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Review

Internet of Things (IoT) Technologies for Managing Indoor Radon Risk Exposure: Applications, Opportunities, and Future Challenges

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Abstract: Radon gas is a harmful pollutant with a well-documented adverse influence on public health. In poorly ventilated environments, that are often prone to significant radon levels, studies indicate a known relationship between human radon exposure and lung cancer. Recent technology advances, notably on the Internet of Things (IoT) ecosystem, allow the integration of sensors, computing, and communication capabilities into low-cost and small-scale devices that can be used for implementing specific cyber-physical systems (CPS) for online and real-time radon management. These technologies are crucial for improving the overall building indoor air quality (IAQ), contributing toward the so-called cognitive buildings, where human-based control is tending to decline, and building management systems (BMS) are focused on balancing critical factors, such as energy efficiency, human radon exposure management, and user experience, to achieve a more transparent and harmonious integration between technology and the built environment. This work surveys recent IoT technologies for indoor radon exposure management (monitoring, assessment and mitigation), and discusses its main challenges and opportunities, by focusing on methods, techniques, and technologies to answer the following questions: (i) What technologies have been recently in use for radon exposure management; (ii) how they operate; (iii) what type of radon detection mechanisms do they use; and (iv) what type of system architectures, components, and communication technologies have been used to assist the referred technologies. This contribution is relevant to pave the way for designing more intelligent and sustainable systems that rely on IoT and Information and Communications Technology (ICT), to achieve an optimal balance between these two critical factors: human radon exposure management and building energy efficiency.

Keywords: radon; radon management; IAQ; IoT; cyber-physical systems; sensor systems; cognitive buildings; energy efficiency

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1. Introduction

Radon is a radioactive gas considered as the leading cause of lung cancer among non-smokers, according to studies on indoor radon conducted in Europe, North America, and Asia. These studies show that lung cancer due to indoor radon exposure may range from 3% to 14% of all population [1,2]. Due to the prominence of granite rocky soils with abundant amounts of uranium, many territories show high potential for the occurrence of natural ionizing radiation, like the one caused by indoor radon gas accumulation. Thus, as concerns regarding buildings' energy efficiency emerge (thermal insulation, tight windows, and high-performance ventilation systems), indoor radon occupants' exposure in airtight buildings tends to rise [1,3]. The main problem with indoor radon gas exposure is that it increases public health risk to lung cancer, which is well-known and has been studied for many years by the World Health Organization (WHO) [2]. To assess radon concentration, several technologies are available for experimental atmospheric testing, as well as in other fields such as hydrology and geochemical exploration [4]. Still, nowadays, many low-cost IoT systems are emerging for monitoring indoor radon gas and the most relevant will be addressed in this work. The main goal is to systematize recent advances in the design of Cyber-Physical Systems that take advantage of IoT technologies for radon risk management, which are of great value for integrating the so-called cognitive buildings, and therefore contributing to the reduction of occupants' exposure to radon gas.

The adopted methodology was based on the research of scientific documents focusing on technologies currently used for the development of CPS-based systems for radon management, that has been specifically designed to include indoor radon monitoring and management. Moreover, the definition of relevant criteria is crucial for the comparison between the most relevant features of each identified system, in a table format, and the preparation of a critical analysis and discussion.

This article overviews the most relevant concepts and the legal framework regarding indoor radon exposure, as well as its relationship with the building's energy efficiency, followed by the description of the adopted research methodology. Following, a review regarding state-of-the-art concepts, techniques, and technologies for indoor radon management is presented. Lastly, a critical analysis of the obtained results is undertaken, and a final discussion is put forward with a focus on identifying current opportunities and future challenges within the topic.

2. Compatibility between Indoor Radon Exposure and Buildings' Energy Efficiency Improvement

2.1. Radon Public Health Risk

Radon is a natural radioactive gas that belongs to the noble gas family, characterized by being invisible, odorless, and tasteless. It is released from the decay chain of uranium to the atmosphere by emanation, mainly from the mineral grains in soils and granitic rocks, and it is transported to the surface of the earth by exhalation. Radon exhalation is driven through the porous zones of minerals, carried out by the air and/or through the water. In smaller amounts, radon can also be liberated from the construction materials of buildings and water supply systems [5].

Radon can enter the body by inhalation, ingestion of drinking water, food, and der-mal exposure. Nevertheless, since it is ubiquitous in the outdoor atmosphere, inhalation is the primary source of human radon radiation exposure. Outdoors, radon level varies from 5 to 15 Bq/m^3, and it is consensual among the scientific community that concentration in this range does not offer any kind of public health concerns. However, indoors the scenario is different due to the lack of ventilation since in enclosed spaces indoor radon concentration can be considerably higher than outdoors, varying from 10 to more than 10,000 Bq/m^3 [5]. Furthermore, people spend most of their time inside buildings, where they live, work, shop, and relax. To guarantee this protection, the International Agency for Research on Cancer (IARC) in 1988, in Lyon, classified radon as a carcinogenic agent belonging to the 1st group-carcinogenic for humans, alongside other agents such as smoking tobacco, nickel, particles resulting from diesel-burning, etc. According to the WHO, it is recognized worldwide that radon and its direct descendants are inducers of pulmonary tumors in humans [6].

The higher the radon concentration in the air we breathe and the longer the exposure time, the greater is the risk of developing lung cancer. According to several studies [7–9], the risk increases linearly due to long-term permanent exposure to high radon concentrations within the buildings. In general, radon is the major contributor to the ionizing radiation dose to which the human being is naturally exposed, and it is, therefore, essential to adopt all measures that can mitigate the presence of this gas indoors [2]. Sources of ionizing radiation include high voltage machines—used in radiotherapy treatments or in therapeutic diagnosis, radioactive materials—natural or man-made, and cosmic radiation that can reach the earth's surface. External exposure to ionizing radiation occurs when the radiation source is outside the body, deposited on the skin or clothes, such as dust, liquid, or aerosols, and can be removed simply by washing. Internal exposure occurs when the radioactive material is inhaled, ingested, or absorbed by the skin. These materials can be dispersed by the human organism through physical, chemical, and biological processes causing radiation exposure to other parts of the body [10].

2.2. Radon Level Measurement Units

The radon decay speed in the air is measured in becquerels per cubic meter (Bq/m^3) or picocuries per liter (pCi/L), where 1 pCi/L equals 37 Bq/m^3 and 1 m^3 equals 1000 L:

- Becquerels per cubic meter corresponds to the International System (SI) of Units for measuring the rate of radioactive decay, being widely adopted in Europe. One becquerel per cubic meter corresponds to 1 nuclear disintegration per second within a cubic meter of air;
- Picocuries per liter is a measure of the rate of radioactive decay of radon. One pCi is one trillionth of a Curie, 0.037 disintegrations per second, or 2.22 disintegrations per minute.

Depending on the country's national law, acceptable radon levels vary. A generally accepted action level, established by the WHO, is 100 Bq/m^3, or 2.7 pCi/L. If this level cannot be implemented under the prevailing country-specific conditions, then the upper limit should not exceed 300 Bq/m^3, or 8 pCi/L, as required for most European countries. For indoor radon concentrations higher than 300 Bq/m^3, it is advised to take remedial action to lower the radon level [2].

Required by federal law, the pCi unit is used in the United States of America (USA). According to the US Environmental Protection Agency (EPA), an action level of 4 pCi/L is the standard, above the WHO specified level [10,11]. A value of 4 pCi/L corresponds to approximately 12,672 radioactive disintegrations in one liter of air for 24 h [12].

Another important unit is the Sievert (Sv) that represents the radiation exposure dose that the human body receives. The larger the value expressed in sieverts, the larger the effects of radiation to which the human body is exposed [6].

