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Review

A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk

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Abstract: People spend up to 90% of their time indoors where they continuously interact with the indoor environment. Indoor Environmental Quality (IEQ), and in particular thermal comfort, Indoor Air Quality (IAQ), and acoustic and visual comfort, have proven to be significant factors that influence the occupants' health, comfort, productivity and general well-being. The ongoing COVID-19 pandemic has also highlighted the need for real-life experimental data acquired through field measurement studies to help us understand and potentially control the impact of IEQ on the occupants' health. In this context, there was a significant increase over the past two decades of field measurement studies conducted all over the world that analyse the IEQ in various indoor environments. In this study, an overview of the most important factors that influence the IAQ, thermal comfort, and the risk of virus transmission is first presented, followed by a comprehensive review of selected field measurement studies from the last 20 years. The main objective is to provide a broad overview of the current status of field measurement studies, to identify key characteristics, common outcomes, correlations, insights, as well as gaps, and to serve as the starting point for conducting future field measurement studies.

Keywords: indoor environmental quality; thermal comfort; indoor air quality; virus airborne transmission risk; field measurement studies

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1. Introduction

According to recent studies, people nowadays spend most of their lifetime indoors [1]. Undoubtedly, the Indoor Air Quality (IAQ) is one of the key factors that influence the quality of the indoor environment, as well as the human health [2]. Various health problems have long been known to arise from poor IAQ, with the most severe ones to include lung cancer, carbon monoxide poisoning, pneumonia, asthma, and various allergies [3]. In fact, household air pollution was the main cause for 3.8 million deaths according to the World Health Organization (WHO), which corresponds to 7.7% of the worldwide mortality in 2016 [4]. Note that household fuel combustion is a key contributor for indoor air pollution, especially in developing countries, where the cooking and heating primarily rely on solid fuels including wood, charcoal, and crop waste [5]. The recent lock-downs due to the current COVID-19 pandemic forced most people to work remotely from their homes and has highlighted more than ever before the importance of Indoor Environmental Quality (IEQ) monitoring.

All environmental aspects have a massive impact on the quality of people's lives [6]. Inadequate ventilation and poor IAQ are the key contributors to the Sick Building Syndrome (SBS) [7] which considerably influences the human health and workers productivity. In the United Kingdom and the United States, it is estimated that the State loses roughly 15 billion pounds and 38 billion dollars, respectively, due to reduced productivity of workers and illnesses caused by inadequate supply of fresh air alone [8]. In fact, a workplace with high IEQ obviously improves the workers' health and mood, thereby increasing their productivity and plays a crucial role on the profitability of businesses. Generally, investing on improving IEQ in workplaces is characterized by a short pay back period and generates additional monetary returns thereafter [9]. Studies on the quality of IEQ among students have shown that inadequately set parameters can have a drastic impact on students' cognitive abilities [10]. It should be noted that buildings being rated as "sustainable and green" do not truly guarantee their compliance with the desired IEQ level [11–14]. Hence, the stringent need to build NZEB (Nearly Zero Energy Buildings) [15–17], whose design requires a holistic approach based upon the principles of sustainability, should also focus on ensuring IEQ while designing new buildings, as well as when retrofitting old ones. The need to include IEQ in the building design has also been identified over the last two decades by various green building certification systems, such as the Building Research Establishment Environmental Assessment Method (BREEAM) from the UK, Green Star from Australia, and Leadership in Energy and Environmental Design (LEED) from the US [18–20].

The quality of an indoor space in relation to the health, comfort, well-being, and productivity of occupants forms the IEQ. The concept of IEQ is very broad and depends on many variables such as temperature, relative humidity, air velocity, air flow, occupancy, concentration of pollutants, noise and lighting. These are commonly grouped into four major areas [21] that define the quality of the environment inside a space, namely: (i) Indoor Air Quality (IAQ) [22], (ii) Thermal Comfort [23], (iii) Acoustic Comfort [24–26], and (iv) Visual Comfort [27,28], as depicted in Figure 1. As shown in the Figure, we additionally propose that (v) Virus Risk, also becomes an essential IEQ pillar. The subject of airborne viruses has been extensively investigated by various research communities in the last two decades. Experimental studies on the presence of virus in air samples are carried out mainly under controlled laboratory conditions. The impact of environmental parameters (e.g., temperature, humidity) on airborne viruses has been also explored, but it still not clear due to the complexities involved. Regarding the estimation of the probability of virus transmission indoors, a number of risk assessment models have been proposed for this purpose. However, only a limited number of IEQ field measurement studies so far have considered the use of real environmental measurements for computing the airborne virus risk.

IEQ evaluation depends on numerous factors that can be subdivided into four categories: external conditions (temperature, air pollution, noise, sun and natural lighting, green environment), building (enclosure, construction material, furniture), building services (HVAC systems, lighting) and human activities (HVAC use, cleaning, use of paints, varnishes, and glues) [29]. The assessment of IEQ is mainly performed by two approaches, Post-Occupancy Evaluations (POE) and field measurements [9]. In the case of POE, a subjective assessment of the IEQ is performed based on data collected using occupants' questionnaires. In the latter case, an objective assessment of IEQ is performed using data collected by instruments (i.e., sensing devices, portable loggers or passive samplers). Data acquired by both field measurements and occupants' questionnaires can contribute towards a more accurate and comprehensive analysis of the indoor environment as perceived by the occupants. To achieve a complete and reliable characterization of thermal comfort and IAQ levels in the built environments and related energy needs, several challenging issues must be addressed with regard to properly designing measurement campaigns (not only from technical and operational perspectives, but also by managing psychological and physiological issues) and effectively elaborating huge amounts of field data.

A number of review studies have appeared in the recent literature covering different aspects of IEQ [30–33]. Specifically, in [30] the influence of different IEQ factors on human health and productivity is investigated for both residential and commercial settings, with an emphasis on IAQ, ventilation, and thermal, visual and acoustic comfort. Furthermore, various green building certifications (i.e., LEED, BGCA, and BREEAM) are reviewed together with their impact on IEQ. Similarly, in [31], IEQ is further investigated with the addition of other influential parameters such as personal characteristics, building-related factors, outdoor climatic conditions and seasonal variation. Various case studies are considered in different indoor environments including climate chambers, schools, office buildings, residences, and commercial buildings. Based on the presented results, thermal comfort was ranked by the occupants as the most important influential factor on occupant IEQ, as compared with other factors such as air quality, visual and acoustic comfort. In [32], the impact of IEQ was further analysed with a focus on occupant health and well-being. Specifically, the considered factors included the IAQ in office environments, the SBS, thermal comfort, as well as acoustic and visual comfort. The survey argued that green certified buildings did not necessarily guarantee a comfortable indoor environment and the users well-being because of the building design. In addition, in [33], the last two decades of IAQ research is comprehensively reviewed with a focus on the broad variety of air pollutants found in several indoor settings and how different IAQ factors influence the air pollution. The reviewed literature is grouped in two main categories, residential and commercial buildings, to help identify possible trends and gaps for each category.

