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Review

Review of Communication Technology in Indoor Air Quality Monitoring System and Challenges

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Abstract: In the past decade, with the development of communication technology, indoor air quality (IAQ) monitoring technology has made significant progress, which improves the real-time performance of the monitoring system, and reduces potential impacts on health-related pollutants. To investigate and analyze the development of IAQ monitoring technology and the application of communication technology in this field, this review conducts a comprehensive search, collation, and analysis of the literature in the relevant fields over the past decade, and reviews 91 articles from the usage scenarios, monitoring parameters, and communication technology of the IAQ monitoring system. The review shows the development and main research direction of IAQ monitoring, and focuses on the selection and application of communication technology in different projects. In addition, this study also discusses the problems and challenges in the IAQ monitoring system, which provides a reference for researchers and promotes the rapid and all-around development of IAQ monitoring.

Keywords: indoor air quality; communication technology; sensors; air quality monitoring

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1. Introduction

Indoor air quality (IAQ) constitutes a major problem for both the developing and developed worlds. As one of the fundamental rights of all, the right to breathe healthy air should also be guaranteed. Almost all of the global population breathe air that exceeds World Health Organization (WHO) guideline limits containing high levels of pollutants, with low- and middle-income countries suffering from the highest exposures, causing 7 million deaths annually [1]. However, most people tend to think that air pollution is only happening in outdoor environments, such as exhaust fumes from vehicles, the burning of fossil fuels in industries, or from forest fires. In fact, exposure to indoor and ambient air pollution increases the incidence of stroke, heart disease, lung cancer, and chronic respiratory diseases [2]. The World Health Organization linked 4.3 million deaths globally in 2012 to household cooking using coal, wood, and biomass stoves, compared with 3.7 million deaths for outdoor air pollution. People spend nearly 90% of their time indoors [3], which means that indoor air pollution will be more seriously damaging. Therefore, it is of great significance to monitor the IAQ similar to residences, classrooms, offices, and hospitals, among others [4–6]. Indoor air pollution might be polluted by volatile chemicals from building materials, cleaning products, cigarette smoke, and the burning of fuels from stoves and ovens, which has led to the provision of guidelines for selected indoor air pollutants, including benzene, carbon monoxide (CO), formaldehyde, nitrogen dioxide (NO_2), particulate matter (PM), and even carbon dioxide and ozone, which are easy to be ignored by people [7].

With the swift growth in commerce and transportation in modern civilization, in order to improve the indoor air environment, IAQ monitoring becomes indispensable. However, existing monitoring systems are unable to provide sufficient spatial and temporal resolutions of the data with cost-efficient and real-time solutions [8]. In the traditional IAQ monitoring system, the expensive monitoring cost, complex monitoring equipment, low data utilization rate, lack of timeliness, and short distance data transmission, limit the large-scale promotion of IAQ monitoring. However, with the development of communication technology in recent years, these problems have the opportunity to be solved [9].

The long development process from simple IAQ detection to a complex indoor air detection system is closely related to the development of communication technology. The timely use and management of data through wired transmission was a breakthrough in IAQ monitoring [10]. With the popularization of wireless communication technology widely used in the past decade, including Wi-Fi, Bluetooth, mobile communication, LoRa, and ZigBee, etc. [11], wireless communication technology has been applied in more and more IAQ monitoring systems. Using ZigBee and Wi-Fi communication technology to achieve IAQ measurement and effective data transmission, the application of 3G and other mobile communication technologies in IAQ monitoring systems reduces the monitoring conditions [12]. The use of visible light communication (VLC) technology reduces the impact of electromagnetic interference (EMI) on the human body during IAQ monitoring [13]. At the same time, IAQ monitoring is combined with the Internet of Things (IoT) including perception layer, network layer, and application layer, which builds a bridge between IAQ monitoring and the client and adds more advanced functions, such as a real-time alarm function [14] and a mobile app view data function [15].

However, with the rapidly increasing number of studies, projects, and grey literature based on IAQ monitoring systems, information got scattered. Although there have been some reviews on IAQ monitoring, most of them only discuss the development process of IAQ monitoring systems or focus more on sensors and the deployment of sensors in IAQ monitoring systems [8,16–20]. No review has been published which focuses on the research progress of communication technology in the IAQ monitoring system. In particular, there is a lack of discussion on the development process of communication technology in IAQ monitoring systems, analysis, and suggestions for communication technology under different monitoring environments, or on the application direction of communication technology in IAQ monitoring systems in the future. In addition, there is a critical but overlooked gap in the literature that looks at the problems, challenges, and development direction of IAQ monitoring systems in recent years, especially under the background of the rapid development of communication technology, and the outbreak of epidemic. Therefore, this study aims to review and identify scientifically validated literature on the development of IAQ monitoring systems in the past decade, with an emphasis on communication technology in IAQ.

The structure of the paper is organized as follows. Section 1 provides an introduction and discusses the background of the study. Section 2 introduces the review methodology. Section 3 presents the distribution results, as well as a review table of the study. Section 4 shows the discussions and analysis of the results. Section 5 puts forward problems and challenges, with suggestions. Finally, Section 6 includes the discussion on critical conclusions and future outlook.

2. Methodology

In this review, we incorporate studies on communication technology in IAQ monitoring systems, which have been carried out and reported in scientific literature over the last ten years. The present review includes studies published from 2010 to 2021 in the following databases: Scopus, ScienceDirect, and Web of Science, all of which were written in English. The keywords and their combinations used were: “indoor air quality”, “indoor environment quality”, “indoor air pollution”, “IAQ”, and “monitor”. With no previous review articles on this topic, an exhaustive search was carried out, and published research and conference articles were also included. As the specific types of communication technologies used in relevant researches, such as Wi-Fi, ZigBee, and LoRa, are displayed in the title, abstract, or keyword of the article, or in the content of the article, it is difficult to directly use “communication technology” as keywords to retrieve information. Therefore, communication technology is not mentioned in the keywords, and the classification of communication technology is screened by follow-up studies reviewed in detail.

From all the studies retrieved using the above-mentioned keywords, we found a total of 782 publications with potential interest from the initial search and their titles were screened based on their context of research. The publications not delving into device development and focusing on sensor development were eliminated. From those, 170 publications remained and their abstracts were appropriately reviewed. Then, the following criteria were used for further exclusion: (i) focus on outdoor monitoring or special indoor monitoring such as cars and mines were excluded; (ii) articles which did not mention communication technology were excluded; and (iii) devices serving non-human, such as greenhouses for smart agriculture, were excluded. After this, 61 abstracts were excluded and 109 articles were carefully reviewed. Multiple publications of the same equipment were deleted or merged, and after rejecting five publications that did not have enough information regarding communication module development, 91 articles were finally organized into tables. These final eligible studies contain the following information: authors’ nationality, usage scenarios, monitoring parameters, and communication technology. Figure 1 shows a flowchart of the number of studies identified and included/excluded in the review process.

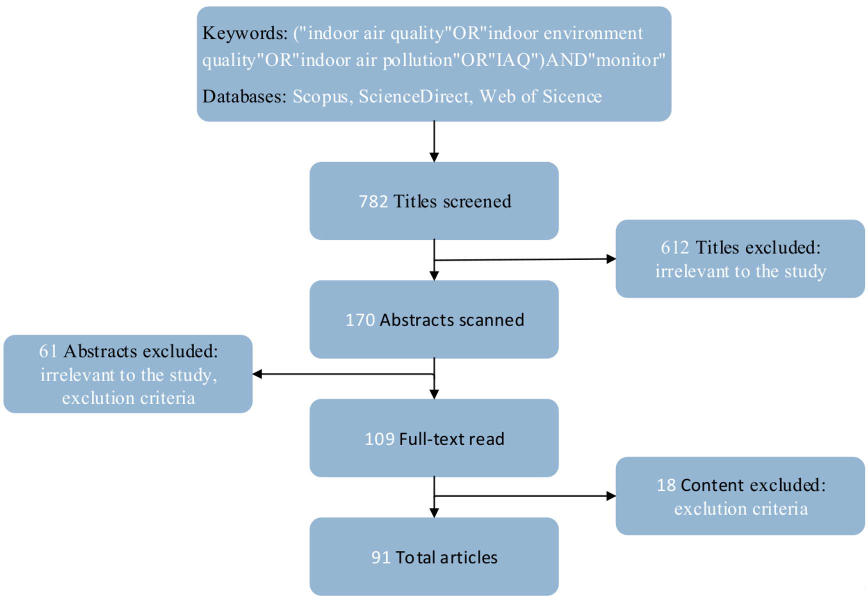

Figure 1. Systematic review flowchart.

3. Distribution Results

In this review, 91 projects were reviewed to provide basic information on IAQ monitoring equipment, such as the publication date of projects, the geographical distribution of projects, the scene of equipment use, and the monitoring parameters. In addition, this paper focuses on reviewing and discussing the use of communication technology in each project.

3.1. Distribution by Year of Publication

To understand the research and development of the IAQ monitoring system, this review is not focused on a specific region or time, but collects projects from across the world. At the same time, it has taken 10 years as a period of study, to better show the development trend of the related research.

The distribution of the number of academic papers from 2010 to 2021 is shown in Figure 2. First, from the general trend, there is an increasing number of papers applying effective communication technologies in IAQ monitoring systems over time. Of these, in 2021 only six papers were published before September; in 2019 and 2020 there were

19 and 20 papers published, respectively; and in 2017 and 2018, there were 11 and 13 papers, respectively. The remaining years all had under ten papers published, with only one each in 2010, 2011, and 2012.