2.3. Indoor Radon Management

The amount of radon that reaches the terrestrial surface depends on factors related to the uranium content in the bedrock, soil permeability, mineral porosity, and the potential existence of failures or cracks in the soil substrate. Outdoor radon concentrations are on average about 10 Bq/m^3, representing no harm to human health. On the other hand, radon penetration from foundation soils and rocks to the building's environment determines an increase of indoor concentration due to the atmospheric pressure difference between outdoor and indoor air. Usually, the indoor air pressure is lower thus facilitating the gas entry, mainly through the cracks in the floors and walls, or in the plumbing, or even through the construction materials joints, etc., [13].

Indoor radon concentration varies both on a daily and seasonal basis, therefore it does not show a constant value throughout the day or the year. Radon concentration tends to be higher at night than during the daytime and reaches a higher value in winter when compared to other seasons [2]. In the summer, natural ventilation by windows opening causes air movement and consequently lowers indoor radon concentrations. On the opposite, in winter buildings are airtight and the heating systems are generally on, so heat movement contributes to air pressure differences that generate a suction effect of the radon present in the soil.

Usually, the most effective way to improve indoor air quality is to eliminate individual sources of pollution or to reduce their emissions. In many cases, source control is a more cost-effective approach to protect IAQ, because for increasing the ventilation rate it is only necessary to enlarge the number of air renovations. This approach is adequate for lowering indoor air pollutants' concentration; however, it can drastically raise energy consumption for heating and compromise energy efficiency.

2.4. Energy Efficiency Management vs. Indoor Radon Exposure

The new energy efficiency challenges arising both from increasingly restrictive regulatory frameworks [14–16] and a more demanding society seeking more comfortable and less costly buildings, brought profound transformations into the building's design [17]. With the emergence of new construction methods and solutions—high-performance windows, new thermal insulation technologies, high-efficiency air-conditioning systems, and other climatization devices—the paradigm of Nearly Zero-Energy Buildings (NZEB) was built. Therefore, the current tendency of modern times is to reduce energy consumption by improving thermal insulation and investing in the replacement of conventional windows by airtight double-glazed frames, and by reinforcing the performance of heating and cooling systems. Hence, the focus is set on buildings' energy efficiency and thermal comfort reinforcement instead of promoting its balance along with indoor radon exposure and an overall IAQ improvement [18–23].

The lack of balance between these variables (energy efficiency versus indoor radon exposure) has led to the construction of "hermetically" sealed buildings, with very reduced ventilation openings and low air renovation, where automated air conditioning systems has ensured the control of air temperature and relative humidity, however, completely ignoring radon levels and its relation to IAQ improvement [24–27].

In addition to an increased radon exposure scenario new sources of indoor air contamination have emerged, essentially composed of toxic materials used for finishing materials and furniture, such as paints and varnishes, wallpapers, adhesives, carpets, among others [28]. The progressive reduction in the air exchange rates is associated with the increased concentration of physical, chemical, and biological pollutants in indoor environments. Therefore, to prevent occupants' health problems, it is crucial to increase indoor air renovation [29], promoting the mitigation of radon levels and the elimination visible fungi or mold growth, and keeping the interior room well ventilated, clean, and sanitized. Ventilation stands out as a fundamental factor in radon management, improving overall IAQ, and it can be provided by either natural or mechanical means, but both need a specialized design to avoid malfunctioning [30–35].

Already in the 1980s, the specialists have recognized the radon problem along with many other air pollutants that affect occupants' health and well-being [36]. In 1982, this phenomenon took huge proportion with the Sick Building Syndrome (SBS), at that time recognized by the World Health Organization (WHO) as a public health problem [37], after 34 confirmed deaths and 182 contaminations by indoor air through Legionella pneumophila, at the Hotel Bellevue-Stratford (Philadelphia, USA) [38,39].

IAQ assessment is related to the characterization of a set of polluting sources arising from three main origins: physical origin (lighting, noise, electromagnetic fields, temperature, humidity); chemical origin (carbon dioxide, carbon monoxide, VOC, nitrogen dioxide, ozone, formaldehyde, sulfur dioxide, ammonia, radon); and biological origin (bacteria, fungi, viruses, protozoa, arthropods, animal excrement in general) [40,41]. Thus, a building can be considered "sick" when [42]:

- Around 20% of building occupants exhibit symptoms for more than 2 weeks, such as headaches, eye, nose, and throat irritation, nausea and malaise, skin problems, con-centration difficulties, fatigue, sensitivity to odors, etc.;
- The cause of the symptoms is not known;
- Complainants' symptom relief is checked shortly after leaving the building.

Contamination of the environment can also trigger new disorders, or even aggravate pre-existing diseases (such as rhinitis and asthma) [4]. According to the WHO, up to 30% of European buildings built between the 1970s and 1980s are likely to suffer from this type of syndrome, with possible sources of contamination being both pollutants that come from the outdoor air and those generated indoors [43].

To prevent issues related to “sick buildings” in 1987, WHO published the 1st edition of the “Air Quality Guidelines for Europe” [44], containing the health risk assessment of 28 chemical contaminants in the air. In 2000, it published the 2nd edition which includes a section on indoor air pollutants, being radon gas one of them [45]. In 2005, it updated the air quality guidelines and developed specific guidelines for IAQ [46]. In 2009, it published the guidelines for the protection of public health from health risks due to dampness, associated microbial growth, and contamination of indoor spaces [37]. In 2010 it published the standard values for 9 indoor air pollutants [47] following the recommendation that came out of the meeting with international experts held in 2006 within the framework of the European air quality program.

Ideally, indoor environments must combine low radon concentration, IAQ, energy efficiency, and thermal comfort [48]. Energy efficiency projects aim to reduce energy consumption to acceptable levels, and consequently increasing thermal comfort, however, its compatibility with indoor radon concentration is not trivial, as it covers the interaction of numerous variables that increase the complexity of the study. On the other hand, thermal comfort depends not only on external variables such as color, shape, light, ambient temperature, relative humidity, air quality, air exchange rate, etc., but also on people’s behavior [48–53]. Radon levels and IAQ depend on variables that are common to thermal comfort, but contain others that are distinct, namely the presence of odors, the concentration of microorganisms or airborne dust, the noise level, and lighting, among others [54].

The “sick buildings” analysis has been an object of numerous scientific studies by several authors, who present a wide range of solutions [34,43,48,55–58].

2.5. IoT Technologies Contribution

Among the studies related with indoor radon exposure management and the previous “sick buildings” overview, Internet-of-Things appears as an emerging area useful in various domains and applications, composed of sensor networks capable of working in real-time. These sensors are installed at strategic locations in buildings and periodically collect relevant data for storage, processing, and analysis on a central server (in the cloud). Afterward, the necessary corrective or preventive actions can be taken automatically, and practically in real-time [59].

Thus, IoT technologies are perhaps the ideal way to assess and manage radon levels and IAQ autonomously, in all types of buildings (commercial, scholar, offices, factories, service provision, etc.). The contribution of this research is relevant to pave the way for designing more intelligent and sustainable systems that rely on IoT and Information and Communications Technology, to achieve an optimal balance between these two critical factors: human radon exposure management and building energy efficiency [60–64].

2.6. Legal Framework

In Europe, the reference level for radon concentration is 300 Bq/m^3 according to the European Union (EU) legal requirements, established in the Council Directive 2013/59/Euratom, of 5 December 2013, laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation [65] (transposed by member states according to Table 1). According to the legal framework, the reference level is not a threshold value that cannot be ever exceeded, but rather a guide value to benchmark a safe degree of health protection. Whenever indoor radon concentration during an assessment campaign exceeds the so-called reference level, it may be reasonable to consider mitigating actions to reduce occupants’ exposure by lowering radon levels.

Table 1. 2013/59/EURATOM Council Directive national transposition by the Member States. Data obtained from [66].

