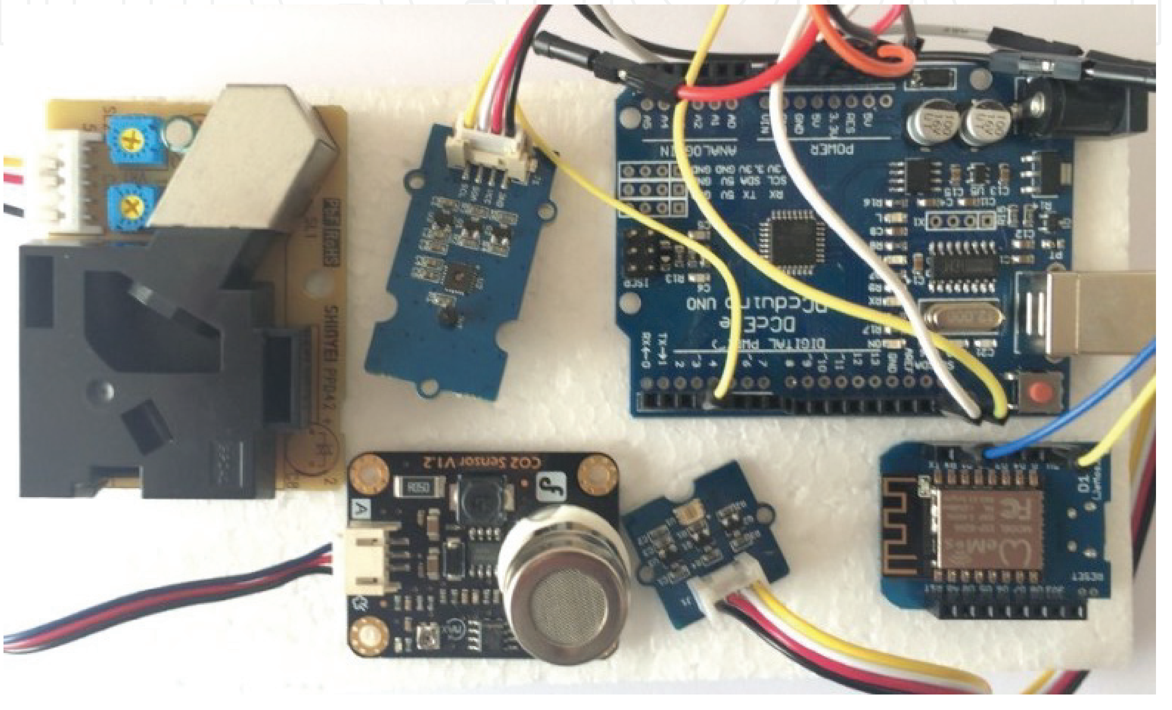

Figure 5.
iAQ Wi-Fi prototype, from [34].