In this work, an overview of the most important factors that influence the IEQ and a comprehensive review of the most recent field measurement studies with a focus on IAQ-related studies are presented, while multiple key statistics are extracted. Among the aims of this work is to provide a broad overview of the current status of field measurement studies, to identify key characteristics, common outcomes and correlations. Most importantly, this study aims to provide insights, identify gaps and provide suggestions to serve as the starting point for conducting future field measurement studies. Our emphasis is placed on IAQ and thermal comfort field measurement studies as well as the influencing factors, measured parameters and associated quality indices, standards and outcomes. Additionally, we introduce for the first time the Virus Risk as an essential element of the IEQ (see Figure 1), that should also be considered in future field measurement studies.

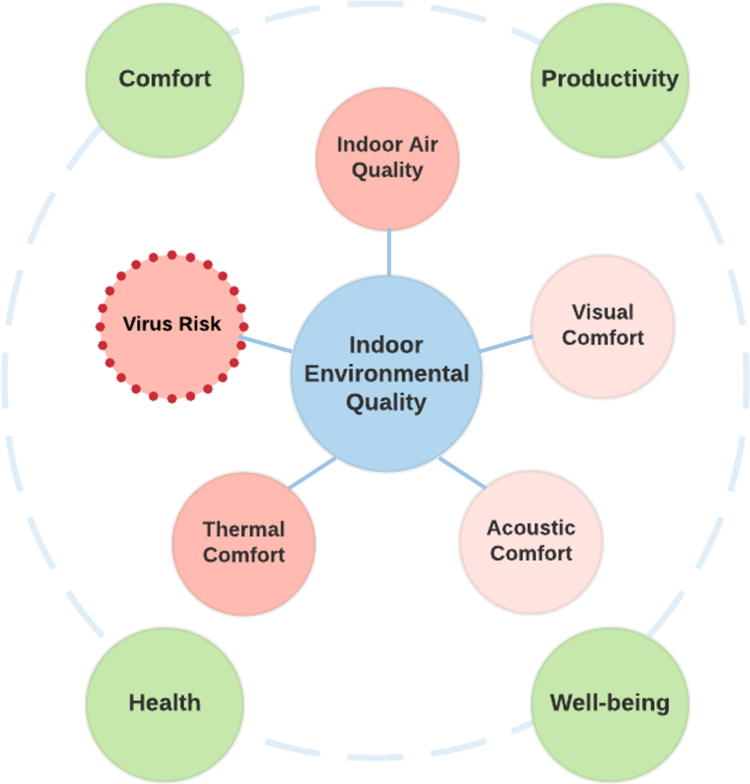

Figure 1. Typical influencing factors of the IEQ.

The rest of the paper is organised as follows. In Section 2, the methodology for conducting the literature review is detailed and useful statistics are drawn with respect to the number, the years and the venues of the reviewed articles. Next, in Section 3, important background information on Thermal Comfort, Indoor Air Quality and Virus Risk is reviewed as related to the measured parameters and associated indices and standards. Section 4 includes the comprehensive review of the field measurement studies organised in terms of the indoor environment into offices, educational facilities, residential, care centers and other. In Section 5, a critical evaluation of the field measurement studies is performed and useful insights are extracted together with guidelines for future research. The paper concludes with Section 6.

2. Methodology

The purpose of the current literature review was to record the state-of-the-art literature and present the main field case studies conducted for monitoring the IEQ in different indoor environments. Mainly peer review journal articles, but also surveys, conference articles, government publications, and guides on IEQ were used to shape this review. A systematic search was conducted on Google Scholar, ScienceDirect, and PubMed literature databases between 2001 and 2021 using the keywords: indoor environmental quality, indoor air quality, thermal comfort, field case studies, field measurements, COVID-19 and air quality, environmental factors and airborne virus, virus risk assessment models. The topics cover multiple disciplines, including environmental science, engineering, and energy, as well as physics and medicine.

The preliminary search, after screening the search results based on the articles' titles, abstracts, keywords, number of citations and the year of publication, led to a total of more than 150 publications. Subsequently, after carefully reading the entire articles, a filtration procedure was used to select the most relevant articles taking into account the following selection criteria. An emphasis was placed on IAQ-related studies, thermal comfort and airborne virus transmission, while field measurement studies exclusively on acoustic and visual comfort were not considered. Additionally, a significant effort was made to facilitate objective comparisons between different field measurement studies in terms of test location, measured parameters, measurement methods, and measurement times, so a preference was given to large-scale studies containing this information. Finally, a filtration procedure was used to remove duplicates.

Based on the above criteria, 41 field measurement studies were selected for the purposes of the review. For the selected studies, Figure 2 shows the number of publications per year, while Figure 3 depicts the various publication venues. From the figures, it becomes evident that the number of publications has an increasing trend over the last 20 years, while year 2017 stands out with 8 publications. Furthermore, 93% of the publications appeared in journals with the highest number appearing in Building and Environment and Indoor Air with 6 and 4 publications, respectively.

Limitations of This Study

The limitations of this study stem primarily from the criteria used for selecting the 41 field measurement studies that were included in the comparison. An emphasis was placed on IAQ-related studies over the last 20 years, thermal comfort and airborne virus transmission, while field measurement studies exclusively on acoustic and visual comfort were not considered. Furthermore, this review primarily focuses on the quantitative comparison (objective evaluation) of the field measurement studies in terms of the measured parameters, the sensing equipment, and the data analysis performed. As a result, health-related studies and clinical trials, which use subjective evaluations and dosage response methods to establish the precise relationship between IAQ, human health and well-being, are beyond the scope of this work.

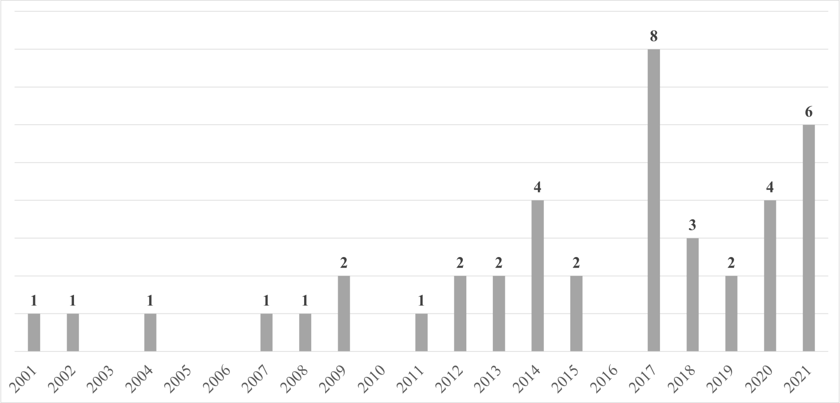

Figure 2. Year of publications.