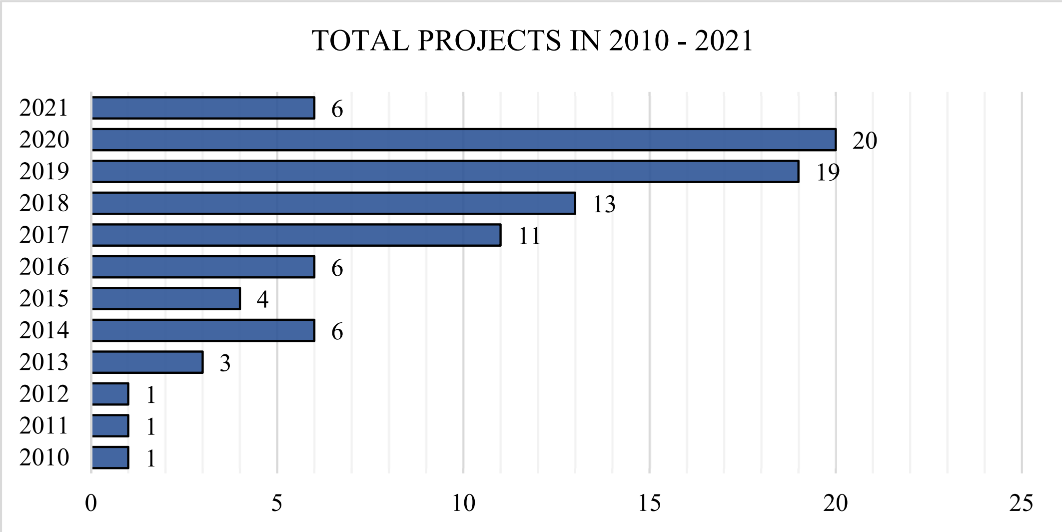

Figure 2. Number of the research time distribution of projects from 2010–2021.

3.2. Distribution by Authors' Nationality

In order to show more clearly the geographical distribution of projects developed for the IAQ monitoring system, Figure 3 labels the number of projects associated with each country by color. The study cases on IAQ monitoring systems reviewed in this review are from 23 countries. Of the 91 articles, the largest number of authors were from China, with a total of 20 authors, followed by India and the United States with 14 and 12 study cases each, respectively. This was followed by Indonesia and Italy, with six each; South Korea with five; Malaysia and Australia with four each; Portugal and the UK with three each; Hungary with two; and Romania, The Philippines, Turkey, Spain, UAE, Sri Lanka, Oman, Qatar, Germany, New Zealand; Saudi Arabia; and the Czech Republic with one study case each.

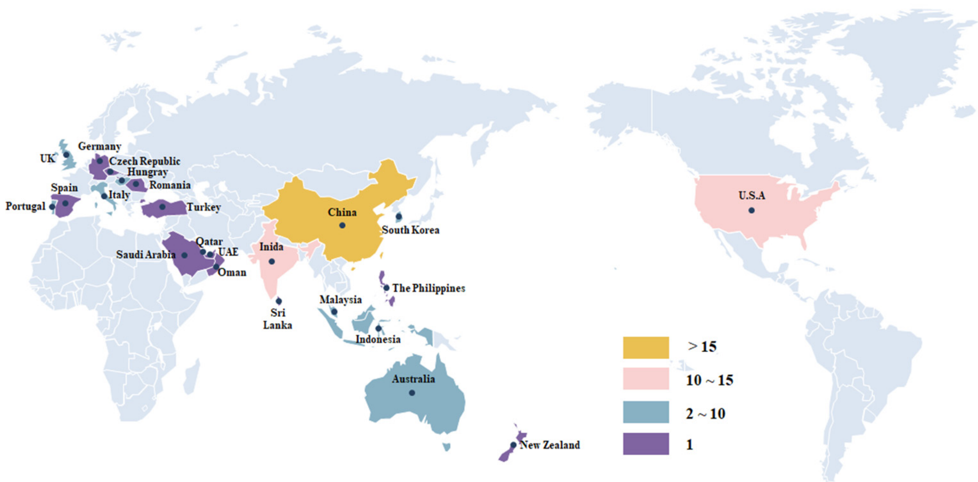

Figure 3. Geographical distribution of the projects on the world map.

3.3. Distribution by Category

Of the 91 items reviewed, 21 explained specific scenarios to which the system applied, with the specific content illustrated in Figure 4. Most of the remaining projects were only for the general indoor environment. Of the 21 monitoring systems with a clearly defined environment, most were for homes, e.g., eight residential buildings with installed fresh air systems were selected to monitor IAQ, which showed that the IAQ varied with seasonal characteristics [21]. Of the remaining studies, one was for monitoring CO_2 for the healthcare environment of hospitals [6]; four were for office buildings [22–25]; and the remaining seven studies were for school buildings, such as university lecture halls, laboratories, and dormitories. Therefore, in specific application scenarios, apart from private residential buildings, IAQ monitoring within the public indoor environment is the main research focus.

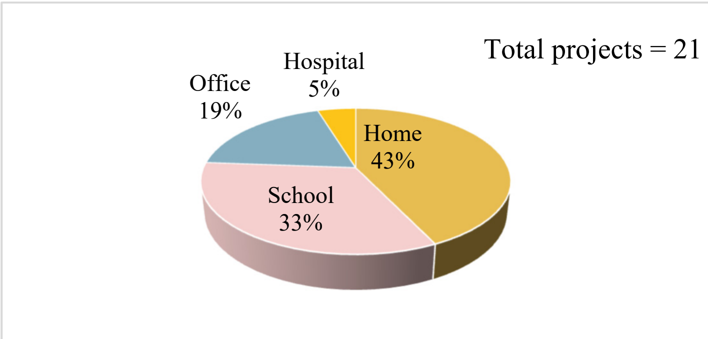

Figure 4. Percentage of each building category.

A detailed summary of the various IAQ monitoring projects has been presented in chronological order, as shown in Table 1, including the publication date of the projects, the geographic distributions, the site of equipment use, and monitoring parameters.

Table 1. The results of device design characteristics are summarized in chronological order of publication.