Country	Publication Date	National Transposition Root Measures
Austria	29/07/2020	*Bundesgesetzblatt II Nr. 339/2020*—General Radiation Protection Ordinance 2020
Belgium	17/05/2018 19/08/2020	*Law 2018/202303*—Amendment of the Federal Agency for Nuclear Control (FANC) *Arrête Royal du 20/07/2020 (2020015187)*—Amendment of *Arrête Royal du 20/07/2001*
Bulgaria	04/05/2018 19/04/2019	*Държавен вестник брой37*—Radiation protection of radionuclides sources activities *Наредба № РД-02-20-1 от3.04.2019*—Requirements for radon protection buildings
Croatia	09/03/2018 27/12/2018	*NN 24/2018 (458)*—Radiation protection against ionizing radiation *NN 118/2018 (2380)*—Radon action plan 2019–2024
Cyprus	21/12/2018	*L.164(I)/2018*—Radiological safety and security law of 2018
Czechia	10/08/2016 23/12/2016	*Zákon č. 263/2016 Sb.*—The atomic act *Vyhláška č. 422/2016 Sb.*—Radiation protection and security of radionuclide sources
Denmark	16/01/2018	*Lovtidende A Nr. 23 Strålebeskyttelsesloven*—Ionizing radiation and radiation protection
Estonia	26/06/2018 30/08/2018	*RT I, 26.06.2018, 6*—Amendment of the radiation act *RT I, 03.08.2018, 4*—Reference level for radon in workplaces and measuring procedure
Finland	13/11/2018 29/11/2018 05/12/2018	*SäädK 859/2018*—Radiation act *SäädK 1034/2018*—Government decree on ionizing radiation *SäädK 1044/2018*—Ministry of social affairs and health decree on ionizing radiation
France	05/06/2018 31/12/2020	*Décret n° 2018-434/Décret n° 2018-437/Décret n° 2018-438* National action plan 2020–2024 for radon risk management (4th radon plan)
Germany	27/06/2017 29/11/2018 24/04/2019	Radiation Protection Act (StrlSchG) Radiation Protection Ordinance (StrlSchV) Radiation Protection Act (StrlSchG)—Publication of the radon action plan
Greece	20/11/2018 18/05/2020	*Τεύχος-A 194, Αριθμ. 101*—Basic security standards against ionizing radiation *Τεύχος-B 1881, Αριθμ. 43374*—National action plan for long-term radon exposure risks
Hungary	09/07/2018 13/03/2019	*21/2018. (VII. 9.) EMMI rendelet*—Protection to ionizing radiation *1114/2019. (III. 13.) Korm. határozata*—Adoption of the national radon action plan
Ireland	15/01/2019	*Statutory Instruments (S.I.) No. 256*—Ionizing radiation regulations 2018
Italy	12/08/2020	*Decreto Legislativo 31 luglio 2020, n. 101*—Protection against ionizing radiation
Latvia	30/12/2015	*Ministru kabineta noteikumi Nr. 752, 22.12.2015*—Ionizing radiation
Lithuania	03/07/2018 30/11/2018	*Įstatymas Nr. XIII-1283*—Amending law No. VIII-1019 on radiation safety *Lithuanian hygiene standard HN 73:2018*—Basic radiation protection standards
Luxembourg	07/06/2019 05/08/2020	*Journal Officiel du Grand-Duché de Luxembourg Mémorial A389*—Radiation protection act *Journal Officiel du Grand-Duché de Luxembourg Mémorial A528*—Radiation protection
Malta	25/05/2018 05/05/2020	*Gazetta Nru. 19,996*—Nuclear safety and radiation protection act *Gazetta Nru. 20,400 L.N. 184*—Basic safety standards for ionizing radiation (amendment)
Netherlands	07/11/2017	*Décret royaux 404*—Basic safety standards for radiation protection
Poland	11/09/2019 12/02/2021	*Dziennik Ustaw 2019 poz. 1792*—Consolidated text of the atomic law act *Monitor Polski 2021 poz. 169*—Radon action plan for indoor long-term risks
Portugal	03/12/2018	*Decreto-Lei n° 108/2018*—Legal framework for radiological protection
Romania	25/06/2018 26/06/2018 25/07/2018	*Ordinul nr. 752/3978/136/2018*—Rules on basic radiological safety requirements *Ordinul nr. 61/113/2018*—Management of nuclear or radiological risk *Hotărârea de Guvern nr. 526/2018*—Radon national action plan
Slovakia	27/04/2017	*Zákon č. 96/2017*—Amendment to act No. 541/2004 on the atomic act
Slovenia	26/04/2019 20/03/2018	*Uradni list št. RS 26/2019*—Amendment of ionizing radiation protection act RS 76/2017 *Uradni list št. RS 18/2018*—Regulation on the national radon program
Spain	31/10/2019 24/06/2020	*Real Decreto 601/2019 (B.O.E. num. 262/2019)*—Radiation protection of individuals *Real Decreto 586/2020 (B.O.E. num. 175/2020)*—Nuclear or radiological emergency
Sweden	03/05/2018 31/05/2018	*Svensk författningssamling (SFS) 2018:506*—Radiation protection regulation *Strålsäkerhetsmyndighetens författningssamling (SSMFS) 2018:10*—Radon in workplaces
UK [1]	01/01/2018 17/04/2018 01/09/2018 27/03/2019	*Statutory Instruments (S.I.) No. 1075*—The ionizing radiations regulations 2017 (IRR17) *S.I. No. 242*—The ionizing radiation (BSS) (misc. provisions) Regulations 2018 *S.I. No. 428*—Environmental permitting (amendment) (No. 2) Regulations 2018 *S.I. No. 703*—Radiation Regulations 2019 (REPPIR)

[1] Member State until 31 January 2020.

Since July 2018, European Directive 2018/844 [14] is in force amending the European Directive 2010/31/EU [6] on buildings' energy performance, and the European Directive 2012/27/EU [16] on energy efficiency. Guided by European Directive 2018/844, the European Union (EU) is engaged to build up a decarbonized energy system by 2050. To fulfill this objective, the EU must implement energy-efficient measures both for new and existing buildings, to drastically reduce greenhouse gas emissions and consequently decarbonize EU building stock by transforming all buildings (new and existing) into NZEB [67].

3. Materials and Methods

This research was conducted to carry out a state-of-the-art survey on IoT technologies for radon monitoring and active mitigation by using the following research engines: Google Scholar, IEEE Xplore, DOAJ, and PubMed with the search query using the following combination of keywords:

- In Google Scholar (by title):

  allintitle: radon "Air Quality Control" OR IoT OR "Internet of Things"

- In other databases (by all fields):

  ("Air Quality Control" OR IoT OR "Internet of Things") AND Radon

The search will focus on articles and publications related to methods, techniques, and technologies used for radon monitoring and mitigation in indoor or outdoor environments, excluding the remaining. Table 2 includes the criteria defined to assist with the selection of the most relevant publications from the existing databases.

Table 2. Eligibility and exclusion criteria for the survey.

Eligibility Criteria	Exclusion Criteria
Articles or publications that: • Are based on IoT technologies for radon monitoring and management. • Include active sensing IoT devices for radon monitoring and an overview of the system architecture. • Provide insights into relevant methods, techniques, and technologies.	Articles or publications that: • Are duplicated. • Are written in languages other than English. • Are not focused on the survey subject. • Contain unclear details about the used technologies.

The association of radon sensors with IoT technologies is a recent trend, so there are a few reliable studies concerning the integration of monitoring radon concentration campaigns with IoT-based integrated systems. Figure 1 summarizes the flow diagram of the adopted procedure and quantifies the number of processed documents in each specific phase:

- First, from the 46 indexed publications found, all duplicates were removed along with those written in languages other than English;
- Second, from the remaining records, some titles and abstracts were excluded for lack of relevance or because they are not focused on the survey subject;
- Third, the publications that did not refer to integrated systems with active sensing on radon monitoring, or denote the absence of web architectures, and the ones with unclear or incomplete details about used technologies were removed;
- Finally, following this approach, 9 publications that comply with all these requirements were included in the survey.