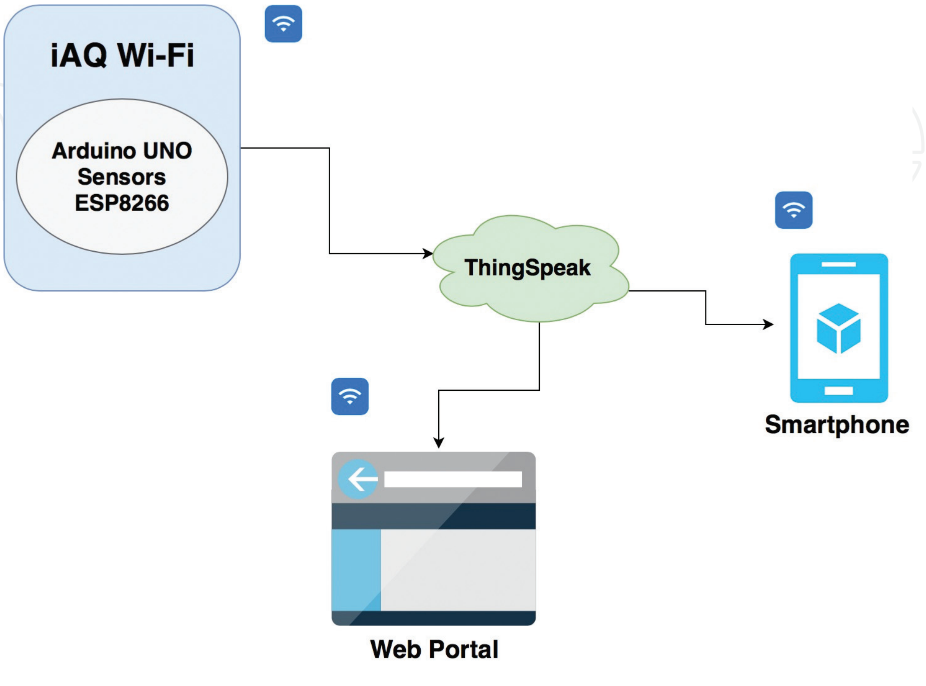

Figure 6.
iAQ Wi-Fi system architecture, from [34].

ESP8266 is connected to the Internet using Wi-Fi and is responsible for uploading the data received to the *ThingSpeak* platform.

The mobile application is denominated by *iAQ Wi-Fi Mobile* (**Figure 7**), and is developed using *XCODE* IDE and *SWIFT* programming language. The *iAQ Wi-Fi Mobile* has the iOS 7 as the minimum requirement. The mobile application provides authentication to authorized users. The end user after login can analyze the history-monitored data in numerical or graphical representation.

3.5 *iAirC system*

iAirC is a solution for carbon dioxide (CO_2) real-time monitoring based on IoT architecture. To have a low-cost system, only one type of indoor air pollutant was chosen [35].

In one hand, when the CO_2 level extends 7–10%, an individual can lose consciousness within minutes and might stand at risk of death. On the other hand, a low intensity of CO_2 stands inoffensive to humans. It is well known that CO_2 levels are linked with dizziness and sleepiness leading to low productivity at work [36]. Therefore, it is significant to provide a real-time CO_2 supervision and develop a notification system for enhanced living environments. The intensity of CO_2—the main greenhouse gas—is steadily increased to 400 ppm (ppm), reaching new records every year since they began to be produced in 1984 [37].

CO_2 was chosen because it is easy to measure, and it is produced in quantity from multiple sources (by people and combustion equipment). Consequently, it should be assumed as an indicator of other contaminants, and consequently of IAQ in common.

The *iAirC* solution incorporates a prototype for environmental data collection and a mobile application for data access and supervision. This solution use Wi-Fi for Internet access, which conduct to a diversity of advantages such as modularity, scalability, low-cost and easy installation. The data are stored in the *ThingSpeak*