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2021	Romania	To develop a dual monitoring system based on IoT to assess the IAQ and risk of COVID-19 transmission.	Indoor	Wireless	Wi-Fi	T, H, TVOC	[26]
2021	China	To design a set of indoor environment monitoring systems with dual data transmission mode based on the Interconnect of Things.	Indoor	Wireless	GSM/Wi-Fi	C2, F, VOC, PM, T, H, NL	[27]
2021	Indonesia	To develop a system which can record air quality data and connect to an Internet server to monitor indoor air.	Indoor	Wireless	Wi-Fi	A, H_2	[28]
2021	USA	To develop an IAQ monitoring and prediction solution based on the latest IoT sensors and machine learning capabilities.	Indoor	Wireless	GSM/Wi-Fi	A, C1, NO_2, M, C2, PM2.5, T, H	[29]
2021	Italy	To develop an approach based on a social humanoid robot that monitors indoor environmental quality and interacts with occupants providing appropriate suggestions.	Office	Wireless	BLE (Bluetooth Low Energy)	T, LL, NL	[22]
2021	China	To design an air quality test system, which can monitor and adjust the concentration of harmful substances in the home environment.	Residential buildings	Wireless	GSM	BZ, F, C1, PM2.5, T, H	[4]
2020	Australia	To develop an IAQ monitoring system, which can predict and monitor the indoor environmental conditions in terms of CO_2 and VOC concentrations.	Indoor	Wired	NA	C2, VOC	[30]
2020	USA	To design low-cost, portable particle sensors, which are used to monitor human exposure to particle pollution.	Indoor	Wireless	3G	PM	[12]
2020	Italy	To develop a low-cost Smart and Healthy Intelligent Room System, able to monitor IAQ and infer human presence (headcount) from environmental data analysis.	Indoor	Wireless	Wi-Fi	H, C2, C1, PM, T, AP	[31]
2020	India	To develop a heating ventilation and air conditioning control (HVAC) system that automates the HVAC operation in real time by considering energy management policies and user preferences.	Office	Wireless	Wi-Fi	PM2.5, T, C2	[23]
2020	UK	To design and develop a low-cost, portable IoT IAQ monitoring system with a custom Blynk smartphone app, developed for easy user engagement.	Indoor	Wireless	Wi-Fi	VOCs, C2, PM2.5, PM10, T, H, LL	[32]
2020	Indonesia	To build a monitoring system able to transfer IAQ data to the cloud and publish messages by open source clients.	Indoor	Wireless	Wi-Fi	C2, T, H	[33]
2020	China	To develop a mobile sensing system that employs cooperative robots to monitor IAQ, and aims to minimize the average data latency by properly planning the routes of the robots.	Indoor	Wireless	Wi-Fi	PM2.5	[34]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2020	China	To develop an IAQ system and select residential buildings with installed fresh air systems to monitor, which show that the IAQ varied with seasonal characteristics.	Residential buildings	Wireless	Wi-Fi	T, H, F, VOC, C2, PM2.5	[21]
2020	South Korea	To build an IoT-based IAQ monitoring platform, which relies on an IoT and cloud computing technology to monitor IAQ anywhere and anytime.	Indoor	Wireless	LTE	PM2.5, PM10, VOCs, C1, C2, T, H	[15]
2020	Hungary	To develop an environmental monitoring solution based on the IoT paradigm, primarily for educational facilities, which can be reproduced with minimal investment.	School buildings	Wireless	BLE, Wi-Fi	C2, TVOC, T, RH, AP, UVI, NL	[5]
2020	India	To develop a Smart IAQ Monitoring System for measuring carbon dioxide and particulate matter from household and workplace activities.	Indoor	Wireless	Wi-Fi	C2, PM	[35]
2020	India	To build a wireless air pollution monitoring system which sends alerts to the user by using the Internet, when the concentration of pollutants measured goes beyond a safe level.	Indoor	Wireless	Wi-Fi	A, Smoke, C2, BZ, E, NOx	[14]
2020	The Philippines	To build a system that utilizes supervised machine learning using Support Vector Machines, which monitors parameters and notifies the user about potential risks in the specific location, and helps the system to try and predict new data as accurately as possible.	Indoor	Wireless	Wi-Fi	Smoke, M, C1, C2, PM2.5, T, H	[36]
2020	Indonesia	To build an air quality monitoring system using ESP32 as a controller and several sensors to measure air quality.	Indoor	Wireless	Wi-Fi	T, H, PM, A, C1, NO_2, SO_2	[37]
2020	Indonesia	To develop a system that monitors indoor CO_2 through Arduino UNO Microcontroller and involves the Artificial Neural Network to predict the level of indoor CO_2 during the application of the smart sensor system.	Indoor	Wireless	NA	C2, T, H	[38]
2020	India	To develop an IoT sensing system to monitor and analyze the time variation of carbon dioxide in a university classroom, and using the sensed data, forecast models have been developed to predict the build-up of carbon dioxide, an indicator of IAQ.	School buildings	Wireless	Bluetooth	C2	[39]
2020	USA	To develop a replicable framework and actionable program that monitors and assesses IAQ in a wide range of buildings.	Indoor	Wireless	Wi-Fi	PM, TVOC, C2, RH, T	[40]
2020	India	To design an IAQ monitoring systems based on IoT with an automated prediction system for PM10.	Indoor	Wireless	Wi-Fi	PM10, PM2.5, C2, VOC, T, H	[41]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2020	China	To develop a system that monitors and improves IAQ automatically with the interactive platform triggering events based on certain predetermined conditions, which improve air quality through SMS alerts and circuit actuators.	Indoor	Wireless	LoRa	PM2.5, T, H	[42]
2020	China	To develop an online monitoring and control ventilation system using fast prediction models and micro-control.	Office	Wireless	ZigBee	C2	[24]
2019	Oman	To develop a system that tackles the problems of abnormal changes in the level of air quality through proposing units designed in a level model to collect, manage, and process sensory data of indoor environmental parameters and propose the CPT+ model to predict the air pollutant levels of the next day.	Indoor	Wireless	Wi-Fi	T, H, C2	[43]
2019	India	To develop a Bolt based IoT system that monitors in real time the basic pollutants.	School buildings	Wireless	Wi-Fi	C1, PM2.5, SO_2, NO_2, O_3	[44]
2019	Italy	To develop an experimental low-cost system, which addresses IAQ issues by using a distributed IoT platform to control and monitor the indoor environment in building spaces, while adopting a data-driven approach.	Indoor	Wireless	Wi-Fi	C2, VOCs, AP, RH, T	[45]
2019	USA	To develop a comparatively low-cost, portable, in-home air sampling platform, and a guiding development and maintenance workflow that achieves the goal of characterizing some key indoor pollutants with high sensitivity and reasonable accuracy.	Residential buildings	Wired	NA	C1, PM2.5, NOx	[46]
2019	India	To build a system that identifies the IAQ with the help of the IoT by using the sensors BME680 from Bosch, SGP30, CCS811, and a low-power wide area network for data transfer.	Indoor	Wireless	LoRa	C2, TVOC, E, AP, T, RH, F	[47]
2019	Hungary	To present an environmental monitoring solution based on the IoT paradigm, primarily for educational facilities, which can reproduce the system with minimal investment by using a low-cost BLE wireless sensor.	School buildings	Wireless	BLE	C2, TVOC, T, RH, AP, LL, UVI, NL	[48]
2019	India	To develop an air quality monitoring system, which pushes and stores the data on the cloud and alerts users if IAQ is poor.	Indoor	Wireless	Wi-Fi	C2, Dust, O_2	[49]
2019	Portugal	To develop an IoT system for real-time IAQ monitoring named iAir with a smartphone application for data consulting and real-time notifications.	Indoor	Wireless	Wi-Fi	C1, NO_2, E, H_2, A, M, P	[50]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2019	India	To develop a system with mobile SMS notification and email, which can be used in real time for the indoor environment and provide information for the IAQ Index.	Indoor	Wireless	Wi-Fi	T, H, C1, C2	[51]
2019	Australia	To develop a state-of-the-art monitoring station for continuous, real-time measurements of indoor environmental quality parameters from occupants' work desks, which integrates a low-cost suite of sensors with a software platform designed to automatically analyze and visualize data.	Indoor	Wireless	LTE	C1, C2, PM10, T, RH, AV, F, TVOC, NL, AP, LL	[52,53]
2019	India	To develop a smart home system that monitors and controls the overall power consumption of the home, and keeps a check on healthy environmental conditions by measuring the level of oxygen, thereby producing an alarm when it falls below the safe limit.	Residential buildings	Wireless	ZigBee	O_2, C1, H, T	[54]
2019	South Korea	To develop an indoor environment monitoring system using EMI-free bidirectional VLC technology to aggregate and visualize data in a cloud platform by a graphical user interface.	Indoor	Wireless	VLC	C2, VOCs, O_2, T, RH	[13]
2019	Indonesia	To develop an IAQ monitoring and control system that can monitor the air condition and control the air condition using an exhaust fan.	Indoor	Wireless	Wi-Fi	C2, PM10	[55]
2019	UK	To develop a system that monitors IAQ parameters for real-time visualization and recording of the measured data.	Indoor	Wireless	ZigBee	C2, T, H	[56]
2019	India	To design a portable multi-sensory IAQ monitoring system that sends alerts to users via Wi-Fi.	Indoor	Wireless	Wi-Fi	C2, SO_2, VOC, Dust, T, H	[57]
2019	Turkey	To develop a real-time mobile air quality monitoring system with various air parameters, which is produced with an open-source, low-cost, easy installation and do-it-yourself approach.	Residential buildings	Wireless	Wi-Fi	C2, C1, PM10, NO_2, T, H	[58]
2019	Australia	To design a low-power wearable sensor node for environmental IoT applications that monitors environmental conditions reliably, forming a wireless sensor network (WSN) based on XBee.	Indoor	Wireless	ZigBee	C2, T, H, AP, LL	[59]
2019	China	To design an indoor air monitoring system, which can monitor and collect various parameters of indoor air in real-time, upload them to the data center for analysis, predict the air quality indicator in the next few hours, and push them to the user end for display.	Residential buildings	Wireless	Wi-Fi	PM2.5, PM10, T, H, C2, TVOC, F	[60]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2019	China	To develop an intelligent indoor environment monitoring system combined with ZigBee WSN technology and presents the resulting information by a web-based monitoring platform.	Indoor	Wireless	ZigBee	C1, C2, T, RH, F, VOCs	[61]
2018	Qatar	To present a mechanism for the backup and the restoration of the collected data in the case of Internet outage and develop an end-to-end IAQ monitoring that allows seamless integration of various sensing technologies, WSNs and smart mobile standards.	Indoor	Wireless	ZigBee	C1, C2, NO_2, T, RH, SO_3, O_3, Cl_2	[62]
2018	Australia	To explore a new approach to residential IEQ appraisal which extends the FSTC approach to the visual, aural, and olfactory dimensions using a low-cost data collection system based upon the Arduino microcontroller platform.	Residential buildings	Wireless	3G	C2, PM, T, RH, LL, NL, AV	[63]
2018	China	To develop an air quality monitoring system employing edge-computing based on IoT with power consumption reduction a significant low cost, which reduces the computational burden over sensing nodes and sets up automatic calibration to ensure the accuracy of the sensors reporting.	Indoor	Wireless	ZigBee, Wi-Fi	T, H, C2, PM2.5, PM10, SO_2, NO_2, O_3, C1	[64]
2018	USA	To develop a portable continuous measurement toolbox that provides a robust, easily extendable, and low-cost setup for indoor environmental quality monitoring and performance assessment.	Indoor	Wireless	ZigBee	C2, PM2.5, T, RH, LL, VOCs	[65]
2018	China	To develop an IAQ supervision system using ZigBee wireless networks, in which people could observe the real-time status by using the developed user interface app.	Residential buildings	Wireless	ZigBee	C1, C2, PM2.5, T, H	[66]
2018	China	To design an air quality monitoring system based on ZigBee WSN, which transfers data through GPSR and reminds users when the air quality index deteriorates.	Residential buildings	Wireless	ZigBee, GPRS	T, H, PM2.5, SO_2, NO_2	[67]
2018	Spain	To design and develop a low-cost building environmental monitoring system that has a clear ability to develop monitoring systems for the building sector, which can also be extended to multiple applications of smart environments.	Indoor	Wireless	Wi-Fi	C2, T, RH, AP	[68]
2018	Indonesia	To develop an air quality monitoring system for the indoor workplace so that users could monitor air quality remotely via a web application.	Indoor	Wireless	Wi-Fi	C1, C2, PM2.5, T, H	[69]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2018	Germany	To develop a system with a wireless gas sensor network to determine parameters, which transmits data via a Z-Wave protocol to a central gateway that in turn sends the data to a web-based platform for online analysis.	School buildings	Wireless	Z-Wave	C2, T, H	[70]
2018	UK	To develop a low-cost, portable monitoring system for indoor environment quality with a custom index to rate the parameter readings with a simple scoring system, to calculate on overall indoor environment quality percentage.	Indoor	Wired	I2C/UART	T, H, PM2.5, PM10, TVOC, C2, C1, LL, NL	[71]
2018	UAE	To develop a system with a sensor node with capability for wireless sensor networking.	Indoor	Wireless	Wi-Fi	C1, Dust, H, T, M	[72]
2018	New Zealand	To develop a low-cost, low-power consumption indoor environment monitoring device that monitors the IAQ in primary school classrooms.	School buildings	Wireless	Wi-Fi	C2, PM2.5, T, RH, PM10	[73,74]
2018	Malaysia	To develop a wireless IoT-based air quality device that monitors the air quality in the indoor environment and transfers the data through a wireless network to the Internet and displays the data on the dedicated webpage.	Indoor	Wireless	Wi-Fi	NOx, T, RH, BZ, A	[75]
2017	South Korea	To design a system with a microchip made out of sensors and an efficient algorithm to record measurements periodically, determine the optimal observation period for accurate air quality prediction, and estimate atmospheric changes.	Indoor	Wireless	Wi-Fi	C2, Dust, T, H, LL, VOC	[76]
2017	Saudi Arabia	To develop a low-cost system architecture that has been proposed for automatically monitoring air quality indoors and continuously in real-time.	Indoor	Wireless	ZigBee	T, H, A, NOx, BZ, C2	[77]
2017	Sri Lanka	To develop an IoT-based IAQ monitoring system for tracking the ozone concentrations near a photocopy machine.	Indoor	Wireless	Bluetooth, Wi-Fi	O_3	[78]
2017	China	To develop an IAQ monitoring system with a high precise E-nose, which provides high-precision indoor air pollution concentration monitoring.	Indoor	Wireless	ZigBee/Wi-Fi	M, T, H, A, H_2, C1, E, Toluene	[79]
2017	India	To develop an IAQ system for monitoring the concentrations of parameters, which is controlled through smart devices with GSM network.	Smart buildings	Wireless	GSM	C1, PM2.5, C2, O_3, F	[80]
2017	China	To develop an air monitoring and purifying device indoors, based on wireless transmission.	Indoor	Wireless	RFID	PM2.5, T, H, BTEX	[81]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2017	Italy	To develop an open-source smart lamp, a smart appliance that integrates a wireless communication system for building automation, which is installed in an office to manage the lighting and air quality levels.	Indoor	Wireless	Wi-Fi, Bluetooth	C2, T, RH, AV, LL	[82]
2017	Italy	To develop a low-budget monitoring platform currently for monitoring indoor environment and HVAC system parameters.	Indoor	Wireless	Wi-Fi	C2, T, RH, LL, PM	[83]
2017	South Korea	To develop a low-power system with battery-free smart-sensor devices for monitoring air quality in an indoor environment.	Indoor	Wireless	RFID	AP, VOCs, T, RH	[84]
2017	Czech Republic	To develop a system with real-time measurement and early warning system, which also monitors the structure of the building.	Indoor	Wireless	LoRa	C2, PM2.5, T, RH	[85]
2017	China	To develop an open platform of a WiFi-enabled IAQ monitoring and control system for monitoring the IAQ, as well as controlling an air purifier to regulate the concentration of the particulate matter.	Indoor	Wireless	Wi-Fi	PM2.5, PM20, T, H	[86]
2016	USA	To develop a low-cost IAQ monitoring WSN system that is capable of collecting six air quality parameters from different locations simultaneously.	Indoor	Wireless	ZigBee/Wi-Fi	C2, T, H, VOC, C1, O_3	[87]
2016	USA	To develop a suite of inexpensive, open-source devices based on the Arduino platform for measuring and recording long-term indoor environmental and building operational data.	Indoor	Wired	NA	C2, T, RH, LL	[88]
2016	South Korea	To develop a tiny air-quality monitoring system with a real-time comprehensive indoor air-quality level indication method, which effectively copes with dynamic changes.	Indoor	Wireless	Wi-Fi, Bluetooth	PM, VOC, C1, T, H	[89]
2016	Portugal	To develop a low-cost IAQ monitoring WSN system with storage and availability of monitoring data on a web portal in real-time.	Indoor	Wireless	ZigBee	T, H, C1, C2, LL	[90]
2016	USA	To develop a smartphone-based sensor system, which can be conveniently used for personal body area microclimate monitoring.	Indoor	Wireless	Bluetooth	T, RH, C2	[91]
2016	USA	To develop a low-cost indoor air monitoring device that measures the concentration of CO and HCHO gases at a specified rate and communicates over the cloud to notify any wireless device when the threshold of these gases is reached.	Indoor	Wireless	Wi-Fi	LL, C2, F, T	[92]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2015	Malaysia	To develop a WSN monitoring system for monitor air pollution in an indoor environment that displays the data on the web, which can be accessed by the user.	Indoor	Wireless	NA	C2, PM, T, H	[93]
2015	China	To develop a portable, real-time, wireless indoor air monitoring system that can wirelessly monitor parameters in households with acceptable sensitivities within 50 m away.	Indoor	Wireless	Wi-Fi	T, H, VOCs, PM	[94]
2015	China	To develop an intelligent air quality control system that monitors IAQ by combining wireless sensing technology, ARIMA prediction models, and fuzzy theory.	Indoor	Wireless	ZigBee	T, RH, C2	[95]
2015	China	To develop an IAQ monitoring system that simultaneously monitors a variety of parameters and sets alarm values according to the requirements of the indoor environment.	Indoor	Wired	Ethernet	T, H, F, M, PM2.5	[96]
2014	USA	To develop a low-cost IAQ monitoring WSN system with a linear least square estimation-based method for sensor calibration and measurement data conversion.	Indoor	Wireless	ZigBee	C2, VOC, T, H, C1, O_3	[97]
2014	Italy	To develop a WSN deployment for indoor environmental quality monitoring in office buildings to balance the indoor environmental quality and inhabitant comfort level and power demands.	Office	Wireless	LR-WPAN	T, H, LL, C2, C1, VOCs	[25]
2014	USA	To develop an integrated sensing system for real-time IAQ monitoring that provides a timely, real-time basis and overall air quality alert.	Indoor	Wireless	ZigBee	T, RH, VOC, PM, NO_2, C1, O_3, SO_2, C2	[98]
2014	Malaysia	To develop an IAQ monitoring system that gives a real-time alert to the users on the conditions of the current IAQ.	Indoor	Wireless	ZigBee	T, H, VOCs, PM10, C2, C1, O_3, NO_2, O_2	[99]
2014	Portugal	To develop a flexible system characterized by low-cost sensing nodes that assure robust and continuous monitoring of air conditions for IAQ monitoring with application in asthma trigger factors assessment.	Indoor	Wireless	ZigBee/Wi-Fi	T, RH, O_3, PM10, NO_2	[100]
2014	China	To develop an intelligent environmental monitoring system that activates ventilation and an air purifier and an alert message when concentration exceeded a pre-set value.	Hospital	Wireless	ZigBee	C2, T, H	[6]
2013	USA	To develop a portable air quality sensing system that supports accurate personalized IAQ monitoring and quantitative analysis with high energy efficiency.	Indoor	Wireless	Bluetooth, Wi-Fi	C2, T, H, LL	[101]