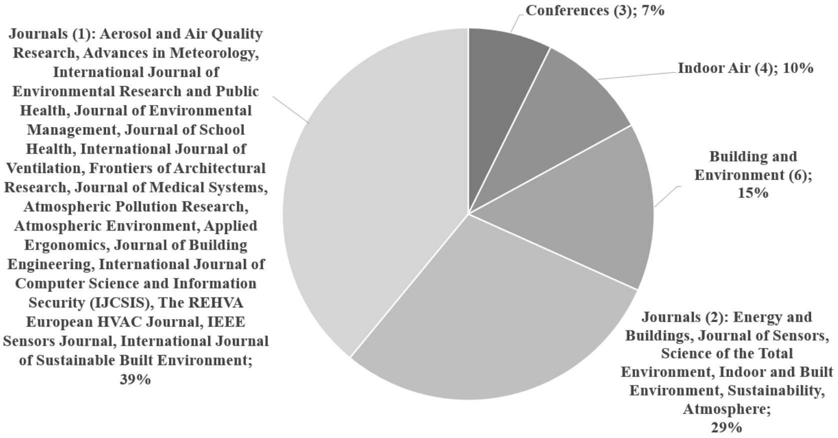

Figure 3. Publication venues.

3. Background

In this section, we present important background information on Thermal Comfort, Indoor Air Quality and Virus Risk related to the measured parameters and associated indices and standards. Figure 4 illustrates the associations with the measured parameters, while their recommended levels for various indoor spaces are provided in Table A1 in the Appendix A.

3.1. Thermal Comfort

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), thermal comfort could be defined as ”that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE Standard 55) [23]. A thermally comfortable environment may be characterised as the environment in which a building’s user does not express any discomfort due to the heat or cold.

3.1.1. Factors Influencing Thermal Comfort

The main factors influencing the human perception of thermal comfort could be categorised into environmental and personal factors. The main four environmental parameters include air Temperature (T), Radiant Temperature (RT), air Velocity (V) and Relative Humidity (RH). RT is the measurement of infrared radiation that is emitted from the different surfaces in a room, such as walls, ceilings, and floors. The use of a Globe Thermometer is a common practice for RT measurements [34]. The two personal factors include the Clothing Insulation (CI) and Metabolic Rate (MR). The MR describes the heat produced within the body and it depends mainly on the physical activity (e.g., sleeping, standing, cooking). These personal factors are difficult to measure in field studies. This information is often obtained from questionnaires filled by occupants during surveys. For example, while the occupants are asked by the surveyor to sit and relax for about 30 min to maintain the MR constant, the value of MR is recorded as 1 met (58 W/m^2) for sedentary activity.

3.1.2. Thermal Comfort Related Indices and Standards

Research on the field of thermal comfort over the last few decades, has led to two major approaches, the heat balance model and the adaptive model. The heat balance model also known as thermo-physiological model has been developed in 1970 by P. Ole Fanger, who is considered one of the pioneers in the field. The main equation model is presented in ISO 7730 [35], which can be used to determine two main thermal comfort indices, the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfaction (PPD). The PMV index is determined as the average response of a group of people on the thermal sensation that they feel in a given space. It considers both environmental and personal factors and can be expressed in a 7-point thermal sensation scale as −3 (cold), −2 (cool), −1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), +3 (hot). PPD index is determined as the average number of people likely to feel uncomfortable in an environment and it can be calculated based on the PMV index. Various researchers have developed software for PMV calculation. However, the majority of the software do not considered all six basic parameters of thermal comfort [36]. There is also an adaptive version of the model that can evaluate thermal comfort for a wider range of temperatures in a not fully conditioned indoor place (i.e., naturally ventilated indoor places). In this model, the occupants are expected to interact with their surrounding environment and adapt to it. Based on this approach, the thermal perception is defined in relation to both indoor and outdoor temperature. Both the heat balance model and the adaptive model are based on current thermal standards, which include ISO 7730 [35], ASHRAE Standard 55 [23] and EN 15251 [37].

3.2. Indoor Air Quality (IAQ)

The quality of indoor air has a very strong impact on the life quality of the occupants in residential as well as commercial buildings. In fact, the percentage of time spent indoors in the various micro-environments is significantly higher compared to outdoors [38]. Furthermore, scientific evidence has demonstrated that indoor air pollution tends to be higher compared to outdoors [39–41]; a critical aspect, especially for vulnerable groups such as elderly people, children, pregnant women, and people who have limited opportunity for outdoor activities. Thus, it is extremely important to recognise, control, and maintain the quality of indoor air [22]. The characteristics of each micro-environment differ greatly, based on the local outdoor conditions, the building structure characteristics, and the different indoor activities. Based on this, and considering all the aforementioned factors, a comprehensive assessment of IAQ may not be a straightforward procedure.

3.2.1. Main Air Contaminants

Indoor environments are characterised by a mixture of indoor and outdoor contaminants. Main categories of these contaminants include chemical, biological indoor air contaminants and Particulate Matter (PM) [42]. Major chemical gases contain Carbon Monoxide (CO), Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ground Level Ozone (O_3), as well as Volatile Organic Compounds (VOCs), Formaldehyde (HCHO), and Radon (Rn). On the other hand, biological agents, mainly include the presence of mould, bacteria, and viruses. In this work, we additionally consider Carbon Dioxide (CO_2). Although not a pollutant, prolonged exposure in high concentrations of CO_2 can cause dizziness and nausea. In the last two decades, CO_2 measurements have been used as an indicator for indoor ventilation and risk of airborne virus transmission. Several studies conducted on school settings showed that inadequate ventilation can be associated with the academic performance of students. CO_2 levels can also provide information on occupancy which can be used for real time ventilation control. The recommended levels for many of these contaminants for various indoor spaces are provided in Table A1 in the Appendix A.

3.2.2. Factors Influencing IAQ

Poor IAQ is often the result of a combination of different factors. Indoor sources derived from occupant activities such as inefficient cooking and heating can be considered one of the dominant contributor factors of indoor air pollution, especially in developing countries. Various air pollutants are emitted in the air by the combustion of biomass fuels (e.g., wood, coal, agricultural residues), in traditional stoves [43]. These inefficient practices can significantly impact the IAQ by releasing pollutants such as CO, PMs, and VOCs.

Another important factor is the outdoor presence of air pollutants, which enter the indoor environment through natural or mechanical ventilation, or even by infiltration. The vehicular traffic and local industrial activities are determined as the dominant outdoor pollution emission sources, which can impact the IAQ. According to the literature on IAQ-related studies, the relationship between indoor and outdoor concentrations is expressed with the well-known Indoor to Outdoor (I/O) ratio [44]. In the case that the value of I/O ratio is higher than unity, this indicates that the indoor exceed the outdoor concentrations. On the other hand, if the value of I/O ratio is less than unity, the outdoor exceed the indoor concentrations. Both outdoor air temperature and RH can affect the indoor thermal conditions and furthermore the IAQ. In many epidemiological studies in the last few years, the link between air temperature, RH, and the transmission of viruses has been investigated. Existing evidence has shown that low outdoor temperature during winter season and low indoor RH, can be positively associated with high weekly incidences of influenza [45].