These baseline studies undertaken by the seminal publications taken as a reference will help to respond to the following questions: (i) What technologies have been recently in use, both in academia and/or available on the market, that integrates radon assessment with IoT technologies? (ii) how do they operate? (iii) what type of radon detection mechanisms do these technologies use? and (iv) what type of system architectures, components, and communication technologies have been used to assist the referred technologies?

An in-depth analysis was implemented to respond to each of the four previous questions, highlighting the innovative functions as well as the best functionalities of the IoT-based architectures and their components (hardware and software). As a result, the limitations, opportunities, and future challenges were discussed and insights into the state-of-the-art of these radon-based and mitigation systems were provided.

This work aims to contribute to the design of better, smarter, and more sustainable systems for indoor radon assessment and control, taking advantage of IoT and ICT technologies. Researchers can use it as a guide for achieving a more transparent and harmonious integration between technology and the built environment. These technologies are crucial for improving the overall building IAQ, contributing toward the so-called cognitive buildings, where human-based control tends to decline, and building management systems are focused on balancing energy efficiency, human radon exposure management, and user experience, among others.

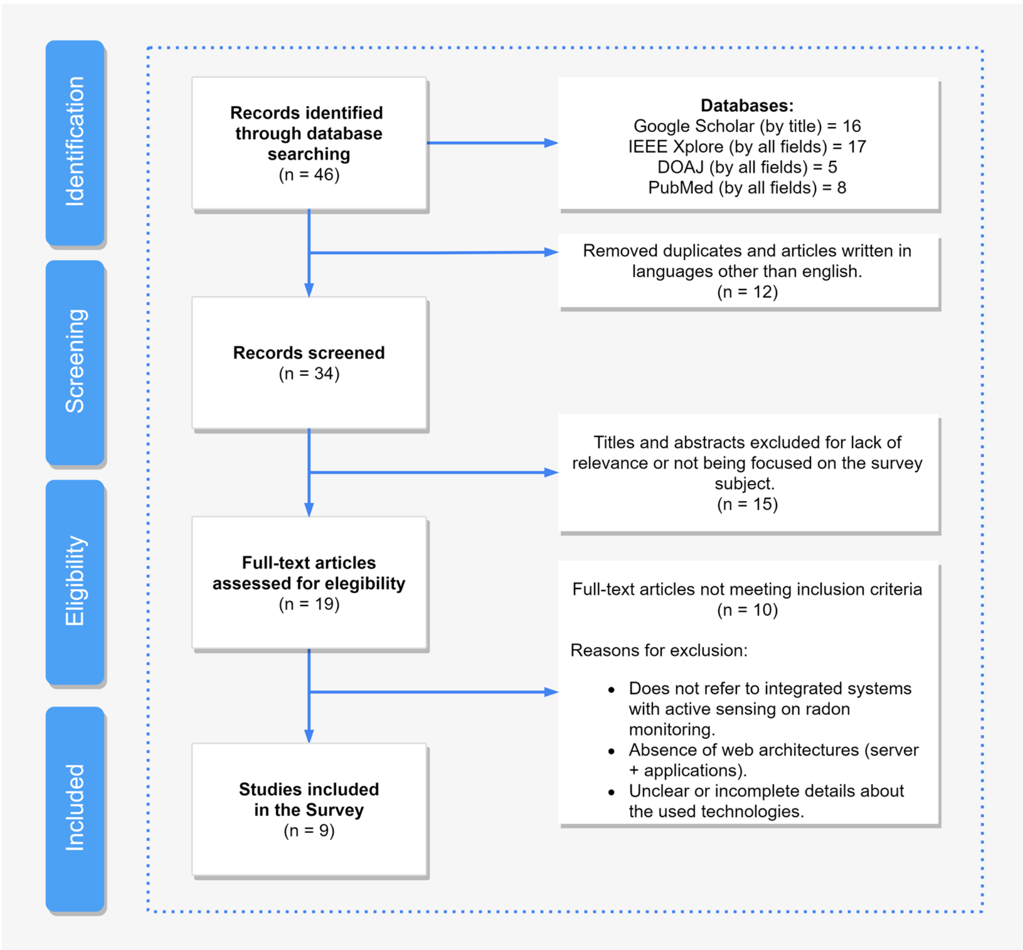

Figure 1. Flow diagram of the adopted methodology.

4. Results

To organize the available information, a hierarchical tree is adopted to compare state-of-the-art technologies for monitoring IAQ as well as the radon mitigation techniques. As it is hard to compare the pros and cons of each solution, to easily engage in compensatory decision-making, the option was to narrow down the number of relevant characteristics into a comparison table presented at the end of Section 4.

4.1. Examined Works

There are two types of radon detection devices: passive and active. Passive detectors are used for measuring radon gas for long periods (3–12 months) without the need for electric energy to function since in many of this devices sampling is carried out by diffusion. They differ from active detector measurements as these can provide continuous measurements or averages by day, week, short-term or long-term and report the results instantly in a digital display [2]. These probes require active components such as pumps or electric energy to carry out sampling and are based on different detection principles: electret ion chambers, scintillation cells, current or pulse ionization chambers, or solid-state silicon detectors [2]. This current investigation only focuses on active detectors-related works.

In [68], Blanco-Novoa et al. presented a cost-effective IoT radon gas remote monitoring system. The IoT device is based on the adaptation of a commercial radon detector (Safety Siren Pro Series 3) interfaced to an ESP8266 MCU. The collected data are then transmitted via Wi-Fi to a cloud database and the results are made available to remote users through a web application that presents a real-time dashboard with reporting capabilities, and a notification service configured to generate alert messages when specific thresholds are exceeded, e.g., 300 Bq/m^3 [65], which may be delivered using distinct mechanisms, e.g., email, SMS. If the threshold is exceeded, an alarm notification is sent to warn users, or automatically activate mitigation mechanisms, such as forced ventilation. After testing the device, the authors concluded that the external hardware (Wi-Fi transceivers and embedded System-on-Chip) do not interfere with radon measurements. Sensor data are collected once an hour for the remote monitoring service, and to guarantee time synchronization and measurements traceability, in the case of network failure, all transmitted messages have a timestamp generated locally at the device, whose synchronization is updated daily via Network Time Protocol (NTP) or forced after a reboot.

In [69], Pereira et al. presented the design and implementation of the RnProbe, an IoT Edge Device, that collects, aggregates, and transmits up to the cloud several IAQ parameters. The RnProbe prototype is based on the RD200M Radon Gas Sensor from FTLab, and is capable of sensing indoor radon level, atmospheric pressure, air temperature, relative humidity, and CO_2 level. These devices transmit IAQ measurements to the cloud for re-al-time processing and analysis. In an alarm situation, the system automatically notifies the building administrator to perform manual or mechanical ventilation to reduce radon gas concentration levels. The common use-case of the detection system is made in three steps: (a) Detects a higher radon level in a specific room of a building; (b) sends an alarm message to the building janitor; and (c) a manual ventilation action is carried out by the building administrator. The conceptual system architecture is an online network with three core elements that depict a common use-case: (i) IoT Edge Devices with LoRaWAN modulation, gateway, and server, (ii) cloud/analytics engine, and (iii) client app/dashboard with notifications. The remaining components are software-based and include an end-to-end security mechanism (AES128 + SSL) and MQTT Secure and HTTPS protocols. The IoT Edge device is equipped with two communication technologies (LoRa and Wi-Fi) for ensuring long-range, low-power, and that the data are always transmitted. More details regarding the overall RnMonitor platform, of which the RnProbe is part, can be found in [70–72], respectively.