Table 1. *Cont.*

Publication Date	Country	Objectives	Category	Connectivity	Communication Technology	Monitoring Parameters	References
2013	China	To develop an air pollution monitoring system with long term monitoring and set up of indoor gases WSN with the consideration of cost, development complexity, and operation convenience.	Indoor	Wireless	ZigBee	VOCs	[102]
2013	Malaysia	To develop a web-based system for monitoring IAQ, in which users can access the collected data using a self-developed server program through the web.	Indoor	Wireless	ZigBee	Dust, PM, T, H	[103]
2012	India	To develop a wireless solution for IAQ monitoring that measures environmental parameters to determine the environmental health of an indoor space.	Indoor	Wireless	ZigBee	C1, C2, PM2.5, PM10, T, H	[104]
2011	China	To develop a cost-effective and user-friendly IAQ monitoring system based on ZigBee WSN.	Indoor	Wireless	ZigBee	T, RH, C2	[105]
2010	India	To develop a framework of sensor networks for monitoring IAQ where the serial common bus communication network, CAN, is used to exchange system information.	Indoor	wired	CAN	VOCs	[10]

4. Discussion

The application of IoT technology liberates IAQ monitoring systems from traditional manual monitoring, and also gives birth to more development possibilities of the monitoring systems. Among them, a WSN has been used in most of the projects in this review. The application of this technology makes indoor air monitoring parameters no longer single, and more pollutants can be monitored at the same time. In addition, all kinds of advanced communication technology can also enter into the field of IAQ monitoring, and data timeliness and efficiency is also improved, making the system no longer just limited to the monitoring of pollutants, but more abundant functions can be achieved, such as combining it with the HVAC system to improve IAQ [45], and prediction of future air quality changes, etc. [95].

4.1. Sensors

Up to 24 IAQ parameters were monitored in 91 projects (Figure 5). The choice of parameters varies according to different equipment requirements. However, among the many monitoring parameters, most concerned the basic indoor temperature, humidity, and carbon dioxide, which are monitored by 81%, 78%, and 70% of the devices. As far as IAQ is concerned, indoor temperature and humidity are not pollutants, but they still have important monitoring significance. First of all, as far as human health is concerned, people have the most obvious feeling about the change in temperature and humidity, and the most basic comfort level is the appropriate temperature and humidity. Secondly, temperature and humidity are correlated with other pollutants, which can assist TVOC measurement [26]. The monitoring of carbon dioxide also has this function [30]. In addition, the amount of carbon dioxide is positively correlated with bacteria and PM [6]. The most important is the influence of carbon dioxide concentration on human health. Some studies show that when the concentration of carbon dioxide in indoor air increases to a moderate level, headache, fatigue, and inattention will be caused, while higher carbon dioxide concentration will lead to vomiting, dizziness, and other symptoms [106]. Therefore, it is an important monitoring content in indoor environments, such as school buildings and offices [24,39].