Ventilation is another major influencing factor of IAQ. In simple words, ventilation is referred to the indoor air removal and replacement with clean ambient air. The most common ventilation methods are the natural and mechanical ventilation. In Natural Ventilation (NV), outdoor air directly enters through the building by the opening of windows and/or doors. Mechanical Ventilation (MV) can be performed using any type of Heating Ventilation and Air Conditioning (HVAC) system. In one questionnaire survey among 3485 adults in China the possible associations between indoor ventilation conditions, outdoor air pollution, meteorological factors and SBS symptoms were investigated [46]. The results indicated that the frequent opening of windows and the use of exhaust fans in the bathrooms could reduce the number of nose and dermal symptoms.

In recent years, new modern building construction practices involve the use of environmentally friendly building materials and energy-efficient processes in the design; aiming at more sustainable buildings and improving the occupant comfort and health. However, poor IAQ is still possible in the modern, green energy-efficient buildings. In fact, in some green practices the use of recycled products and waste-based materials may adversely affect the IAQ. These products can emit toxic compounds and as a result produce increased levels of air pollutants. In addition, energy efficient practices, such as the extensive use of natural ventilation in areas with elevated outdoor air pollution can significantly impact the quality of indoor air [13].

3.2.3. IAQ Related Indices and Standards

The negative impact of air pollution on human health and the environment in general, is a major reason for the development of legislative frameworks around the world. The development of such regulations aims both to improve, control and maintain air quality, as well as to prevent adverse effects on human health. Although there are specific guidelines, directives, and standards related to outdoor air quality in various countries, a legislative context is still missing for indoors. Currently, in Europe, there is still no specific integrated directive legislative outline regarding the IAQ [47]. A harmonised and global methodology is still absent. However, there is a growing number of pre-legislative initiatives, technical-scientific documents, guidelines, and recommendations. The WHO published IAQ guidelines on selected chemical pollutants which are often found in indoor air in levels of concern to health [48]. These selected substances include benzene, CO, HCHO, naphthalene, NO_2, Polycyclic Aromatic Hydrocarbons (PAHs), radon, trichloroethylene, and tetrachloroethylene.

Moreover, there are a number of custom made assessment systems and indices for IAQ developed by various companies and organisations around the world. An example of an IAQ index is the one developed by RESET Air for continuous real time information of the quality of indoor air [49]. Levels of $PM_{2.5}$, TVOCS, CO_2 as well as T and RH are collected by air quality sensors. The collected data can be viewed online based on an internationally recognized standardization procedure through the RESET cloud database. Another commercial product, the Atmocube is an indoor environmental monitoring system which is equipped with IEQ sensors for PM_1, $PM_{2.5}$, PM_{10}, TVOC, HCHO, CO_2 as well as RH, T, atmospheric pressure, Illuminance (I), and Noise (N) levels [50]. This product offers real-time monitoring for IAQ and environmental comfort parameters. The quality of indoor air is expressed with a accumulative indicator, called Air Quality Score (AQS) which is based on air pollutants concentrations. AQS's indications range from 0 for severely polluted air to 100 for very clean air.

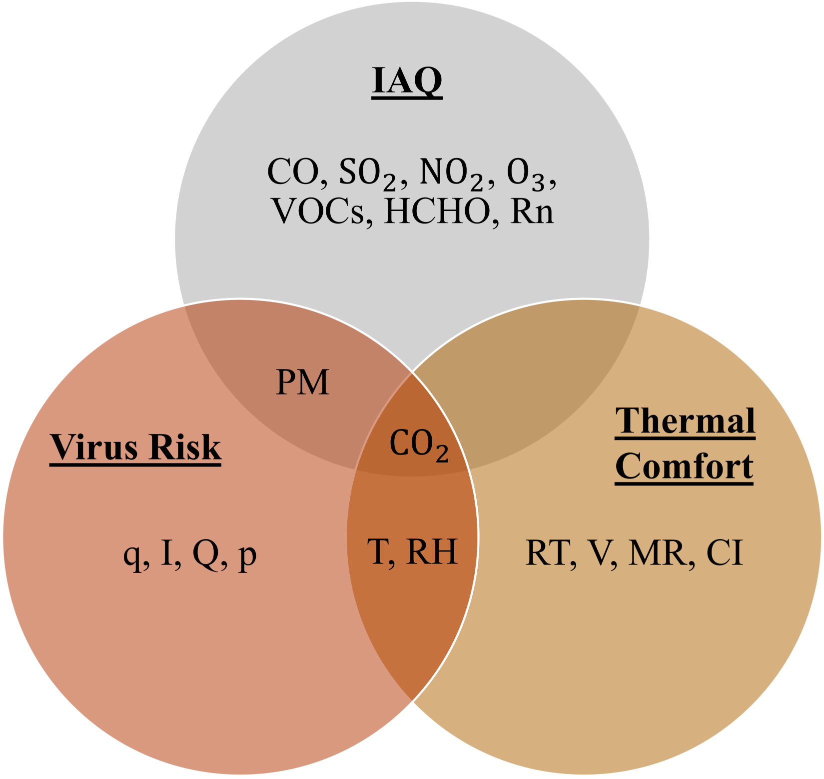

Figure 4. Parameters linked with IAQ, thermal comfort and virus risk.

3.3. Airborne Virus Risk

3.3.1. Factors Influencing Virus Risk

Existing evidence suggests that virus airborne transmission in indoor environments can be one of the main routes of disease transmission [51–53]. Research suggests that the rate of indoor transmission is directly connected with the IEQ conditions. In fact, the ongoing COVID-19 pandemic has highlighted the importance of IEQ monitoring and has raised several questions about how atmospheric air pollution could be linked to viral infections. Recent modelling studies have explored the relationship between air pollution and COVID-19 confirmed cases [54–56] and they showed that the long-term exposure to harmful air pollutants present in the environment negatively influences both respiratory and cardiovascular systems. Recent experiments have also validated the presence of the current corona virus (SARS-CoV-2) on PM [57,58].

The risk of exposure to airborne viruses mainly in confined environments is not something new. As compared to previous airborne viruses such as MERS and SARS-CoV-1, the SARS-CoV-2 has spread more rapidly around the world due to increased adaptation of the virus in different indoor places. Several studies have investigated the effect of climatic conditions on the survivability of various contagious viruses in aerosol form such as MERS, SARS-CoV-1, and SARS-CoV-2 [59–61]. The air temperature and RH are considered two of the main influencing factors on the virus viability, survivability, and stability under controlled aerosolization procedures.