In [73], Alvarellos et al. developed a secure and low-cost radon monitoring and alert system, based on the radon gas sensor RD200M with other additional sensors, a processing unit, a communication module, and a backend with open-source technologies to predict radon levels, issue alerts, and to show the data and alert status in a web page. The system is based on an ionization chamber to continuously sample radon levels in a procedure very similar to the real-time situation. The device measures radon concentration, air temperature, relative humidity, atmospheric pressure, some high-level air quality indicators, and has Wi-Fi and Sigfox connectivity. The system architecture has two main components: the sensors and the server. The sensors will send information periodically to the server, which will store the data and make a linear regression-based prediction of the radon level for each device.

The alerts are based on MQTT messages that trigger events to inform interested parties by email, either that the levels are above the threshold or back to normal. The corrective actions must be taken by a human operator (opening windows, turning on airflow control systems, etc.). This work also considers the security of end-to-end communication (HTTPS with SSL) to avoid data forging attacks. To address secure networking, it uses an open-source firewall mainly for load balancing, web content filtering, and reverse proxying for TCP and HTTP-based applications.

In [74], Alvarellos et al. give sequence to the work presented in [73]. This research ex-tends the design implemented in [73] and implements the capability of automatically controlling airflow systems based on the radon concentration as a measure for air quality predictions. Besides this variable, it also monitors the temperature, barometric pressure, relative humidity, and total volatile organic compounds (TVOC). The main objective is to create a fully autonomous system that would maintain the air quality at a certain level. For that, they developed a control device that can be attached to an existing ventilation system and can receive commands from the server to switch it to on/off based on the de-fined metric. If the algorithm predicts a decrease in air quality, it sends a command to the control device to turn on the airflow system they are attached to and located in the same room as the monitoring devices. After the experimental results, the system reactivity was better with a two-hour interpolation window which provided the lowest mean radon concentration, considering as metrics both the measured radon concentrations and the exposure time to high radon concentrations. The authors concluded that the system could achieve an 86% reduction in the radon concentration, maintaining it low for 90% of the time, by having a ventilation system on during only 34% of the time (every week), demonstrating that it is possible to keep indoor air safe using low-cost resources.

In [75], Terray et al. presented the first network of outdoor air radon sensors for monitoring radon diluted in the air of a volcanic environment. To achieve this purpose, a commercial low-cost radon sensor (Algade ÆR Plus) was tropicalized to be operated continuously in harsh conditions (mainly high temperatures and acidic corrosion) and high altitudes with autonomy for several months. The main intention of this work is to study a possible way to predict volcanic eruptions. The system consists of the installation of two stations on Mount Etna volcano, in Italy, at ~3000 m of elevation and the deployment of a private network to transfer the measurements from the stations directly to a server in France. LoRaWAN technology was chosen to connect the sensors, due to its tweaking capabilities, and include a gateway connection to the Internet by SIM card (3G). The two ra-don stations are connected to specific LoRa end nodes that transfer the frames, that contain a few measurement results, to the gateway. The latter then sends the data over the Internet to a data lake, structured with an open-source LoRaWAN Network Server stack. The authors concluded that the sensor tropicalization has proven to be very efficient under harsh conditions for near real-time surveillance of active volcanoes. The LoRa network allowed several months of autonomy with transmission rates near to 100% and very low latency, even with the gateway locked inside a shelter with metallic walls for protection against meteorological conditions.

In [76], Amato et al. developed an innovative open CPS to monitor and control human exposure to ionizing radiation tested with a PIN Diode Radiation Sensor (RN53 from Teviso Sensor Technologies) and front-end electronics. Each prototype node realized in a printed circuit board (PCB) has an intelligent component with inherent physical sensing and actuation capabilities in real-time, as well as mature communication resources. The recent IoT and CPS technologies allow interaction with the monitored environment to implement various policies to mitigate radon gas concentration. It has an open architecture that permits integration with several data sources, and easy adaptation of the services as well as the interface area, according to the different users' requirements. The main com-ponents involve various sensor/actuator nodes twinned with a virtual software agent in cyberspace for data transmission into databases and policy negotiation with the service providers. The processing unit is an SBC to handle the sampling process and timestamps. The data are sent to the application server by 4G modem or Wi-Fi network, using a client/server socket application on TCP/IP connection. In the interface area, there's a versatility to adapt various codes of signs, including a specific mobile app for the evaluation of personal risks related to radon exposition. This interface intends to deal with the lack of involvement of the scientific community in achieving appropriate language codes that can support recognizable and effective communication.

In [77], Medina-Pérez et al. carried out a radon gas monitoring campaign based on a case study to obtain real-time radon measurements and display the results on a website, through a novel IoT architecture based on ITU-T Recommendations Y.4113 [78] and Y.4208 [79], lightweight messaging protocol MQTT, and Node-RED for managing data flows. It is noteworthy, a brief survey of the most popular elements that apply to each of the referred components. The proposed IoT system architecture includes the Radon Scout sensor interfaced to a USB port on a Raspberry Pi 3, a lightweight open-source message broker (Mosquitto), tools for data flow, a management database, and a web server. The authors emphasize that the system supports any type of sensor and combines different measurements on a map and allows the monitoring of many sensors spread across a territory or city with automated measurements. Radon concentrations are stored on the webserver and the web application can sign up and log in, visualize the data in real-time and the sensor locations, and query the radon measurements stored in the database.

In [80], Forsström et al. developed an easy to install, simple to use, and secure IoT platform, aimed at small and medium enterprises (SME) for fast and easy product development, recurring to cheap off the shelf hardware, and standardized protocols. The platform provides means for monitoring sensors on the devices as well as for sending com-mands to actuators. The generic implementation includes a Raspberry Pi computer, an Internet connection, and a ready-to-use open-source solution, prepared by the authors to be downloaded into an SD-card. The edge devices communicate via Wi-Fi using the MQTT protocol, and the messages are handled by a Mosquitto broker that utilizes OpenSSL for TLS-PSK encryption. The platform was tested and evaluated with sensors and actuators in 2 real-world specific use cases: the first one being a radon sensor from MidDec Scandinavia AB attached to a Raspberry Pi 3 A+ to connect to Wi-Fi and persistently save data to an SD-card. The second case was tested with an actuator that includes a ventilation unit from Air Green Sweden AB with a built-in micro-controller and heat exchange system that can keep the warmth indoors but still exchange stale air for fresh air. The results show that this IoT platform can be used to help SME to leverage their existing products into the IoT era but has certain limitations as it scales well only in scenarios up to 50 sensor values per second, mainly due to slow SD-card read/write speed on the Raspberry Pi and its limiting processing power.

In [81], Moreira developed an IoT-based system to reduce radon levels in closed and inhabited environments, mainly consisting of the radon gas sensor RD200M (FTLAb) as-sociated with an automated 5V switch, which allows the control of several 100 mm diameter fans, model Vortice lineo 100 V0, installed on a building. The conceptual design and implementation include an Arduino Uno Rev3, Microsoft SQL Server, and the use of various programming languages (Java, Json, HTML, PHP) and open-source applications. These tools combined result in a web application that stores radon sensor records and permits to manually activate the fans, or automatically by editing a radon threshold value. All communication is done through HTTP protocol. In face of potentially dangerous situations, it also allows the consultation of radon concentrations statistical data, and the author had the purpose of implementing a machine learning algorithm for linear regression that would allow to predict future concentrations and take decisions based on radon and IAQ sensor records. However, the prediction model failed to run due to the malfunction of the sensors and to lack of useful time to order new ones in time to complete the study in a COVID-19 pandemic situation. Nevertheless, the system was tested in a real context, in a dwelling with high levels of radon concentration, and the results showed that it can be applied on a larger scale, on average, there was a 93% reduction in indoor radon concentration over the initial value.