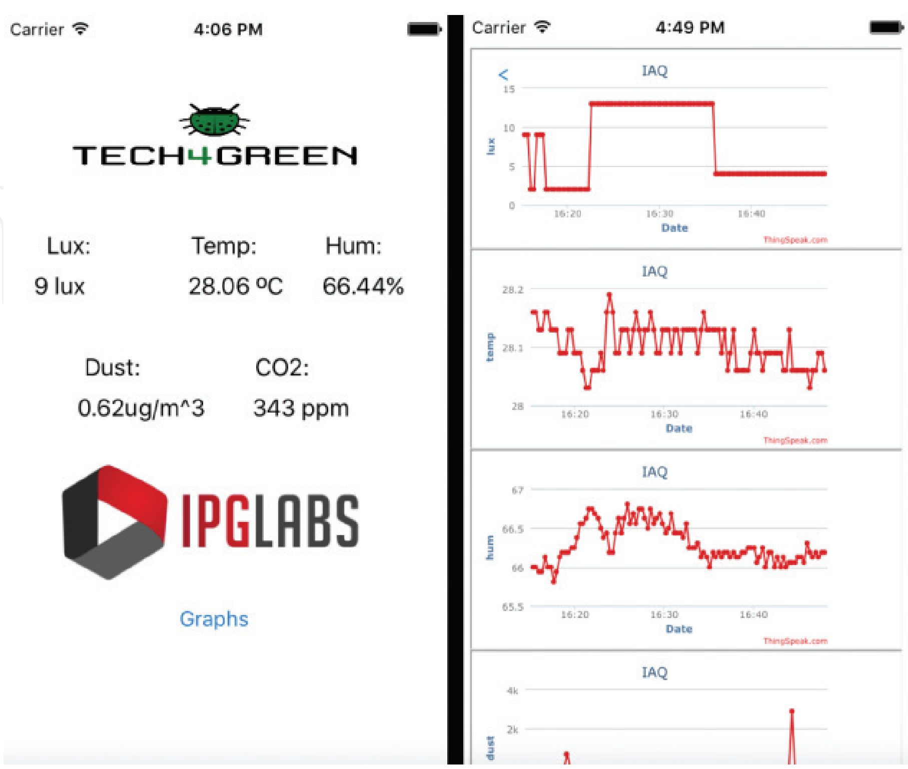

Figure 7.
iAQ Wi-Fi mobile app, from [34].

cloud platform and then can be consulted using the mobile app or *ThingSpeak* Web portal.

iAirC consists of two components, an *ESP8266 Thing Dev (Sparkfun) microcontroller* and an MHZ-19 carbon dioxide sensor developed by *Winsensor* (**Figure 8**).

The *ESP8266 Sparkfun* microcontroller incorporates integrated *Wi-Fi* features and is used mutually for data processing and communication. The *iAirC* is a low-cost, reliable system that can be easily configured and installed by the average user. For this, *iAirC* incorporates a low cost but very reliable carbon dioxide sensor and a microcontroller with native *Wi-Fi* support.

The mobile application is denominated by *iAirC Mobile* (**Figure 8**), and is developed using *XCODE* IDE and *SWIFT* programming language [38]. Using the *iAirC Mobile,* the end user after authentication not only can access to real-time CO_2 levels but also to be notified when the IAQ is defective (**Figure 8**).

Ample physical evidence shows that CO_2 is the single most important climate-relevant greenhouse gas in Earth's atmosphere and high external charges mean that they naturally lead to higher indoor concentrations due to the contribution of the internal sources (human metabolism and combustion equipment) [39, 40]. It is imperative to control the concentration of CO_2 effectively and the authors believe that the first step is to monitor to perceive its variation in real time and to plan interventions for its reduction.

3.6 *iDust*

PM is related to numerous serious health problems. *iDust* is a real-time PM exposure monitoring system and decision-making tool for enhanced healthcare based on an IoT architecture [41]. It was developed using open-source technologies and low-cost sensors.

This architecture has been developed in order to provide an evaluation platform that can be acceded to by the building manager in order to analyze the PM behavior of the indoor environment in detail. Furthermore, the build manager can take action in real time in order to provide a safe and healthful place for the occupants.