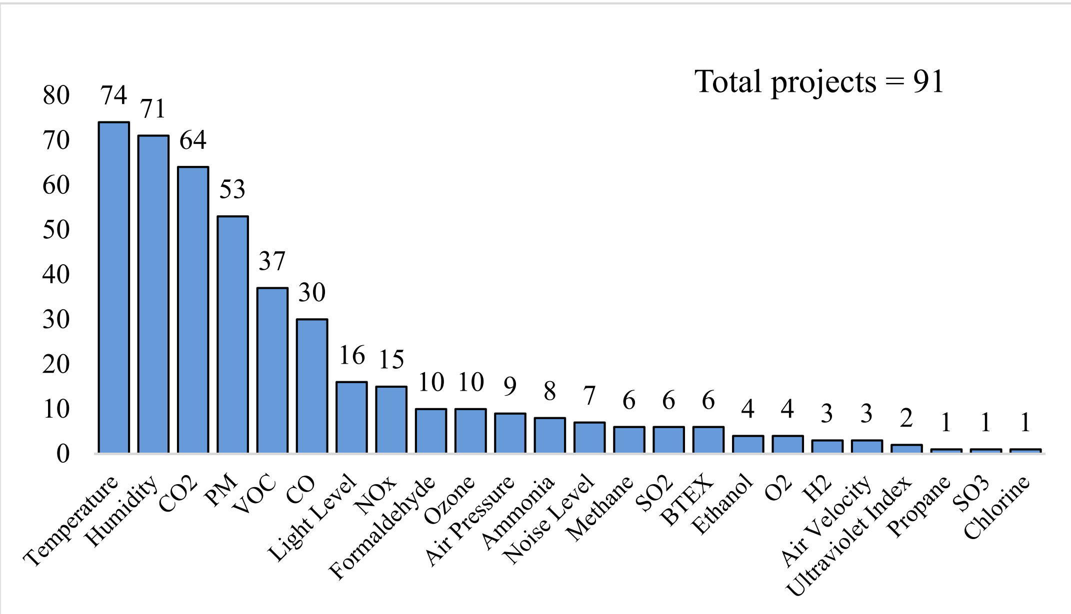

Figure 5. Monitoring parameters in the reviewed projects.

The monitoring of PM has received increasing attention due to the dramatic impact of adverse weather in recent years, such as haze, and no exception is made in indoor air monitoring systems. Long-term exposure to the environment with higher concentrations of

PM can easily lead to respiratory diseases, trigger asthma, and so on. Of the 91 projects, 53 monitored parameters contained PM, with at least five kinds of PM, including $PM_{2.5}$, which were mentioned in the reviewed projects. It is important in IAQ monitoring of the facing kitchen because it mainly originates from the cooking process [36]. As relevant pollutants described by WHO, the monitoring of VOC (40%) and carbon monoxide (33%) also accounts for a large number because of their common sources and serious health effects. These compounds can cause several health issues with symptoms such as nausea, headache, dizziness, tiredness, nose, eye, and throat irritations [107]. Common symptoms of CO poisoning include vomiting, nausea, weakness, dizziness, headache, and loss of consciousness. Nitrogen oxides, sulfur oxides, and ozone measurements were sporadic with <15 projects, less than 7% of the equipment detected BTEX (Benzene, Toluene, Ethylbenzene, Xylene), which was identified as pollutants by WHO, and 16 projects also focused on other indoor environmental parameters, such as light, wind speed, noise and so on.

4.2. Communication Technology

The data detected by sensors need to be transmitted to the control center, forming a sensor network. For IAQ monitoring of an intelligent building system, the sensor network needs to have the characteristics of low initial network complexity, be easy to expand, have stable topology, and must meet the most basic needs of different levels. The transmission process is divided into wired, wireless, and hybrid wired-wireless. In this review, hybrid wireless-wired systems are classified as wireless. Among the 91 projects, except six of which were wired, wireless communication technology was adopted. Tiele et al. [71] used Inter-Integrated Circuit (I2C) and Universal Asynchronous Receiver/Transmitter (UART) technology. Zhang and Zhao [96] designed an automatic detection device to monitor the air quality of buildings and used ethernet technology. The Serial Common Bus communication network CAN is used to exchange system information in another project [10]. In addition to being limited by the development of communication technology, some projects also choose to use wired communication technology in order to reduce costs and improve the security and integrity of data transmission [46].

More than 93% of projects use wireless transmission networks with diverse communication technologies. Figure 6 shows the number of 83 articles mentioning the types of wireless communication technology used, a large number of which use IoT technology. The rapid development of IoT technology promotes the application of wireless communication technology, which is used to transfer data to the cloud platform, in the IAQ monitoring system. This change has resulted in better timeliness and data processing application capabilities than traditional monitoring and realizes remote monitoring and control, which also provide an excellent direction for the development of IAQ monitoring. As can be seen from Figure 7, the usage of Wi-Fi and mobile communication shows an obvious increasing trend, while the use of Bluetooth is relatively stable. In addition, ZigBee decreases from the highest proportion of 71% (2014) to 5% (2021). These changes are closely related to the high-cost performance of Wi-Fi and the excellent short-distance communication capability of Bluetooth. The advantages and disadvantages of various wireless communication technologies, as well as their application in this review paper, will be introduced in detail below.

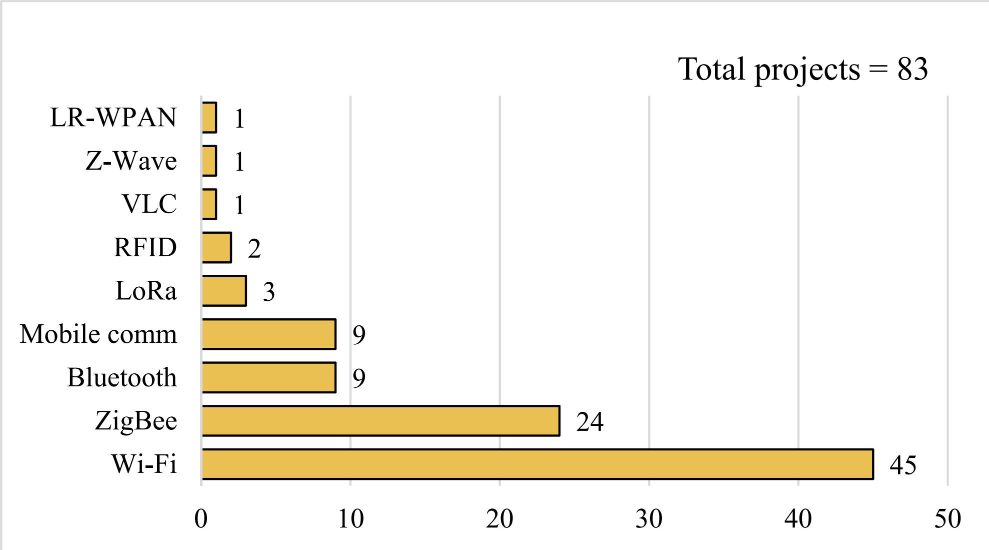

Figure 6. The use of communication technology in the projects.

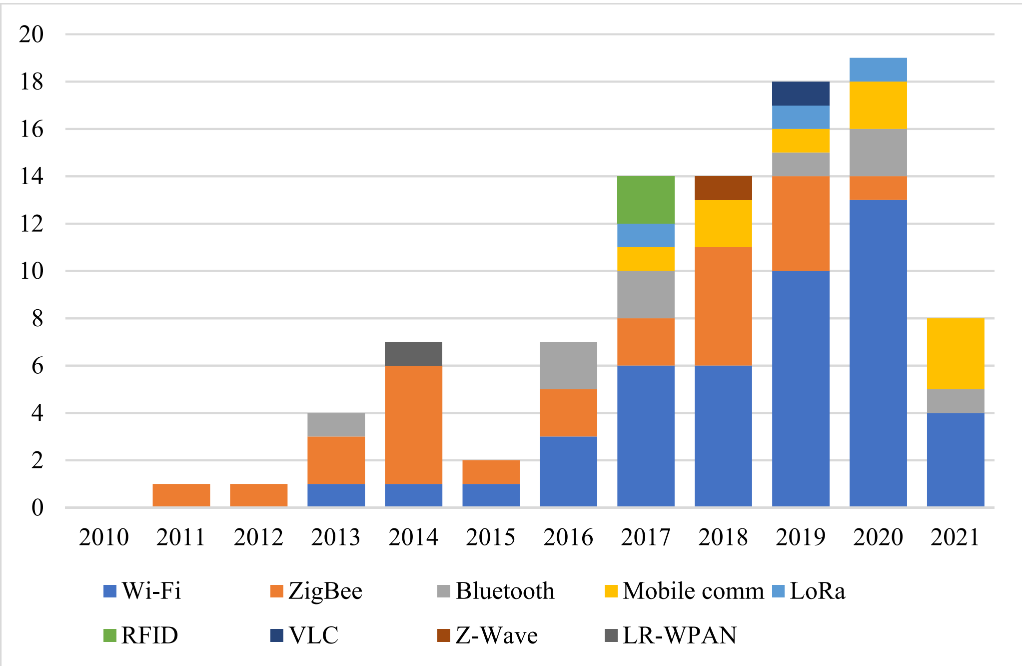

Figure 7. Percentage of types of communication technology per year.

4.2.1. Wi-Fi

Wi-Fi is the most popular wireless technology used in a CPN. It is based on IEEE 802.11 standards and operates within 5–60 GHz unlicensed ISM (Industry, Scientific and Medical) frequency bands. It provides a coverage range of up to 100 m, which is widely used in schools, families, and other networks. Almost all mobile phones, personal computers, game consoles, and other electronic devices, provide a means to access the network through Wi-Fi [108]. Due to the advantages of Wi-Fi communication technology, such as reliability, safety, and high speed, and the low-cost of promotion, more than half of the projects in this review used Wi-Fi communication technology in their IAQ monitoring systems, mainly for communication from gateways to IoT servers [21,28,35,44,68,92].

Projects using Wi-Fi have taken many steps to address or reduce the impact of short-range transmission and relative high-cost and power consumption among short-range wireless technologies. In the selection section of Wi-Fi modules, AbdulWahhab, Hapsari et al. [33,43] used the ESP8266 module. It has eight digital pins I/O and also one analog pin in one board with low-price, small size, and low-power consumption, which makes it one of the best choices for IoT microcontrollers. Tastan and Gökozan, Esfahani et al. [32,58] developed the system using the ESP32 module, which is called an improved version of ESP8266. The ESP32 has a dual-core architecture and has many internal modules, such as Wi-Fi, Bluetooth, RF, IR, CAN, and ethernet modules, etc. It costs slightly more than the ESP8266, but has better performance and lower power consumption. The ESP32 is a good choice for systems that require a more powerful processor, superior connectivity, and ultra-low power consumption. In addition, Ladekar and Daruwala [49] used the onboard Wi-Fi of Raspberry Pi, which makes the coding easier. In addition to the choice of hardware, Scarpa et al. [83] set the time interval for Wi-Fi connection to save battery by limiting the use of Wi-Fi modules.