4.2. Criteria for Comparing the Relevant Characteristics

Table 3 summarizes the comparative analysis implemented for the publication selected to develop the survey. In short, most works follow the general guidelines on monitoring radon, hygrometric variables, and other IAQ pollutants, including threshold-based alerts and further corrective actions taken by human operators. Yet, there is already a study, carried out by Alvarellos et al. in 2021 [74], that goes further in fulfilling risk mitigation needs without human intervention and presents a more comprehensive IoT architecture with a prediction model to act preventively before reaching the risk level.

Table 3. Monitoring systems-summary of most relevant characteristics.

Reference	[68]	[69–72]	[73]	[74]	[75]	[76]	[77]	[80]	[81]
Monitor's radon concentration.	✓	✓	✓	✓	✓	✓	✓	✓	✓
Monitors hygrometric variables (temperature, air pressure, relative humidity).	✗	✓	✓	✓	✓	✓	✗	✓	✓
Monitors other IAQ pollutants (CO_2, TVOC, CO, etc.).	✗	✓	✓	✓	✗	✗	✗	✗	✗
Send alerts based on a radon threshold.	✓	✓	✓	✓	✓	✗	✗	✗	✓
Prediction model/algorithm interpolation window capabilities (with radon concentration as the air quality metric).	✗	✗	✗	✓	✗	✗	✗	✗	✗
Prediction model/algorithm capabilities with other measured variables: energy efficiency, thermal comfort, noise pollution, etc.	✗	✗	✗	✗	✗	✗	✗	✗	✗
Corrective actions or measures taken by human operators (manual ventilation, population alerts, etc.).	✓	✓	✓	✗	✓	✓	✓	✓	✗
Equipped with actuators (relays-board to interact with airflow control systems).	✗	✗	✗	✓	✗	✓	✗	✓	✓
Autonomous airflow control system (ventilation system, motorized window, etc.).	✗	✗	✗	✓	✗	✗	✗	✗	✓

After analyzing the selected radon monitoring systems (architectures and components) with consistent information and experimental results, Tables 4–6 present the extracted data for the comparative study. The data extraction was applied to all selected publications where the criteria for the relevant characteristics were organized in groups as follows:

- System-on-Chip (SoC);
- Communication technologies;
- Radon gas sensor;
- Environmental sensors included;
- Back-end web architecture;
- Prototype dimensions, estimated power consumption, and price.

Table 4. Comparative study for radon monitoring technologies.

Criteria	Blanco-Novoa et al. [68]	Pereira et al. [69–72]	Alvarellos et al. [73]
System-on-Chip (SoC):			
Microcontroller (Single-Board Computer)	WeMos Mini D1 ESP8266 Wi-Fi ESP-12F	ESP8266 (Espressif Systems)	Arduino mkr
Based CPU	Tensilica Xtensa Diamond 32-bit (80/160 MHz)	Tensilica L106 32-bit RISC processor (160 MHz)	ARM Cortex-M0 + CPU (48 MHz)
Wireless module	IEEE 802.11 b/g/n transceiver	ESP-WROOM-32	Arduino Mkr Wi-Fi 2020
Cryptographic coprocessor	WEP, WPA, TKIP, AES	-	ATECC508A
Communication technologies:			
Gateway	-	LoRaWAN: Microchip RN 2483	-
Wireless Protocols (available)	Wi-Fi (IEEE 802.11 b/g/n)	Wi-Fi (IEEE 802.11 b/g/n) and LoRaWAN	Sigfox and Wi-Fi (IEEE 802.11 b/g/n)
Hardware communication protocol	-	UART/ADC/OneWire/I^2C	UART/I^2C
Wireless Communications (used):	**Wi-Fi** (licence-free 2.4 GHz and 5 GHz):	**LoRaWAN** (licence-free sub-1 GHz):	**Sigfox** (licence-free sub-1 GHz: 868 MHz):
Center frequency	2.4/5.0 GHz	868 MHz	868,130 MHz
Bandwidth	20/40 MHz	125 kHz	200 kHz (ultra-narrow)
Data rate (bits/s)	<300 Mbps	250 bps~50 kbps	100
Effective isotropic radiated power	-	+14 dBm (receiver sensitivity: −146 dBm)	16 dBm
Constraints	Max. payload 64 KB	Limited message sizes (230 bytes at most)	140 messages/day (ETSI regulations)
Radon gas sensor:			
Radon sensor	Safety Siren Pro Series 3	Radon FTLab RD200M	Radon FTLab RD200M
Academic prototype/Commercial sensor	Commercial sensor (for indoor dosimetry)	Academic prototype (for indoor dosimetry)	Academic prototype (for indoor dosimetry)
Radon detection technique	Photodiode detection for alpha particles	Pulsed Ion chamber	Pulsed Ion chamber
First data out	-	<60 min	<60 min
Data interval	Update's readings every hour (mean, max/min)	10 min update (60 min moving average)	10 min update (60 min moving average)
Sensitivity	-	0.81 cph @ 1 Bq/m^3	0.81 cph at 1 Bq/m^3
Operating range	0~40 °C, RH < 80%	10~40 °C, RH < 80%	10~40 °C, RH < 80%
Measurement range (Bq/m^3)	0~37,000	7~3700	7~3700
Typical accuracy (precision)	±10%	<±10% @ 370 Bq/m^3	<±10% at 370 Bq/m^3
Guaranteed accuracy	±20% or 37 Bq/m^3 (the highest of both)	-	-
Display	LED Display (four-digit seven-segment-based)	None	OLED Display
Other information	Discontinued	Built-in vibration sensor to prevent errors	Built-in vibration sensor to prevent errors
Environmental sensors included:			
Gas sensor (IAQ)	-	MQ-135 (indoor CO_2 variations)	CCS811 (TVOC, eCO_2, MOX)
Relative humidity/temperature:	-	Aosong DHT11 (repeatability: ±1%, ±2 °C)	BME280
Barometric pressure	-	NXP MPL3115A2	-
Back-end web architecture:			
Open-source virtualization platform	-	-	Proxmox VE (KVM hypervisor + LXC Containers + Storage + Networking func.)
Programming tool for wiring devices and API	-	-	Node-RED (browser-based editor)
Geographic Information System (GIS)	-	GeoServer	-
Threshold for issuing alerts (action level)	200 Bq/m^3	300 Bq/m^3	300 Bq/m^3
Messaging protocols		MQTT	MQTT and SMTP (email)
Security protocols	None	128 bits AES keys (AppKey, AppSKey and NwkSKey) + SSL + MQTT Secure	HTTPS (SSL with ACME protocol)
NFC device to secure credentials configuration	-	-	NXP NTAG I^2C plus
Prototype dimensions, estimated power consumption, and price:			
Dimensions	12.0 × 7.9 × 5.3 cm	10.0 × 10.0 × 15.0 cm	15 × 15 × 30 cm
Overall power consumption (Wh)	n/a	1.65	n/a
Overall price of the system	n/a	n/a	n/a

Table 5. Comparative study for radon monitoring technologies.