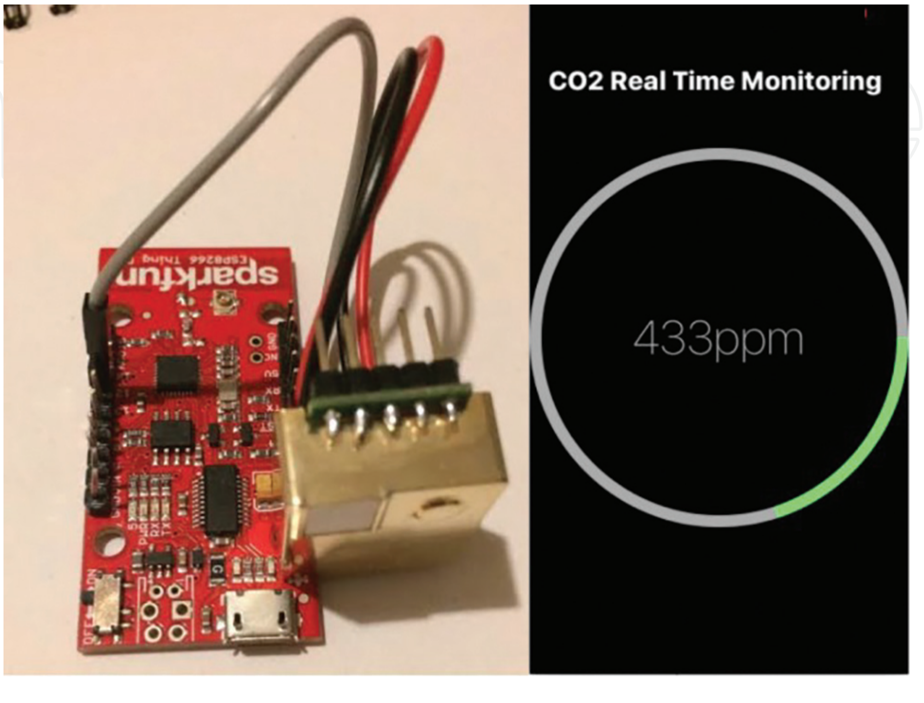

Figure 8.
iAirC prototype (left); and iAirC Mobile (right), from [35].

PM exposure data can be exceptionally precious to provide support to a clinical examination by medical experts as the therapeutic panel could analyze the record of IAQ factors of the environment everywhere the patient resides and link this reports alongside his health problems. On the other hand, by supervising IAQ, it stands plausible to identify the air quality circumstances appropriately plus, if required, plan interventions to drop the PM exposure concentrations.

iDust stands as an ICT solution for real-time IAQ managing that allows the end user, as the building manager to analyze the PM exposure behavior. This system incorporates *WEMOS D1 mini* as a microcontroller and is developed using the *Arduino IDE*. The parameters are supervised using the *iDust* prototype, which is responsible for data collection. The monitored data are stored in a *SQL SERVER* database using Web services built in .NET. An authenticated user is able to access the IAQ information using the Web portal created in *ASP.NET*. The information collected is accessible in a dashboard in mutually numeric values or graph form. Likewise, the Web portal stores the history of the PM exposure behavior. The Web application incorporates a important notification manager that notifies the build manager when a particular parameter exceeds the maximum value. *iDust* is a cost-effective, consistent method, which can easily be parametrized and installed by the regular people. On behalf of this, the authors had selected a cost-effective but very reliable PM sensor and a microcontroller with built-in *Wi-Fi* communication technology. This architecture incorporates of two components: a microcontroller and a PMS5003 PM sensor (*Plantower*), which features scattering method to quantify the rate of particles suspended in the air with a diameter of 10 microns or less (≤PM10), 2.5 microns or less (≤PM2.5), and 1.0 microns or less (≤PM1.0)(**Figure 9**).

The Web application allows the build manager to save the parameters' history as is presented in **Figure 10**. Providing a history of changes turns possible to do an accurate and detailed analysis of the PM exposure behavior.

iDust system uses the *ESP8266* for both processing and Internet connectivity. The incorporation of the *ESP8266* has an additional significant functionality as it offers to the regular user an easy configuration of the *Wi-Fi* network. The *ESP8266* is by default a *Wi-Fi* client, although when a known *Wi-Fi* network is not available, or in case there are no wireless networks available, the *ESP8266* will turn to hotspot mode and will transmit a *Wi-Fi* network with an service set identifier (SSID) "IAQ-iDust." After that, the regular user could be connected to this Wi-Fi network to configure the *Wi-Fi* network to which the *iDust* is going to be connected. The regular user must introduce the SSID and password using a Web form as represented in **Figure 11**.