3.3.2. Virus Risk Related Indices

In the last few years, different types of mathematical models have been developed for infection risk assessment, that can be useful in understanding the airborne transmission dynamics of contagious diseases and in forecasting the risk of these diseases to the community. The two main methods are the dose-response model and the Wells–Riley model. Both models aim at the quantification of the infection risk related to airborne transmission of infectious respiratory diseases, however the Wells–Riley method finds greater applicability since the dose-response method requires the availability of experimental infectious dose data. The Wells–Riley equation, on the other hand, evaluates the probability of a susceptible person to become infected, inhaling a randomly distributed amount of infectious airborne particles into the air of a confined space [62] using the following equation:

$$P_I = \frac{C}{S} = 1 - e^{\left(\frac{-Iqpt}{Q}\right)} \tag{1}$$

where, P_I is the probability of infection $(-)$, C is the number of infectious cases $(-)$, S is number of susceptibles $(-)$, I is the number of infectors indoors $(-)$, p is the average pulmonary ventilation rate of susceptibles $(\mathrm{m}^3/\mathrm{h})$, q is the quanta generation rate (i.e., the amount of quanta produced by an infector) $(\mathrm{quanta}/\mathrm{h})$, t indicates the exposure time interval (h) and Q indicates the room's ventilation rate $(\mathrm{m}^3/\mathrm{h})$. It is important to note that the only IAQ related influencing factor on the probability of infection risk is the ventilation rate (Q). To complement some of the restrictions and increase the practicability of this model, different modifications and expansions have been developed by various scientists [63,64]. Beyond the use of the ventilation rate itself (Q), some researchers modelled the CO_2 concentrations indoors for the calculation of exhaled breath [65]. The idea was that the exhaled breath can act as the means for the release of infectious aerosols into the room air.

The ongoing pandemic has attracted the interest of various researchers and engineers from different disciplines. An interesting initiative is the RESET Viral Index [66] that can provide real-time assessment of the probability of airborne viral transmission in an indoor environment. This index is scientifically founded on publications regarding virus survivability, immune system health, and viral load and is able to also integrate real-time information coming from sensors measuring $PM_{2.5}$, RH, T, and CO_2 as well as occupancy levels and ventilation. Another important result, is the virus risk indicator developed by AIRTHINGS [67] that uses a numerical scale 1–10 to quantify the risk of virus transmission indoors by integrating other environmental factors and combining real time measurements of CO_2, T, RH, and PM. Recently, researchers from the Harvard T.H. Chan School of Public Health have developed a spreadsheet-based tool for estimating air ventilation rates in classrooms using the steady state CO_2 method [68]. In this tool, the users can insert their target Air Changes per Hour (ACH) via ventilation and details about the studied classroom, and the tool returns to the user the estimated value of CO_2 concentration based on a simple guide developed for classrooms [69]. The purpose of this calculator is to provide to the users an easy way to control the ventilation efficiency based on CO_2 measurements in an effort to mitigate the risk of COVID-19 disease transmission. Also, the CoronaSense Project [70] aims at the development of a 3D airborne transmission risk index for COVID-19 in the indoor environment based on CO_2 measurements that also takes into account environmental conditions (i.e., T and RH) and air pollution (i.e., PM).

4. Field Measurement Studies

In this section the selected field measurement studies are comprehensively reviewed, organised according to the building type in 5 categories: (i) Offices, (ii) Educational facilities, (iii) Residences, (iv) Care centers, and (v) Other. For each category, an attempt was made to group together related studies according to the objectives and list large-scale studies first. The detailed characteristics of the measurement studies reviewed in this section can be found in Table A4 in the Appendix A.

4.1. Offices

Two large-scale field measurement studies were conducted in Europe and the US to study the IEQ for office environments. The European project OFFICAIR [71] investigated the IAQ in terms of seasonal variations in 148 offices from 37 buildings in Europe. Both field measurements and on-line questionnaires were used to examine the quality of indoor air. Field measurements were recorded by passive samplers for VOCs, aldehydes, O_3, NO_2, and $PM_{2.5}$. Two sampling campaigns were conducted in the winter and the summer season, respectively. The main results showed significant seasonal variations for all the studied pollutants except for the xylenes. Specifically, the analysis results indicated higher indoor concentrations of almost all the target pollutants in the summer season compared to the winter season. Another large-scale study presented in [72] explored the relationship between IEQ parameters and occupants' satisfaction in 400 offices from 20 different buildings in the US. Both field measurements and questionnaires were used to assess the occupants' satisfaction levels. The measured parameters included temperature, RH, CO, CO_2, particulates, and VOCs, as well as V, RT, noise, and illuminance levels. Data analysis showed significant difference in thermal sensation between male and female workers during the summer season. Specifically, female workers were significantly less satisfied with their thermal environment than male workers. According to the authors, the different clothing insulation was the main factor for these observations.

A number of smaller field measurement studies concerning office environments have also been reported from different parts of the world. A Wireless Sensor Network (WSN) monitoring system was developed for the exploration of influencing physical parameters of thermal comfort in a building in Italy [73]. The sensor nodes were placed in different rooms for the measurement of T, RH, RT, and air flow speed. The main findings showed that the air flow was almost constant in all studied rooms when the HVAC system was switched off. In addition, the penetration of sunlight through windows and the exchange of heat between the building and outdoor environment were the main influencing parameters of the temperature variations. A sharp change was also observed in both air flow direction and temperature the moment the windows were opened. In another study, the impact of different parameters of indoor air on the overall IEQ was investigated both indoors and outdoors [74] for an office building in UK. Field measurements were conducted with a custom portable monitoring device for T, RH, $PM_{2.5}$, PM_{10}, VOCs, CO_2, CO, as well as light and sound levels. Short term experiments provided insights of the effects of the variations of IEQ parameters and their impact on a custom IEQ indicator. The proposed IEQ indicator was based on the field measurements with a scoring system to compute a final overall percentage of IEQ.

The effectiveness of the utilization of CO_2 measurements for the activation of the mechanical ventilation system in a high-rise office building in Hong Kong was analyzed in [75]. In this case study, a CO_2-based controlled ventilation strategy was developed to improve the building's energy efficiency and maintain a high satisfaction rate related to IAQ. Deployed CO_2 sensors in the Air Handling Units (AHUs) and in each individual building zone were used to test the proposed ventilation approach. Both field and simulation tests conducted to evaluate its performance, by comparing with the initial implemented fixed outdoor air flow rate control approach.

In the Middle East Area, the frequent presence of dust storms episodes can significantly affect the IAQ of a building. In this context, a case study conducted in an office building in

Doha aimed to identify the influencing factors of indoor $PM_{2.5}$ and PM_{10} concentrations [76]. The results indicated that the HVAC's system operation could considerably influence the indoor PM levels. On the other hand, when the HVAC system was not in operation, penetration of outdoor particles to the indoors was observed and attributed to cracks or other openings of the building. This study also observed that anthropogenic emission sources and dust were the main contributors of PM composition.