Criteria	Alvarellos et al. [74]	Terray et al. [75]	Amato et al. [76]
System-on-Chip (SoC):			
Microcontroller (Single-Board Computer)	Arduino mkr	Included in radon sensor	Unreferenced
Based CPU	ARM Cortex-M0 + CPU (48 MHz)	-	-
Wireless module	Arduino Mkr Wi-Fi 2020	-	-
Cryptographic coprocessor	ATECC508A	-	-
Communication technologies:			
Gateway	-	Wirnet IoT Station-developed by Kerlink	-
Wireless Protocols (available)	Sigfox and Wi-Fi (IEEE 802.11 b/g/n)	LoRaWAN	Wi-Fi (IEEE 802.11 b/g/n) and 4G
Hardware communication protocol	UART/I^2C	UART	-
Wireless Communications (used):	**Sigfox** (licence-free sub-1 GHz: 868 MHz):	**LoRaWAN** (licence-free sub-1 GHz):	**Wi-Fi** (licence-free 2.4 GHz and 5 GHz):
Center frequency	868,130 MHz	868 MHz	2.4/5.0 GHz
Bandwidth	200 kHz (ultra-narrow)	125/250/500 kHz (CSS Modulation)	20/40 MHz
Data rate (bits/s)	100	250 bps ~50 kbps	<300 Mbps
Effective isotropic radiated power	16 dBm	+14 dBm (receiver sensitivity: −146 dBm)	-
Constraints	140 messages/day (ETSI regulations)	Limited message sizes (230 bytes at most)	Max. payload 64 KB
Radon gas sensor:			
Radon sensor	Radon FTLab RD200M	Algade ÆR Plus	RN53 (PIN diode)-Teviso Sensor Technologies
Academic prototype/Commercial sensor	Academic prototype (for indoor dosimetry)	Commercial sensor (for indoor dosimetry)	Academic prototype (for indoor dosimetry)
Radon detection technique	Pulsed Ion chamber	Photodiode detection for alpha particles	Photodiode detection for alpha particles
First data out	<60 min	24 h	-
Data interval	10 min update (60 min moving average)	15 min~4h (60 min/1 month/LT moving average)	-
Sensitivity	0.81 cph at 1 Bq/m^3	0.05 cph @ 1 Bq/m^3 (15~20 Bq/m^3 per hit per hour)	150 cph/1000 Bq/m^3
Operating range	10~40 °C, RH < 80%	0~40 °C, RH < 80%	−20~60 °C, RH = 20%
Measurement range (Bq/m^3)	7~3700	0~99, 9 kBq/m^3	-
Typical accuracy (precision)	<±10% at 370 Bq/m^3	±20% at 300 Bq/m^3 (in 24 h)	±10% typical @ 1000 Bq/m^3
Guaranteed accuracy	-	-	-
Display	OLED Display	Contrast e-paper Display	None
Other information	Built-in vibration sensor to prevent errors	Data storage and retrieval via USB	Must be isolated from visible light, for accuracy
Environmental sensors included:			
Gas sensor (IAQ)	CCS811 (TVOC, eCO_2, MOX)	-	-
Relative humidity/temperature:	BME280	Included in radon sensor	Included in the prototype circuit board
Barometric pressure	-	-	Included in the prototype circuit board
Back-end web architecture:			
Open-source virtualization platform	Proxmox VE (KVM hypervisor + LXC Containers + Storage + Networking func.)	ChirpStack-LoRaWAN Network Server stack Elastic Stack Suite (Beats-Logstash-Elasticsearch)	Set of human-computer interfaces
Programming tool for wiring devices and API	Node-RED (browser-based editor)	Grafana (dashboards, monitoring, alarm trigger)	-
Geographic Information System (GIS)	-	GeoNetwork	-
Threshold for issuing alerts (action level)	300 Bq/m^3	The emergence of volcanic eruptions	Unreferenced
Messaging protocols	MQTT and SMTP (email)	MQTT	-
Security protocols	HTTPS (SSL with ACME protocol)	None	None
NFC device to secure credentials configuration	NXP NTAG I^2C plus	None	None
Prototype dimensions, estimated power consumption, and price:			
Dimensions	15 × 15 × 30 cm	40 × 30 × 21 cm (after tropicalization)	n/a
Overall power consumption (Wh)	n/a	n/a	n/a
Overall price of the system	n/a	n/a	n/a

Table 6. Comparative study for radon monitoring technologies.

Criteria	Medina-Pérez et al. [77]	Forsström et al. [80]	Moreira [81]
		System-on-Chip (SoC):	
Microcontroller (Single-Board Computer)	Raspberry Pi 3 Model B v1.2	Raspberry Pi 3 A +	Arduino UNO Rev3 (2 units)
Based CPU	Quad Core 1.2 GHz Broadcom BCM2837 64 bit	Broadcom BCM2837B0, Cortex-A53 (ARMv8) 64-bit SoC @ 1.4 GHz	ATmega328P
Wireless module	BCM43438 wireless LAN and BLE onboard	2.4/5 GHz IEEE 802.11.b/g/n/ac transceiver	Sparkfun WiFi Shield-ESP8266 (2 units)
Cryptographic coprocessor	-	-	-
		Communication technologies:	
Gateway	-	-	-
Wireless Protocols (available)	Wi-Fi (IEEE 802.11 b/g/n)	Wi-Fi (IEEE 802.11 b/g/n)	Wi-Fi (IEEE 802.11 b/g/n)
Hardware communication protocol	-	-	-
Wireless Communications (used):	**Wi-Fi** (licence-free 2.4 GHz and 5 GHz):	**Wi-Fi** (licence-free 2.4 GHz and 5 GHz):	**Wi-Fi** (licence-free 2.4 GHz and 5 GHz):
Center frequency	2.4/5.0 GHz	2.4/5.0 GHz	2.4/5.0 GHz
Bandwidth	20/40 MHz	20/40 MHz	20/40 MHz
Data rate (bits/s)	<300 Mbps	<300 Mbps	<300 Mbps
Effective isotropic radiated power	-	-	-
Constraints	Max. payload 64 KB	Max. payload 64 KB	Max. payload 64 KB
		Radon gas sensor:	
Radon sensor	SARAD Radon Scout sensor	Radon sensor from MidDec Scandinavia AB	Radon FTLab RD200M
Academic prototype/Commercial sensor	Commercial sensor (for indoor dosimetry)	Academic R & D sensor	Academic prototype (for indoor dosimetry)
Radon detection technique	Photodiode detection for alpha particles	-	Pulsed Ion chamber
First data out	120 min to 95% of the final value	-	<60 min
Data interval	1~3 h or customized (1~255 min, adjustable)	-	10 min update (60 min moving average)
Sensitivity	1.8 cpm @ 1000 Bq/m^3 (immune to humidity)	-	0.81 cph at 1 Bq/m^3
Operating range	-	-	10~40 °C, RH < 80%
Measurement range (Bq/m^3)	0~10,000,000 Bq/m^3	-	7~3700
Typical accuracy (precision)	±20% at 200 Bq/m^3 or <10% @ 1000 Bq/m^3	-	<±10% at 370 Bq/m^3
Guaranteed accuracy	-	-	-
Display	None	-	OLED Display
Other information	Setup/Data download via Radon Vision Software	-	Built-in vibration sensor to prevent errors
		Environmental sensors included:	
Gas sensor (IAQ)	-	-	-
Relative humidity/temperature:	Included in the sensor (0~100% and −20~40 °C)	Included in the sensor	BME280
Barometric pressure	-	-	-
		Back-end web architecture:	
Open-source virtualization platform	-	Open-source project (MIT licensed) download: www.smeiot.se	-
Programming tool for wiring devices and API	Node-RED (browser-based editor)	-	GlassFish and SoapUI
Geographic Information System (GIS)	Leaflet javascript library	-	-
Threshold for issuing alerts (action level)	300 Bq/m^3	-	300 Bq/m^3 (adjustable)
Messaging protocols	MQTT (Mosquitto broker)	MQTT (Mosquitto broker with OpenSSL)	HTTP
Security protocols	None	TLS with PSK encryption	None
NFC device to secure credentials configuration	None	None	None
		Prototype dimensions, estimated power consumption, and price:	
Dimensions	n/a	10 × 15 cm	n/a
Overall power consumption (Wh)	n/a	n/a	n/a
Overall price of the system	n/a	n/a	±625.00 € (material expenses)

5. Discussion

CPS, IoT, and cloud computing, are key technologies enablers for the Industry 5.0 paradigm [82,83], and as a result for the implementation of cognitive buildings. This re-search is a piece of evidence that these technologies are of utmost importance in designing complex systems for building management applications such as real-time radon monitoring and management. To achieve this goal, each edge device must provide accurate ra-don sensing (among other collected IAQ parameters/indicators), computing power, and communication capabilities. Typically, all remaining tasks (data storage included) are performed in a cloud computing approach. The system architectures, communication technologies, and hardware requirements were analyzed in-depth to provide insights into the state-of-the-art of IoT-based systems for radon monitoring and management.