4.2.2. ZigBee

ZigBee is another highly used wireless communication technology, with nearly a third of all studies using ZigBee in their systems. As a wireless personal area network (WPAN) based on the IEEE802.15.4 standard, ZigBee operates in the 2.4 ghz ISM band, which has a low data rate of 250 kbps. But its low-cost, low-power consumption, support for a large number of network nodes, and a variety of network topologies, makes it popular. ZigBee has a long service life of up to 10 years. Zhu et al. [24] used the ZigBee communication system to establish a network topology and bridge between sensor system, controller, and central control system. By monitoring indoor carbon dioxide, the optimal ventilation mode is determined to realize automatic control of IAQ. Due to the low transmission range of ZigBee, the XBee module, a low-power device, can be selected, which makes transmission distance up to 305 m indoors. [59]. XBee's coverage can effectively meet the needs of indoor systems. In addition, XBee modules can be embedded in data collection circuits without the need to integrate external microcontrollers, which can save onboard space and weight, which is an advantage in indoor environments where space is limited [65].

4.2.3. Bluetooth

Bluetooth is low-power consumption and low-cost wireless communication technology based on the IEEE802.15.1 standard. It operates in the 2.4 GHz unlicensed ISM band. Bluetooth is a popular short-range wireless communication technology. It is commonly used in portable personal devices and is used in about one in ten systems in the papers reviewed. Bluetooth is used for communication between sensors and gateways, or data transmission between sensor networks and mobile phones and other electronic devices. Rastogi and Lohani [39] transmitted the carbon dioxide sensor data monitored in the classroom to the smartphone application using Bluetooth for subsequent data processing. Smith and Li [91] took Bluetooth as a means of communication between sensor systems and smartphones. Application software running on the user's smartphone can be programmed to query sensor readings periodically or on-demand from the sensor system through Bluetooth, while the smartphone's built-in Wi-Fi and cellular wireless transceivers can easily transmit sensor data to the cloud server in a tiered manner. The ultra-low power, low-cost version of this standard is named BLE, and three of the nine projects that used Bluetooth explicitly used BLE [5,22,48].

But Bluetooth does not have a strong layer of security to prevent eavesdropping, so it doesn't meet the stringent security requirements of other wireless communication standards. Secondly, Bluetooth has low transmission coverage and some interference issues with 802.11, which makes the application of Bluetooth very limited.

4.2.4. Mobile Communication

There are different generations of mobile communication standards including second generation (2G including GSM), third generation (3G), fourth generation (4G including LTE) and GPRS, and devices based on these standards can communicate over cellular networks. When the monitoring system is abnormal, the main control system sends an SMS alarm to the user through GSM communication [4]. About one in ten of the systems reviewed in this review use mobile communications. Mobile communication is widely used in portable IAQ monitoring systems [12]. This is because the uncertainty of the monitoring location of portable equipment makes part of the wireless communication technology unable to meet its communication requirements, while mobile communication has a wider range of network coverage, which can realize the transmission, reception, and execution of data in the entire cellular are. Jo et al. [15] used LTE to deliver real-time data directly to a web server for sorting and visualization of air quality, eliminating the need for a gateway and a data logger. Secondly, mobile communication is also the main means of communication between sensor networks and smartphones, besides Bluetooth [67]. However, although mobile communication covers a wide range, its advantages in the IAQ monitoring system are not obvious, and the high cost and power consumption limit its large-scale promotion. This is one of the reasons why 5G, a new generation of broadband mobile communication technology characterized by high speed, low latency, and large connections, has not been applied to all the projects in this review.

4.2.5. LoRa

LoRa, a telecommunication protocol developed by the LoRaTM Alliance, is also used in the IAQ monitoring system. It has rates ranging from 0.3 KB/s to 50 kb/s and operates in the 868 and 900 MHz ISM bands. Due to LoRa's low-power consumption, low-cost, and extremely long node battery life, it is widely used in outdoor monitoring fields such as intelligent agriculture, which is also an advantage for IAQ monitoring systems. LoRa is mostly used in the central unit to transmit sensor data to the cloud [42,47,85]. During LoRa's deployment, portable home gateways were required, making it less simple than mobile communications, Wi-Fi, and other communication technologies. Secondly, LoRa technology's exclusive private security protocol has many security problems, such as weak key management and a simple authentication mechanism, which makes environmental monitoring data easy to be stolen and it cannot support large-scale smart home application scenarios.

4.2.6. RFID

RFID technology is used in two articles in this review. RFID, radio-frequency identification, is a two-way RFID system consisting of a tag and a reader, where the tag receives and transmits radio waves. These labels are transmitted through the chip to the reader to identify the object. It can interface with handheld computing devices or personal computers, following the Electronic Product Code (EPC) protocol. RFID operates over a wide range of frequency bands, ranging from 120 kHz–10 GHz, with detection ranges from 10 cm to 200 m, and can provide data rates of up to 4 Mbps. RFID, as a communication technology, is used to connect sensor equipment and central units in IAQ monitoring [81]. However, in addition to communication, Tran et al. [84] used RFID technology to design a new battery-free sensor module to monitor IAQ. The RF energy harvester can sufficiently collect the available RF energy to supply power for sensing and wireless communication operation of the smart-sensor tag, which reduces the size and cost of the sensor.

4.2.7. Visible Light Communication

The EMI generated by radio frequency (RF) wireless communication for indoor environment monitoring may adversely affect the human body, especially with the elderly, patients, and infants, while it concurrently affects the operation of electronic devices. The application of bidirectional VLC technology without electronic interference can effectively solve this problem so that the indoor environment monitoring system can be applied to more special environments. Pham et al. [13] proposed an average-voltage tracking algorithm, enabling LED to be used as both a lighting system and a remote wireless communication system. VLC can cover the range of indoor lighting, up to 6 m, for short-distance communication technology. Because of its non-RF wireless communication, green communication technology has a broader development prospect. The characteristics of VLC itself, that is, visible light cannot penetrate objects, and the signal will be cut off if the signal terminal is blocked, which can ensure high information security. However, at the same time it is also a limitation of communication, so that it can be used as a backup choice for indoor wireless communication, and is an effective supplement to the existing RF communication technology.

4.2.8. Z-Wave

Designed specifically for remote control applications in residential and lightweight commercial environments, Z-Wave is a reliable, low-power, low-cost proprietary wireless communication technology. However, the communication distance of Z-Wave is short, and the data transmission rate is low, supporting the data rate of 40 kbps, covering a distance of 30 m. Perez et al. [70] used Z-Wave to transmit data from sensor nodes to the central gateway. To better monitor IAQ on campus, each node is equipped with a Z-Wave module, which improves the physical range of transmission to about 100 m in an undisturbed environment. Z-wave can be used with ordinary wireless devices because it is interferes less with other communications in the same band. However, it is a tree-like networking structure. Once the upper end of the branch is broken, all the devices at the lower end cannot communicate with the gateway. In addition, the frequency band used by Z-Wave is not legal in some countries, so it is seldom used in the IAQ monitoring system.

4.2.9. Heterogeneous Communications

Heterogeneous communication is also widely used in IAQ monitoring systems, and 10 papers clearly show that two or more wireless communication technologies are used. This combination of multiple communication technologies is more complex than the traditional single communication technology, but the communication effect is better. From the perspective of anti-interference to ensure communication, two modes such as GSM and Wi-Fi, ZigBee and Wi-Fi are integrated into the monitor to realize the transmission process of data from the monitor to the cloud platform. In this way, the real-time communication mode can be switched according to the actual situation, which greatly improves the adaptability and flexibility of the monitor [27,29,79,100].

The IAQ monitoring system needs to complete two stages of the communication process from sensor network to gateway, gateway to processing node, or cloud. The data processing methods and communication environment of the two processes are different. Selecting appropriate communication technology and making full use of the advantages of various communication technologies will effectively improve the performance of the system. In the review, most heterogeneous communication is a means of selecting Bluetooth for short-distance communication and other communication technologies [89,101]. As one of the most excellent short-distance communication technologies, Bluetooth has the advantage of low-cost and low-power consumption. It is a good choice to match with other medium and long-distance communication technologies. In Kanal and Tamas's IAQ monitoring system for classrooms and other educational facilities, Bluetooth is used for sensor-to-gateway communication, and Wi-Fi is used for gateway-to-Internet communication [5]. Firdhous et al. [78], an IAQ monitoring system based on the IoT is proposed by using Bluetooth as the communication mode between the sensor and the gateway node, and Wi-Fi as the communication mode between the gateway node and the processing node, which is used to track the air pollution problem during the operation of indoor machines. Salamone et al. [82] designed an intelligent desk lamp, which hid the sensor in the lamp holder, used Bluetooth and ZigBee communication according to demand and integrated the IAQ monitoring system into the office environment.

4.2.10. Results and Suggestions

Table 2 compares the performance of each communication technology. In terms of distance, half of the eight wireless communication technologies we discussed are short distances. This is because the IAQ monitoring system is aimed at a small indoor environment and has little demand for long-distance transmission. Bluetooth excels at low-power consumption and low-cost. To put it simply, Wi-Fi is more suitable for IAQ monitoring in residential buildings due to its low promotion cost and extensive use in ordinary households. ZigBee supports a large number of network nodes and a variety of network topologies with low-cost, so it is suitable for IAQ monitoring communication in schools or office buildings with many monitoring points and complex room distribution. VLC communication takes into account its characteristics, as well as higher security, more to meet the communication needs of special hospitals and indoor buildings where important electronic equipment is stored. Bluetooth has excellent applications in any built environment, especially in combination with other communication technologies. Mobile communication technology has certain advantages in portable IAQ monitoring systems, and its network coverage is very wide. In addition to the particularity of VLC, other communication technologies have not been widely favored in IAQ monitoring systems.