4.2. Educational Facilities

4.2.1. Academic Performance

Poor IAQ has been linked to reduced academic performance. Several field studies conducted on school premises showed that inadequate ventilation associates with impaired cognitive function and decreased academic performance for students. In Scotland [77], field measurements of CO_2 conducted at 60 naturally ventilated classrooms from 30 different schools. The CO_2 levels used as surrogate for the ventilation state. The outcomes showed that the Time Weighted Average (TWA) of CO_2 concentrations was negatively associated with the students' school attendance. Specifically, an increase of 100 ppm in the averaged CO_2 levels, was related to a decreased annual student attendance of 0.2%. In addition, the researchers noted that, an association between poor ventilation and various negative health effects was required for further exploration. In another study at a primary school in UK [78], the effects of CO_2 concentrations on the cognitive function of students were investigated by using computerised cognitive tests. The main results showed that the reaction times of students were prolonged when CO_2 measurements were high (i.e., $>$2000 ppm). The elevated levels of CO_2 showed a decrease of 5% in power of attention. Similar results were also obtained from another study at 2 university classrooms in Malaysia [79]. The study showed that the elevated levels of CO_2 over time due to inadequate ventilation affected the students' concentration during the lecture hours. An association between field measurements of thermal comfort and human perception was performed for 28 classrooms from 7 schools in Italy [80]. It was found that CO_2 levels were extremely high in 15 of the studied classrooms due to insufficient ventilation and that students mostly complained with regards to thermal conditions in warm seasons and poor IAQ conditions.

4.2.2. Health Impact

Strong evidence exists that demonstrates the association between poor IAQ and insufficient thermal conditions to multiple health problems. In this context, several field measurement studies have been published that consider educational environments and the impact of various IEQ conditions on the children's health.

A large-scale cross-sectional study was conducted in 319 classrooms from 115 schools in 23 European countries over a two-year study period [81]. The main findings showed that indoor air pollution was associated with various health problems in children. Both positive and negative associations were observed between VOCs, PMs, and different diseases. In addition, significant associations were observed between CO_2, T, RH, as well as ventilation rate and symptoms of lower airways. In another large-scale study for 70 schools in the US, IEQ parameters including classroom ventilation rate, T, and cleanliness of the high contact surfaces, are found to have a significant effect on students' health and academic performance [82].

Limited field studies related to the infection risk of COVID-19 have been carried out in educational indoor environments. In one study [83], in the Norwegian University of Science and Technology, the authors investigated the probability of infection risk of COVID-19 in a mechanically ventilated lecture hall. The measured parameters were T, RH, and CO_2 levels. The measured CO_2 concentrations in indoor air were used for the calculation of the ventilation rate, which then applied in Wells–Riley equation for the estimation of the probability of infection.

4.2.3. Green Buildings

In relation to newly constructed green/sustainable buildings, it has been shown that the concentration of air pollutants is higher in comparison with conventional buildings. While outdoor conditions and contaminant concentrations affect the overall IEQ, it has been found that user activities in combination with the increased air-tightness, especially in modern green buildings, are among the top factors that influence indoor PM concentrations in naturally ventilated school settings.

In a pilot study presented in [84], the impact of building and occupancy status on the IAQ within newly constructed (LEED-certified), retrofitted, and traditional buildings in a campus setting was evaluated for 3 educational buildings in the US. Field measurements were conducted with a custom-built air sampling station for $PM_{2.5}$, PM_4, PM_{10}, CO_2, CO, NO_x, NO_2, NO, and HCHO, as well as T and RH. The main results showed that the average outdoor levels of PMs were significantly higher than the indoor levels in both classrooms and common areas. The average levels of $PM_{2.5}$ were significantly differed between the different building zones (classrooms/common areas/outdoors). No significant impact of occupancy status was observed on HCHO levels. In addition, both PM_{10} and $PM_{2.5}$ levels were observed to change significantly among different building types. The highest concentrations were observed in the newly constructed buildings. In contrast, the building type appeared to have no significant impact on PM_4 levels. Among all building types, the average levels of HCHO found to be highest in the newly constructed buildings. According to the authors, in the case of newly constructed buildings the occupants' intervention on ventilation equipment (blocking of air vents) led to inadequate air flow in the buildings.

In another study in [85], field measurements were performed in 4 naturally ventilated school buildings in an effort to associate the ambient air pollution levels, IAQ, building defects, and indoor activities. The measured parameters included $PM_{2.5}$, PM_{10}, CO_2 and indoor temperature, and acquired using portable data loggers. According to the researchers, the improved building's air tightness might reduce outdoor air particles' infiltration and help to maintain a higher indoor temperature in winter. At the same time however, the improved air tightness might lead to an increase of indoor CO_2 levels due to insufficient fresh air supply.

In Korea, a field study was performed to explore the different levels of indoor air pollutants within 55 school buildings of different academic grades [86]. The study focused on exploring the correlation of the indoor pollutant levels in relation to the age of the buildings. Considered parameters included CO, CO_2, PM_{10}, TVOCs, HCHO, Total Microbial Count (TMC), as well as T and RH. After a statistical analysis, the results showed that emissions of chemical compounds from building materials or furnishings and inadequate conditions of ventilation contributed to elevated indoor air pollution levels. Specifically, high concentrations of CO, TVOCs, and HCHO occurred at schools constructed within 1 year. Furthermore, indoor TMC levels in all sampling sites were significantly higher during the summer and the autumn seasons in comparison with the winter season. The I/O ratios of CO in all sampling sites were lower than unity, indicating that the main contributor of CO was an outdoor source. It was also observed that during the summer season the average indoor temperature and RH varied in the range of 23.6–33 °C and 30.1–84.6%, respectively, while during winter, the indoor environmental conditions were 14–28 °C and 16.5–73%.

A subjective evaluation on IEQ was conducted in a University Campus in Italy [87]. Questionnaires were administered to 562 engineering students of the campus. The questions focused on IEQ-related subjects including thermal comfort, IAQ, acoustic and visual comfort, as well as student perception of indoor spaces, aesthetics and orientation. Survey results showed a high percentage of dissatisfied students (>40%) with thermal comfort and IAQ issues in classrooms. Specifically, the main students' complaints were related to poor ventilation and thermal conditions, and the presence of stale air in classrooms. In addition, over 50% of students found it difficult to orient within the campus building facilities. Beyond the subjective investigation, ideas were also proposed for the redevelopment of a sustainable building environment, including topics such as the conformation of places, building facades, classrooms without windows, and ways of signposting for better orientation within the campus.