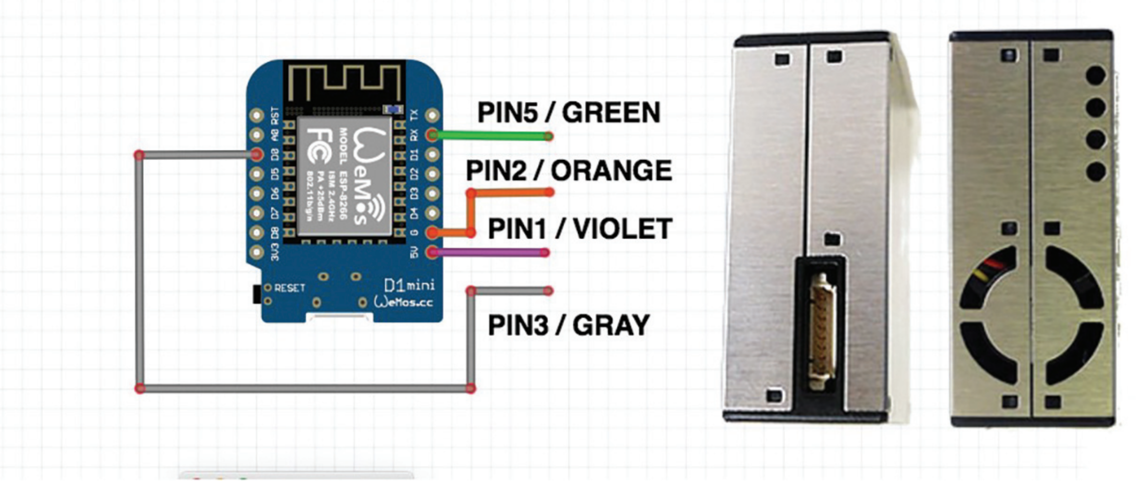

Figure 9.
iDust connection diagram, from [41].

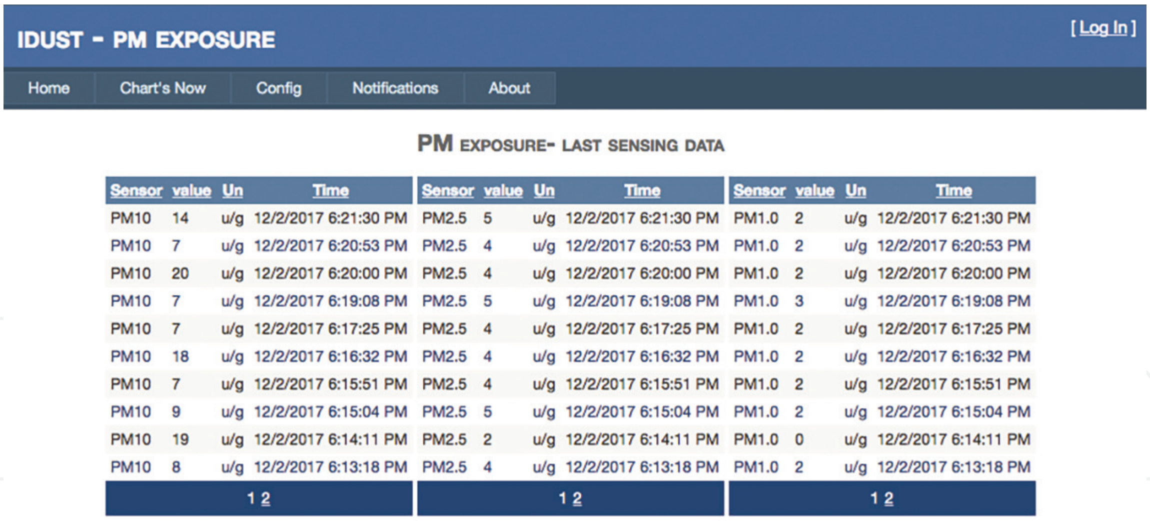

Figure 10.
iDust Web application, from [41].