Table 2. Comparison of communication technologies.

Table	Standard	Frequency Band	Data Rate	Transmission Range	Energy Consumption	Cost
Wi-Fi	IEEE 802.11 a/c/b/d/g/n	5–60 GHz	1 Mbps–6.75 Gbps	20–100 m	High	Medium
ZigBee	IEEE 802.15.4	2.4 GHz	250 kbps	10–20 m	Low	Medium
Bluetooth	IEEE 802.15.1	2.4 GHz	1–24 Mbps	8–10 m	Bluetooth: Medium BLE: Very Low	Low
Mobile communication	2G-GSM, CDMA, 3G-UMTS, CDMA2000, 4G-LTE, GPRS	865 MHz, 2.4 GHz	2G: 50–100 kbps 3G: 200 kbps 4G: 0.1–1 Gbps	Entire cellular area	High	High
LoRa	LoRaWAN R1.0	868/900 MHz	0.3–50 kbps	<30 km	Very Low	Medium
RFID	RFID	120 kHz–10 GHz	4 Mbps	<200 m	Low	Low
VLC	VLC	100 kHz	1 Mbps	<6 m	Low	Low
Z-Wave	Z-Wave	900 MHz	40 kbps	<30 m	Low	Low

5. Challenges and Recommendations

Although the use of various communication technologies based on the IoT has brought many benefits to IAQ monitoring systems, the investigation shows that in the development process of the IAQ monitoring system, some ways of using communication technology cannot maximize the system performance, and there are still related challenges in practical application. As shown in Figure 8, the main challenges, further discussions, and suggestions are listed below, according to the application requirements of IAQ monitoring systems.

5.1. Devices

The IAQ monitoring system is oriented to school, office, and residential environments, so there are special requirements for the system. The first is the shape of the device. The indoor monitoring environment is mostly a small area, and more content, especially the portable design of the system, requires monitoring equipment to be as small as possible. But most of the devices in the project are too big to ignore, some of them are bigger than the palm of an adult's hand. In this case, the placement of the device is very limited, which not only reduces the user experience but may also limit part of the monitoring function of the system.

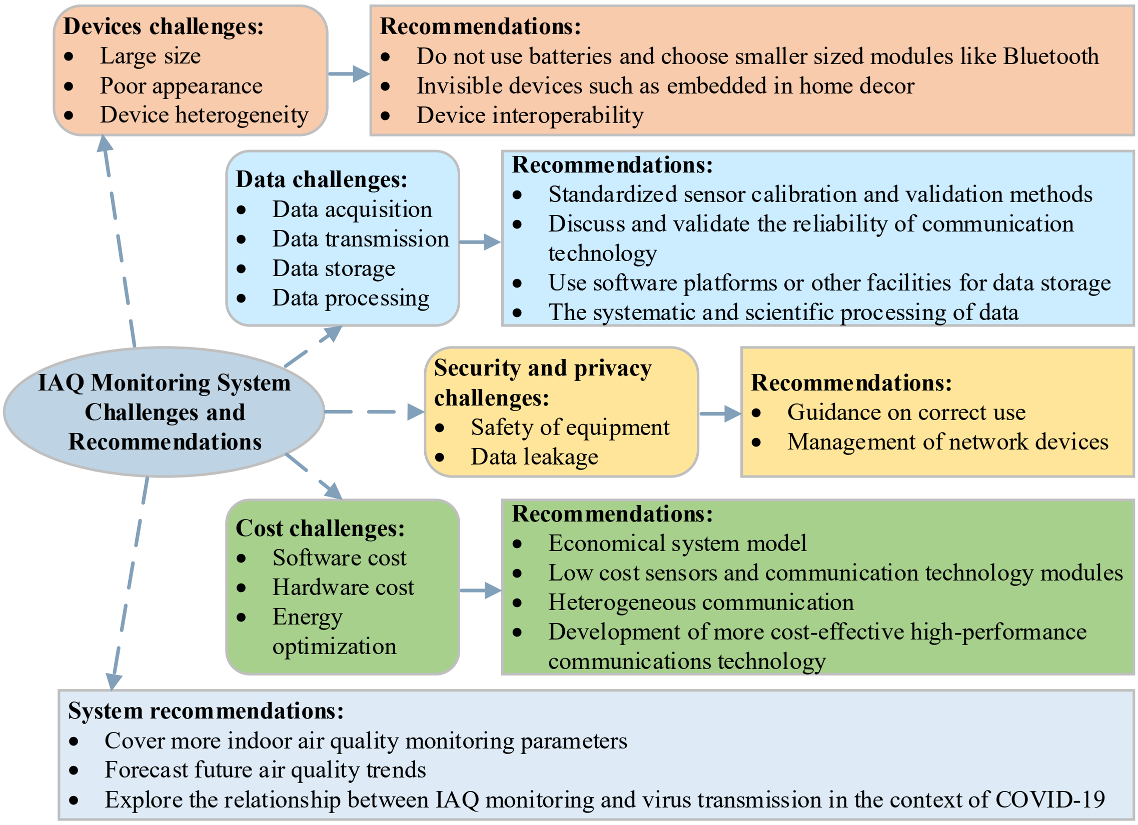

Figure 8. Challenges and recommendations for IAQ monitoring system.

There are two ways to solve this problem. The first is to directly reduce the size, using smaller modules to reduce the final device size. In equipment, the bulk of the main occupation is the battery; this problem is more obvious in outdoor air quality monitoring systems. Since our system is indoor monitoring and can be plugged into power at any time, eliminating the battery can reduce most of the volume. It is this advantage that makes most communication modules battery-free with current technology. In this case, the small nature of the core module itself is more important. In terms of the communication module, Bluetooth is one of the better choices [91]. A Bluetooth module with low-power consumption is far smaller than a coin, which allows it to provide space for other modules, while reducing the volume of the device after it is embedded in the system. The Wi-Fi module also has the characteristic of small size. Although its power consumption is higher than that of Bluetooth, its operation can be guaranteed by the power supply at anytime and anywhere in the indoor environment. Battery-free devices can also be achieved by using RFID technology to collect available RF energy [84]. Secondly, the number of monitoring parameters can be reduced to monitor only one or two major indoor pollutants, which will greatly reduce the volume of equipment [12].

However, directly reducing the size of the system will most likely neuter the function of the system itself; therefore, perhaps "stealth" is a good choice. The simplest method is to embed the monitoring equipment directly into other commonly used interior decoration or equipment, such as lamps [82]. In addition, with the popularity of smartwatches, more and more functions are added to them, and embedding IAQ monitoring systems into them is also an option [59]. Perhaps more novel is the integration of IAQ monitoring systems into a robot. Social robots can interact with residents in a friendly manner, reducing the negative impact of the traditional long-term continuous monitoring process on users. Secondly, the robot is in the process of constant movement, which can monitor IAQ more comprehensively and reduce data errors caused by fixed position monitoring [22,34]. As for the communication module, the use of VLC communication technology can be perfect to solve this problem. LED can be used as a lighting system and a wireless communication system at the same time, which makes it integrated into the indoor environment. This communication mode can be better applied in special environments such as hospitals [13].

The standardization of equipment is very important for the wide application of the system, especially in the smart home. The improvement of interoperability of different communication technologies and data exchange protocols is conducive to the system being suitable for various environments and matching with more intelligent devices. Single air quality monitoring is not enough to meet the demand, and complete systems often involve the processing of air quality monitoring data and cooperation with other equipment, such as HVAC systems, to ensure acceptable IAQ. But communication problems often arise between various devices from manufacturers or companies with different technologies and standards. With the development of communication technology, such as the rapid development of 5G, as a communication technology that can carry more data, 5G will go deep into all fields and has certain development potential in IAQ monitoring. However, the lack of interoperability will make it more difficult to update existing systems. In addition, the large amount of data continuously generated by the device and the access of other devices can cause the network architecture of the device to fail, which cannot be easily resolved with complex heterogeneous devices. Considering the popularity of Wi-Fi in smart homes, it is suggested to use Wi-Fi as the main communication technology for system equipment in ordinary environments, such as the home. However, if the system does not require many updates and pursues low-cost and low-power consumption, this problem can be ignored.

5.2. Data

Data collection, transmission, storage, and processing, need to be solved in the system. In terms of data acquisition, since most IAQ monitoring systems purchase off-the-shelf sensors, it is common practice to use sensors to develop equipment without any prior testing. To compound the problem, studies have shown that some low-cost sensors can indeed have very high measurement errors compared to professional-grade reference devices [17]. In this case, the standardized practice, calibration, and verification of sensors can effectively guarantee the accuracy of data [98]. The transmission of data is also important. Compared with wired communication, wireless communication technology has more interference, such as environmental noise, and the same frequency signal interference. In heterogeneous devices, data loss may occur when faults occur due to different communication technologies. In this review, there is little discussion on the reliability of network communication, and only some papers carefully discuss the packet loss rate of their communication protocols or the reliability of sensor node-to-gateway communication [25]. Therefore, on the premise of ensuring the effective operation of the system, it is very important to discuss and select the appropriate communication technology of transmission distance based on the requirements. For example, VLC communication technology is not suitable for the indoor environment with more occlusion, because once the light is blocked, the communication process will be completely interrupted. The IAQ monitoring system may suffer from various failures during operation, such as communication failures caused by power outages, etc. Appropriate power outage mechanisms should also be considered to solve related failures [62]. Sensors are constantly generating data, and storing large amounts of data is a huge challenge. As a result, the need for data storage has led to the use of various software platforms and facilities, with real-time data and analysis stored in the cloud being the most common practice today. This method makes data storage and use more convenient, provides resources for further analysis, and opens up more possibilities for the application of the system, such as visual display and analysis of data [32]. In the era of data explosion, a more reliable, systematic, and scientific way to deal with data is needed. Data mining is one of the effective processing methods and will be paid attention to in future applications.