4.2.4. Ventilation Strategies

There is evidence that the ventilation strategies and type can significantly affect the IEQ. In this context, in [88], the effects of different ventilation strategies on thermal comfort, IAQ, and sound quality were investigated in 9 schools in England. The field measurements conducted with thermal comfort analysers, data loggers and sound level analysers during the heating season. The classrooms' samples included natural ventilation, mechanical ventilation, and mixed mode ventilation conditions. The main results showed that under both mechanically and mixed mode ventilation, problems arise with cold draughts coming from the ventilation systems which increased occupants' discomfort. Moreover, it was observed that six naturally ventilated classrooms exceeded the daily average of 1500 ppm of CO_2 as determined by the Building Bulletin 101 standard (BB101). Interestingly, the openable area of windows in these classrooms was restricted for safety reasons, resulting in low outdoor air supply rate and thus, elevated CO_2 levels in these classrooms. In the Netherlands, an experimental study was conducted in 17 schools to assess the effects of different ventilation settings on the IAQ in the classrooms [89]. For the field measurements, passive samplers and data loggers were used for CO_2, $PM_{2.5}$, PM_{10}, and NO_2 concentrations as well as endotoxin and β(1,3)-glucan levels while a mechanical ventilation device was used to change between different ventilation rates. The main findings of the study showed that the increased ventilation rate led to a significant reduction in endotoxin, β(1,3)-glucan, and PM_{10} levels. On the other side, no significant changes were observed in the levels of $PM_{2.5}$ and NO_2.

4.2.5. IEQ Analysis

Investigation of IEQ conditions as compared to the recommended levels and standards have also been reported by many educational facilities around the globe. In Turkey, a field study investigated the effects of outdoor air on the IAQ in four classrooms in Batman University [90]. On-site measurements were conducted both indoors and outdoors with handheld air quality devices for temperature, relative humidity, CO_2, Rn, and PMs. The main objective of this study was the comparison between the field measurements and various air quality standards. Overall, the average indoor CO_2 and PMs concentrations were significantly higher than the upper recommended limits of ASHRAE, EU, WHO and Hong Kong. The dominant factors for elevated indoor concentrations were insufficient ventilation and the outdoor air pollutant emissions by heavy traffic. Another case study presented [91] investigated the IAQ in 32 mechanically ventilated classrooms in Qatar. Indoor and outdoor field measurements were conducted with portable data loggers and passive samplers for temperature, RH, CO, CO_2, and PMs. According to the authors, the increased number of pupils in small classroom volumes combined with insufficient ventilation systems could increase the indoor CO_2 concentrations. Furthermore, the infrequent cleaning of surfaces and the direct penetration of outdoor PMs into the classrooms could contribute to elevated PMs concentrations indoors.

The exposure of children to indoor air pollutants, was investigated for 27 primary schools coming from both urban and suburban areas in Belgium [92]. In situ measurements were conducted with passive samplers for $PM_{2.5}$, NO_2, SO_2, O_3, and BTEX (benzene, toluene, ethylbenzene and xylene) concentrations. The study outcomes showed that the average indoor $PM_{2.5}$ levels were higher than outdoors in almost all schools during the sampling period. In addition, a significant difference in elemental composition between indoor and outdoor PMs was identified by a lab analysis. Specifically, elements related to the re-suspension of dust from carpets were identified in the indoor PMs. High concentrations of benzene were also observed in classrooms located at lower levels. Poor IEQ conditions, especially with respect to issues relating to IAQ were also observed in 16 air conditioned schools in United Arab Emirates (UAE) as indicated from the field measurement study presented in [93]. The authors showed that the average levels of TVOCs, CO_2, and PMs exceeded the Dubai municipality standards. In Cyprus, a field measurement campaign was conducted at 42 primary schools following “The 2021 School Temperature and Environmental Pollutants (STEPS) Study [94]”. A variety of different parameters were measured both indoors and outdoors using sensor instruments (T, RH, bVOCs, CO_2, and PMs), as well as passive samplers (benzene, toluene, ethylbenzene, xylenes). There is an ongoing investigation to assess the results of this study in terms of IAQ related standards and guidelines.

4.2.6. Wireless Custom-Built Solutions

Low cost Wireless Sensor Network (WSN)/IoT-based solutions have also been proposed for the IAQ assessment of educational facilities. The development of a low cost WSN monitoring system for IAQ assessment in real time was presented in [95]. The custom-built IAQ system consisted of sensors measuring temperature-RH, CO_2, CO, and illuminance. To evaluate the system and prove its performance, field measurements were conducted in two classrooms. In [96], the authors proposed a smart air device to collect measurements related to the IAQ. The sensor array in the device consisted of PM, VOC, CO, and CO_2 sensors, as well as a temperature-humidity probe. The collected data can be transmitted in real time to a web server for processing, visualization, and further analysis. It is worth noting that the Korean Ministry of Environment has approved this device using testing protocols as reliable for IAQ monitoring.

4.3. Residences

Only a few field measurement studies exist for IEQ in residences, probably due to the vast variations between the residences and the possible reluctance of homeowners to participate in such studies. The main studied parameters are VOCs and thermal comfort for people living in tropical climate conditions.

One of them is a large-scale study presented in [97], where a large number of air samples $(N = 2242)$ was obtained from 622 flats in Germany. In this study, 60 different VOCs were measured using passive samplers. Two data analysis techniques were performed to identify emission sources and patterns of VOC compounds. The main study results showed that ventilation, occupant activities, furnishings, natural processes, and a combination of these factors considerably influenced IAQ. In another large-scale study, the effect of building characteristics on indoor VOCs levels were investigated in 169 energy-efficient residences in Switzerland [98]. In situ measurements were conducted with passive samplers over one week for monitoring of VOCs and aldehydes in master bedrooms of the residences. The main outcomes showed that interior renovation of residences and absence of mechanical ventilation systems associated with increased indoor levels of HCHO, toluene, and butane. In almost all studied master bedrooms (90%) the levels of HCHO exceeded the chronic exposure limits. Residences with attached garages had higher concentration of TVOC compared to other garage types.

In Indonesia, the thermal comfort perception and preference of occupants in 274 naturally ventilated households were investigated and presented in [99]. A comprehensive analysis was performed using field measurements and questionnaires. Dry bulb temperature, RH, mean radiant temperature, and V as well as clothing and metabolic rate were the main measured parameters. On-site measurements were performed by sensor probes and data loggers, which were all mounted on a tripod. After a statistical analysis, the study resulted that that PMV index predicted warmer thermal perception compared to what occupants actually felt. Occupants living in tropical regions with hot and humid climatic conditions showed preference to cooler temperatures as compared to what the neutral (comfort) temperature showed. They also, seemed to prefer higher air movement by opening the windows to make their indoor environment more thermally comfortable. Similar results were also obtained by [100], who showed using both field measurements and residents' questionnaires that people living in tropical climates expected a cooler environment. In addition, the analysis of gender differences in terms of thermal comfort indicated that females were more sensitive to changes of air temperature than males.

In another study presented in [101], a characterisation of IAQ was performed for six households in Hong Kong. The study showed that the average CO_2 and PM_{10} concentrations were higher in almost all the kitchens in comparison with the living rooms. Further investigation showed that poor ventilation in the kitchens was the main contributor for the elevated CO_2. The major influencing factors of elevated PM_{10} were the infrequent cleaning, and the infiltration of outdoor air through the buildings. In addition, the cooking using Liquified Petroleum Gas (LPG) had more significant impact on VOCs concentrations compared to the use of natural gas.