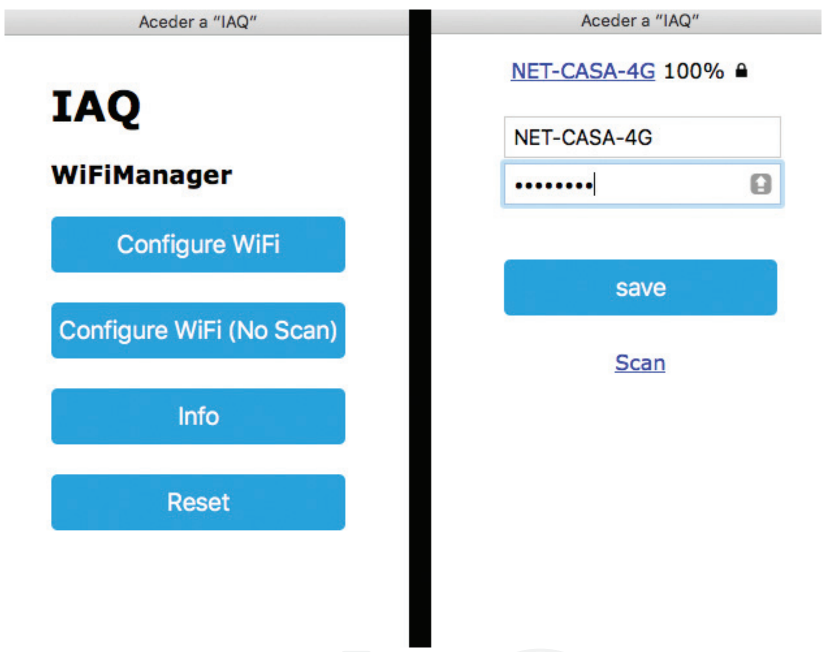

Figure 11.
iDust Wi-Fi configuration, from [41].

4. Discussion

Several solutions for IAQ supervision, which support open-source technologies for data processing, collection, and transmission that offers mobile computing architectures for real-time data accessibility, was presented in Section 3. Mainly, IAQ monitoring is a trending topic for which some other low-cost and open-source monitoring systems had been developed.

A summary of these studies is presented in **Table 1**.

In general, all the systems presented not only use cost-effective sensors and use open-source technologies, but also have notification systems that allow users to act in real time to significantly improve indoor air quality through the ventilation or deactivation of pollutant equipment. The presented solutions make a significant contribution compared to existing air quality monitoring systems due to its low cost of construction, installation, modularity, scalability, and easy access to monitoring data in real time through the Web and mobile applications. All the presented

	MCU	Sensors	Architecture	Low cost	Open-source	Connectivity	Data access	Data storage	User installation
iAQ	Arduino	Temperature, relative humidity luminosity, CO, CO_2	WSN	√	√	ZigBee, Ethernet	Web	MySQL	×
iAQ Mobile	Arduino	Temperature, relative humidity luminosity, CO, CO_2	WSN	√	√	ZigBee, Ethernet	Mobile	MySQL	×
iAQ IoT	Arduino, ESP8266	Temperature, relative humidity luminosity, CO, CO_2	WSN/IoT	√	√	ZigBee, Wi-Fi	Web, mobile	MySQL	×
iAQ Wi-Fi	Arduino, ESP8266	CO_2, particulate matter, temperature, relative humidity	IoT	√	√	Wi-Fi	Web, mobile	Cloud	√
iAirC	Sparkfun ESP8266	$CO_{2,}$	IoT	√	√	Wi-Fi	Mobile	Cloud	√
iDust	Wemos D1 Mini	Particulate matter	IoT	√	√	Wi-Fi	Web, mobile	SQL Server	√

MCU: microcontroller; √: apply; ×: not apply.

Table 1.
Summary of the presented systems for real-time indoor air quality monitoring.

solutions aim to offer the support to a medical examination by clinical professionals as the medical team might analyze the history of IAQ parameters collected from the environments where the patient lives and relate these records with his health complications.

An essential advantage of the use of *ZigBee* communication (*iAQ*, *iAQ Mobile* and *iAQ IoT*) is that we can have many *iAQ Sensors* collecting indoor air quality data, and only one *iAQ Gateway* must be connected to the Internet as *Zigbee* have an indoor RF line-of-sight range up to 50 m. It is essential for some scenarios, in this way, as it is no longer being required for *Wi-Fi* network coverage throughout all area of housing and it needs only an Internet connection at the location of *iAQ Gateway*.