The general architecture of these IoT-based systems follows the ITU-T Y.4113 Recommendation, which is composed of 3 blocks: IoT area network, access network, and core network. The IoT area network includes all the various devices capable of capturing data (sensors), actuators, and MCUs with storage and bi-directional communication capabilities. The access network is responsible for the communication systems, enabling IoT de-vices to connect to the core networks using different technologies, either wired or wireless (Wi-Fi, BLE, ZigBee, 4 G/LTE, etc.). The core network provides the connectivity infrastructure from the access network to the service provider. It provides the connection to web servers, which will process the data and store it into a data storage system (online or physical storage), permits the visualization of received data, analyzes the impact of pollutants in the target premises, and helps end-users to get instant updates about radon and IAQ levels.

It is possible to identify six different types of radon sensors (three commercial sensors and three academic prototypes), using different radon detection techniques, with professional solutions also including IAQ sensing parameters (temperature, relative humidity, and barometric pressure). The preferred architectures for connecting these sensors include different MCUs and interfaces being the most used, the Espressif, Arduino, and Raspberry Pi solutions. The adopted communication technologies for real-time data collection typically include SigFox, LoRaWAN, and Wi-Fi, being the latter widely preferred. The use of electronic systems, in general, involves costs and requires electrical power, however, the authors do not comply with this precept given the absence of estimations for overall power consumption and prices. The sensor's calibration is also an issue, and although referred to by some authors, there's equally a lack of calibration procedures, mostly on prototype solutions, so for these aspects, the comparisons are meager.

On the one hand, the results show that 77.8% of the studies focused on radon monitoring with defined threshold-based alerts and corrective actions or measures taken by human operators (manual ventilation, population alerts, etc.,). On the other hand, 22.2% focused not only on radon monitoring but also on radon management, which included autonomous airflow control systems (ventilated systems, motorized windows, etc.,). Additionally, there are 22.2%, 33.3%, and 22.2% of systems based on ESP8266, Arduino, and Raspberry Pi controllers, respectively. At least 44.4% of the sensors were calibrated individually before the system implementation.

5.1. Opportunities and Future Challenges

This research shows that the use of IoT devices for radon monitoring and management has gradually evolved over the years and has the potential to change the way people perceive risk exposure to such pollutants. This change occurs not only by the inclusion of IoT devices for continuous monitoring but also by the inclusion of visual analytics methods to enhance risk perception [84] and by the proposal of risk management and communication tools for the IoT age, such as the Indoor Radon Risk Exposure Indicator (IRREI), proposed by Lopes et al. in [84,85]. Recent IoT-based system architectures for online radon monitoring and real-time risk management are crucial for improving the overall building IAQ and energy efficiency by allowing the integration of sensors, computing, and communication capabilities into low-cost and small-scale devices. This research presents a survey of recent studies from the last 3.5-year period, with a focus on CPS that take advantage of IoT technologies for radon risk management, by focusing on methods, techniques, and technologies used for indoor radon monitoring and management. It should be noted that most of the surveyed systems are limited to monitoring and evaluating indoor radon concentration, still lacking effective radon mitigation capabilities and assessment. In addition, the lack of correlation between other air quality metrics is still evident, such as those related to energy efficiency, thermal comfort, noise pollution, etc.

5.1.1. Opportunities

The biggest opportunity of IoT technologies is related with the creation of smart and cognitive buildings, where it will be possible to manage the human activity in indoor environments, identifying new opportunities to save and improve the occupant's experience. IoT devices can be used to increase buildings' energy efficiency, thermal comfort, and IAQ as they not only monitor many parameters but can also act physically into spaces. Just to cite a few, these devices can be used for: (i) Collecting indoor data on which devices or operations have the highest energy consumption; (ii) in which period do they use more energy; (iii) how do indoor and outdoor activities affect IAQ; (iv) what are their impacts on the productivity and health of the occupants. Part of these IoT devices can switch autonomously any equipment on and off (even temporarily), for instance, when checking for work inactivity, unadjusted temperatures, or high levels of atmospheric pollutants. Extrapolating this resource management to larger areas, such as entire buildings, using programmable and interconnected IoT switches, it becomes possible to optimize and balance the total resources distribution.

On the other hand, by streaming data from all these IoT-devices to the Cloud, it will be possible to predict future patterns, determining how energy consumption or IAQ patterns will be in the short/midterm. One idea that stands out from the examined works is the prediction of indoor pollution levels even before reaching the threshold levels and acting in a preventive way. So, another opportunity will be the inclusion of autonomous airflow control systems and prediction models/algorithms combined with other measured variables for energy efficiency, thermal comfort, noise pollution, etc. Machine learning and artificial intelligence also work very well with IoT devices and can be a big help in decision-making and preventing strategies.

A major save-energy measure is the development of dashboard control and alert applications for smartphone or tablet use. This can make work easier, as these devices bring mobility in the administration of resources, which can be done anytime and anywhere.

IoT-based systems are extremely versatile and easily adapt to the needs of any type of building or business activity (large or small), offer scalability, and improved security when well implemented. Tasks generally neglected by occupants, such as turning off the lights and equipment, or opening and closing windows to ventilate spaces, will always be fulfilled. So, another opportunity will be to provide systems with capabilities to inform in good time for the need for preventive and corrective actions in the various installed systems and equipment, avoiding downtimes in the control of smart building resources.

5.1.2. Future Challenges

A major challenge faced using IoT technologies is related with data privacy and security, as no entity would like to have IAQ sensitive data of its buildings available to the public. In the surveyed articles, only a few authors included messaging security protocols. From an ethical point of view, third parties can develop ways to earn money from these data, creating a market for the sale of information.

Another challenge is the connectivity between IoT devices, and with back-end platforms, which may open gaps for attacks and intrusions into systems by malicious hackers. It is safe to say that the risk of an attack increases exponentially the more the system is connected to the Internet, and it is evident that most of the surveyed systems go with Wi-Fi communication technology, instead of looking for autonomous and independent solutions. At the forefront of this challenge are manufacturers (in commercial devices) and re-searchers (in prototype systems), with the task to include security keys in IoT devices.

Regarding the communication infrastructure, there is also the challenge to avoid possible constraints in the use of bandwidth, as frequency spectrum is a finite resource. The more devices transmitting at the same time, the worse the transmission quality becomes. This happens either in free use bandwidth or made available by Internet Service Providers, and in the latter, it depends on approval by government authorities.

Due to the massive collection of data, the servers must have an increased storage capacity. This capacity can be allocated on local servers or in a public/private cloud, however, it must be considered that invariably there will be an increase in data storage costs.

A final challenge concerns the creation of standards among market providers, as de-vices need to communicate with each other, and work integrated. Whenever a device fails and is discontinued, the substitute device must be compatible to ensure the system's sustainability. In addition, as they are wireless communication devices, the hardware must have the certifications required by the regulatory bodies of the various countries.

6. Conclusions

In this way, the design of IoT-based systems for managing radon risk exposure and IAQ involves planning and has an extensive requirements list. It goes from the meticulous selection of accurate radon and IAQ sensors, processing units (such as microprocessors or microcontrollers), secure low-power wide area wireless communication protocols with "over the air" firmware update management, among others, that are crucial for designing smarter and more sustainable systems that rely on IoT and ICT technologies, and thus achieve an optimal balance between these three critical factors: thermal comfort, building energy efficiency, and IAQ.

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