5.3. Security and Privacy

Security is one of the great challenges faced by IAQ monitoring systems, which is divided into the safety of the equipment itself and data security, that is, user privacy security. In terms of the system itself, proper design is very important. This means that the system is in the process of ensuring the maximum safe operation, as far as possible, to simplify the user's use process, reduce the user's operation difficulty, especially in the face of the elderly or children's home IAQ monitoring system. Safe packaging and correct installation location are also important. Secondly, in the use of communication technology, reducing the impact of EMI on human health and electronic equipment also needs to be considered.

Data safety is also very important. The monitoring data of IAQ can intuitively show users' living and working conditions in the monitored environment. For example, indoor lighting times or change in carbon dioxide concentration can reflect people's sleeping and working time rules. The lack of security in the communication process may lead to the theft of users' private data, attract malicious attackers, or send wrong information to harm the users' security. In London, approximately 27% of Wi-Fi networks are poorly secured or not secure at all [109]. To solve this problem, we can start from many aspects, such as authorization, authentication, and access control. Only 2 of the 91 papers considered and solved data privacy-related issues, and they protected privacy in the two processes of storage and transmission, respectively. The channel in the IoT platform can be set to private so that the data in the cloud is secured [14]. Marques and Pitarma [50] designed a system in which end users use Wi-Fi-enabled mobile devices, such as smartphones, to connect hot spots and configure service set identifiers (SSID) and required Wi-Fi passwords. In addition, when installing the program, the system supports an easy installation process that can be carried out by the end-user. On one hand, the easy configuration feature avoids installation costs. On the other hand, this feature avoids the "invasion" of privacy related to the entry of unknown persons into the home of the end-user. Therefore, adding proper data encryption and proper authentication will help improve device security.

5.4. Cost

Cost control is one of the important issues to be considered in system development. Cost reduction is the main impetus to promote IAQ monitoring systems in homes and schools. Firstly, in terms of software, the cost involves the development, maintenance, and deployment of the system, as well as the continuous subscription of the IoT platform. Reducing software costs is also a big challenge for many researchers, so it is important to design and develop an economic model. In the hardware part, choosing low-cost sensors and communication modules can reduce the cost of the system. Due to a large number of applications of low-cost sensors, there have been reviews and discussions [17]. In terms of communication, the use of wired communication can reduce the cost to a certain extent, but it also limits the realization of some functions of the system, such as the use of I2C or UART communication technology [46,71]. Wired communication cannot flexibly change the detection position, which will significantly reduce the effect of air quality monitoring in more complex indoor environment. The most widely used wireless communication technologies also have their advantages and disadvantages. The system based on ZigBee registers a small range and exhibits poor through-wall performance, complex protocol, and inordinate price; the network is also exclusive and incompatible with devices in the market. The cost of Wi-Fi communication technology is slightly lower than ZigBee, especially its promotion cost, which is lower than other communication modes [60]. The ESP8266 module is the main choice for many people. However, the problems of small transmission range, high power consumption, and fewer sensor nodes that can access the system also need to be considered. Secondly, low-power Bluetooth is very cheap in terms of price, in addition to its small communication range [48]. Although mobile communication is expensive, many systems still choose this communication mode because of its large transmission range. Therefore, in terms of the selection of communication technologies, we should proceed from the actual needs and choose communication technologies with lower-cost and low-power consumption on the premise of meeting needs [5]. However, the existing problem is still that only by sacrificing part of the communication function can the cost be reduced. In addition to developing more economical high-performance communication technology, heterogeneous communication can also solve this problem to a certain extent. In the link that requires communication distance, the communication technology with slightly higher cost and power consumption is selected, and in the link that requires less communication technology, the communication technology with low-cost and power consumption can achieve the win-win situation of performance and economy.

5.5. System

With the development of the economy and the improvement of science and technology, users have higher and higher requirements for the performance of IAQ monitoring systems. Where the system is going is one of the challenges. On the one hand, the extensive use of all kinds of indoor appliances, such as printers, leads to a variety of indoor air pollution sources. The IAQ monitoring system has to consider adding some parameters based on traditional temperature and humidity and carbon dioxide monitoring parameters when facing the specific indoor environment. According to the survey, there are more and more kinds of project monitoring parameters in the past decade, and more than 57% of projects have more than five kinds of monitoring parameters. It will lose its monitoring significance if the data generated by a large number of monitoring parameters are not effectively utilized and processed. Some projects use existing standards to perform simple visual processing on the collected data and directly display it to users in the form of web pages and mobile apps [32,33,39,91], or set a warning threshold to remind users by email or SMS [14,75].

However, today's requirements for data processing are not limited to traditional statistical processes. Based on monitoring air quality, analyzing data to predict future air quality trends has become one of the new hot research directions. Although this study has been started in 2015 [95], its research and application are not widespread due to the high error rate. However, since 2019, six of the papers in this review have predicted monitoring parameters. Due to the complexity of data processing, five of them have predicted single parameters. Carbon dioxide is not only an important monitoring parameter but also the most important prediction parameter. Four of the five were for carbon dioxide, and the remaining one was for PM_{10}. They used a variety of algorithms, including artificial neural networks, auto-regressive moving average (ARMA), auto-regressive integrated moving average (ARIMA), support vector regression, XGBoost Regressor, and Compact Prediction Tree [38,39,41,43,60]. Mumtaz et al. [29] used the Long and Short Term Memory (LSTM) model to predict the six parameters with an accuracy of 99%. The prediction of future changes in air quality parameters marks a breakthrough in the study of IAQ monitoring systems, which means that people can take more active measures in the face of air quality than monitoring and remedial programs.

The requirements for the integrity of the IAQ monitoring system have always existed, and the system should consider solving the air quality problems while monitoring them. Many projects have already taken action, and cooperation with other equipment, such as ventilation equipment, can automatically realize the control of IAQ and ensure a good indoor air environment [30,36,45,55].

In the future, there are more requirements for the development of IAQ monitoring systems, covering more pollutants, more accurate sensors, more reliable communication, more effective data utilization, more perfect functions, and safer and cheaper products. In addition, social distancing in the wake of the COVID-19 pandemic has led to more people spending more time indoors. Poor air quality in a closed environment will be conducive to the spread of the virus, and monitoring of the indoor environment becomes more important. The survey shows that a number of projects have begun to conduct new research on IAQ monitoring systems in the context of the COVID-19 epidemic [26].

6. Conclusions

In this study, we review the scientific literature on the development of communication technologies in IAQ monitoring systems to address the growing grey documentation and scattered information. The latest developments in this field are studied to gain insight into emerging trends in technology applications by investigating and classifying related work, and to be particularly helpful to researchers developing new devices.

The number of studies on IAQ monitoring systems is increasing year by year. Most of the projects have some similarities, that is, the choice of popular monitoring parameters and communication technology is universal. However, in specific application scenarios and conditions, different projects show certain personalization. Ninety-one papers were reviewed and classified by category, year, and nationality of the author. The application of various communication technologies in the IAQ monitoring systems from 2010 to 2021 is discussed in detail. The results show that each communication technology has its advantages and limitations, and different wireless communication technology is suitable for different scenarios. In addition to the special monitoring parameters selected according to needs, the choice of communication technology also varies according to the needs. They are either wired or wireless, single, or combined. However, most projects prefer the more advanced and mature communication technology as the communication tool of their systems. The three most popular communication technologies on the market are Wi-Fi, ZigBee, and Bluetooth, but emerging technologies, such as 5G and other high-speed communication technologies, could still have a big impact on the current situation. To adopt more appropriate emerging communication technologies, researchers must be aware of emerging trends and technologies. We also carried out an in-depth analysis of different articles and analyzed the current problems and challenges of IAQ monitoring from five aspects: devices, data, security and privacy, cost, and system. To solve these problems, we also put forward the corresponding suggestions, based on which we pointed out the future development direction of IAQ monitoring systems. In particular, low-cost, high-performance solutions with low maintenance, energy efficiency, ease of operation, and a robust architecture are required.

This review of the literature may not be comprehensive and perfect, but it also reveals some problems and directions. The research and development of communication technology is rapid, but in the IAQ monitoring system, the related research of communication technology still lacks some attention. Few analyses and studies have been done on the communication technology specially designed for IAQ monitoring to optimize the communication technology selection in system development. However, it is believed that with the development of communication technology, the combination of IAQ monitoring research and communication technology will be more mature, while other new technologies will gradually be applied to IAQ monitoring research, and the technology of IAQ monitoring will be more mature and diverse.

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Abbreviations

A	Ammonia/NH3	NO_2	Nitrogen dioxide
AP	Air Pressure/Atmospheric Pressure	NOx	Nitrogen oxides
AV	Air Velocity	O_2	Oxygen
BLE	Bluetooth Low Energy	O_3	Ozone
BTEX	Benzene, Toluene, Ethylbenzene, Xylene	P	Propane/C3H8
BZ	Benzene	PM	Particulate matter
C1	CO/Carbon monoxide	PM2.5	Fine particles with a diameter of 2.5 µm (µm) or less
C2	CO_2/Carbon dioxide	PM10	Particles with a diameter of 10 µm (µm) or less
Cl_2	Chlorine	PM20	Particles with a diameter of 20 µm (µm) or less
E	Ethanol	RH	Relative Humidity
F	Formaldehyde/HCHO	SO_2	Sulfur dioxide
H	Humidity	SO_3	Sulfur trioxide
H_2	Hydrogen	T	Temperature
LL	Light Level/light luminosity	TVOC	Total Volatile Organic Compounds
M	Methane/CH4	UVI	Ultraviolet Index
NA	Not Available	VLC	Visible Light Communication
NL	Noise Level	VOC, VOCs	Volatile Organic Compounds

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