Of about 56% of American adults are now smartphone holders [42]. In Netherlands, 70% of the regular people and over 90% of teenagers have a smartphone [43]. The usage of mobile phones represents on average 86 min per day (median 58 min) as proposed by [44]. People use the smartphone even when they are close to the computer [45]. Mobile computing offers the possibility to check the data and gather notifications anytime and anywhere. Real-time notifications provide a reliable method to maintain healthy indoor environment to increase the occupant's health, productivity, and well-being as the building manager can react at time. Consequently, mobile applications were been created in *iAQ Mobile*, *iAQ IoT*, *iAQ Wi-Fi*, and *iAirC*.

iAQ IoT system incorporates not only wireless communication technologies to interact between *iAQ Sensors* and *iAQ IoT Gateway* but also for Internet connection. Therefore, the implementation and installation cost is lower when compared with other solutions that use Ethernet to connect the gateway to the Internet. This solution could easily be designed to use only as many *iAQ Sensors* as needed due to their modularity and integrates the benefits of the *WSN* and IoT architectures.

iAQ Wi-Fi and *iAirC* use cloud service for data storage and data access. The use of cloud service has several advantages referring the cost and security of the storage data.

iAQ Wi-Fi, *iAirC*, and *iDust* have benefits both in easy installation and configuration, not only due to the use of wireless technology for communications, but also because they were developed to be compatible with all domestic house devices and not only for smart houses or high-tech houses. These systems are particularly useful for the analysis of IAQ. These functionalities create an easy product installation, which is directly related to IoT concept. The common IAQ supervising architectures should be installed by specialized professional, although the iAQ Wi-Fi, iAirC, and iDust solutions can be installed by the regular people using a gadget with Wi-Fi connectivity, which decrease the costs related to the installation.

Compared to other systems, *iAirC* and *iDust* systems incorporate only one sensor, which provides advantages both in ease of installation and configuration due to the use of wireless technology but also due to its small size. These systems use the *ESP8266* for both processing and Internet connectivity. This method not only delivers numerous benefits concerning the decrease of the system cost, but also increases the processing power as the *ESP8266* has an 80 MHZ CPU, while the *Arduino UNO* has a 16 MHZ CPU, for example.

5. Conclusions

This chapter has presented several solutions for indoor air quality monitoring and decision-making tools for enhanced healthcare. All the given solutions were developed using open-source technologies, cost-effective sensors, low price of construction, installation, modularity, scalability, and easy access to monitoring data. The results obtained by these solutions are auspicious, as this kind of systems might be used to provide a detailed stream of data that can be used by the building manager for correct maintenance to offer not only a safe but also a healthy environment for enhanced living environments.

On the one hand, the real-time monitoring is a significant method to support the clinical analysis by medical specialists as the therapeutic team could analyze the history of IAQ conditions of the environment where the patient resides and link these data with his health problems. On the other hand, by supervising IAQ, it is conceivable to identify the poor air quality situations appropriately and plan interventions for enhanced living environments.

The *WSN* architecture is appropriated to large buildings with no *Wi-Fi* networks available. However, the IoT architecture is appropriated to domestic homes as the majority provide Wi-Fi access points and also because the easy installation and configuration allows the user to start with a few devices and increase the number of them as he needs.

In the opinion of the authors, the future of air quality monitoring solutions focuses on the development of *Wi-Fi* systems that incorporate only one sensor. In this way, the user can not only create an ecosystem to suit them by monitoring the parameters he wants, but can also make the systems more cost-effective and easier to install.

As a future work, the proposed solutions should plan software and hardware improvements to fit specific cases such as hospitals, schools, and industry. It is also essential to create secure methods for data sharing between the medical team in order to support clinical diagnostics. The authors believe that in the future, systems like the presented ones will be used as an integral part of the daily human routine in order to provide safe and productive living environments.

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Conflict of interest

The authors declare no conflict of interest.

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