A low-cost WSN system was developed to assess the IAQ in real time [102]. The sensor nodes were installed in the bedroom, the living room, the office, and the kitchen to monitor temperature, RH, ammonia (NH3), CO_2, NO_x, and benzene. The results showed poor IAQ in the kitchen due to the cooking activities.

4.4. Care Centers

A small number of field studies were conducted in care facilities for elderly people. In Taiwan, the effects of different IEQ parameters were investigated in 12 care centres [103]. The field measurements conducted in the bedrooms space for sampling of CO_2, CO, airborne dust, temperature, RH, air velocity as well as noise and illuminance levels. Noise, and RH level found to negatively impact occupants the most among all the studied physical parameters. In China, the effects of different IEQ parameters were investigated in 15 rooms of a nursing home [104]. Both questionnaire surveys and physical measurements were performed to develop two machine learning predictive models for assessment of the IEQ. The physical measurements were conducted through a WSN system for monitoring of the T, the RH, the CO_2, as well as noise and illuminance levels. Temperature was determined as the most significant contributor on IEQ acceptance level. The characterisation of indoor environmental conditions was performed in three naturally ventilated social housings with elderly people in Spain [105]. On-site measurements were conducted in the living room and bedroom of each studied apartment by two portable data loggers. Sampling data included indoor temperature, RH, and CO_2 concentration. The main results showed unhealthy indoor CO_2 levels (i.e., >900 ppm) and very low indoor temperatures in all monitored locations mainly due to the ventilation pattern of the building users. Decreased levels of CO_2 were also obtained in the bedrooms with doors in open position during sleeping periods.

4.5. Other

There are also some studies that include building types not belonging to the four aforementioned categories or include comparisons between buildings from more than one category. A field study in Florida, US was conducted in both an educational office space and a residential apartment to compare multiple environmental factors [106]. A custom-built air quality monitoring system was used to log the field measurement, where multiple individual sensor modules were integrated onto a low-cost Raspberry Pi 3B Plus board. The measured parameters were T, RH, PMs, NO_2, SO_2, CO_2, CO, O_3, and TVOC. Statistical and correlation analysis were performed to examine the relationships between all air quality factors. The outcomes showed that the average indoor PMs concentration was higher in the residential apartment compared to the office place. The CO_2 concentration was significantly higher in the residential apartment (i.e., 2195 $\mu g/m^3$) than at the office (i.e., 423 $\mu g/m^3$). The average O_3 concentration was also higher (i.e., 12.1 ppb) in the apartment compared to the office (i.e., 2.37 ppb). Moreover, average indoor NO_2, SO_2 and TVOC levels were relatively similar at both sites. According to the correlation analysis, SO_2 was strongly correlated with PMs (i.e., R = 0.9) at both monitoring sites. The levels of RH were significantly higher (i.e., 70.4%) in the office compared to the apartment (i.e., 45.5%).

In India, the IAQ in non-residential urban buildings was investigated within 2 offices and 1 educational building [107]. In situ measurements were mainly conducted with passive samplers for CO_2, $PM_{2.5}$, and VOCs concentrations. The analysis of the measurements and main results of the study were obtained through statistical analysis. The main results showed that ductless air conditioning systems and inefficient air circulation were the main contributors to the high levels of $PM_{2.5}$ inside the studied buildings while average indoor CO_2 concentrations in the same floor might vary in different sampling locations. The authors also noted that large number of office equipment such as copier machines and computers were important sources of VOCs. Moreover, the maximum Total Health Ratio Indicator (THRI) was observed in the building that had the highest air pollutant concentrations compared to the other studied buildings.

The effects of outdoor air pollution on IAQ were investigated for a mechanically ventilated shopping mall in Hong Kong, China [108]. Fixed and mobile indoor sampling was conducted to capture the spatial heterogeneity of air pollutants. Both indoor and outdoor measurements were performed for $PM_{2.5}$, PM_{10}, NO_2, and CO. The quantification of the effect of outdoor air pollution on IAQ was based on the estimation of the well-known Infiltration Factor (IF), which indicates an average fraction of outdoor pollutants that occur indoors over a time period. Regression analysis results showed an increased effect of outdoor air pollution on IAQ during the mall opening hours. In particular, 75% of $PM_{2.5}$, 53% of PM_{10}, and 59% of NO_2 were infiltrated into the mall. Considerable spatial variations were also observed for PMs and NO_2 near the major entrances and the dining area. The authors concluded that the large portion of unfiltered air infiltrated from outdoors and cooking activities, were the main factors for the accumulation of air pollutants at these locations.

One study [109] conducted experiments in 3 different indoor environments using a WSN air quality monitoring system to assess the influencing factors on IAQ. On-site measurements were conducted in a classroom, a living room, and a church. The authors concluded that many factors contribute to the IAQ such as location, airflow, the people density, size of room, and different room materials. In another field measurement study presented in [110], the relationship between indoor and outdoor $PM_{2.5}$ concentrations and the effectiveness of the ventilation systems and the air cleaners were explored. On-site measurements were performed in 7 different mechanically ventilated public and residential buildings in Beijing including a stadium, a hotel, a shopping centre, a research centre, a commercial office, an apartment and a detached villa. The analysis results confirmed the effectiveness of the ventilation systems and the air cleaners to lower approximately 90% the $PM_{2.5}$ concentrations in all sampling sites. A web-based monitoring system for indication of the IAQ parameters in real time is developed for 1 double-storey building in Malaysia [111]. A number of different parameters were monitored using a WSN including T, RH, CO, CO_2, VOC, CH_4, and PM. A high concentration of VOCs was observed at the chemical lab due to the release of different chemical compounds into the room air.

5. Discussion

In this section, a critical analysis of the collected information is presented, with key statistics and interesting observations. In addition, current challenges and existing gaps related to field measurement studies are also identified and discussed. The detailed characteristics of the measurement studies discussed in this section can be found in Tables A2–A4 in the Appendix A.

5.1. Building Type

Figure 5 illustrates statistics on the type of built environment for the 41 selected field measurement studies presented in Table A4. From the plot, it becomes evident that the majority of field studies were conducted in Educational facilities with a percentage of approximately 49%, followed by Offices and Residences, both with 14.5%, Care centers with 7.5%, while the remaining 14.5% were either conducted in a combination of the aforementioned built environments, or in other types of buildings. It is worth pointing out, that educational facilities are characterized by high levels of occupancy, the young age of occupants, the long duration and the weekly consistency of activities from the same occupants; characteristics which render them ideal environments for such controlled field studies. It is evident however, that a very limited number of field measurement studies exist for other types of indoor environments, such as gyms, hospitals, shopping malls and train stations. Such environments are also of high interest since they exhibit a high number of occupants daily both in terms of staff and visitors with various types of activities and could significantly contribute to the understanding of the impact of poor IEQ.

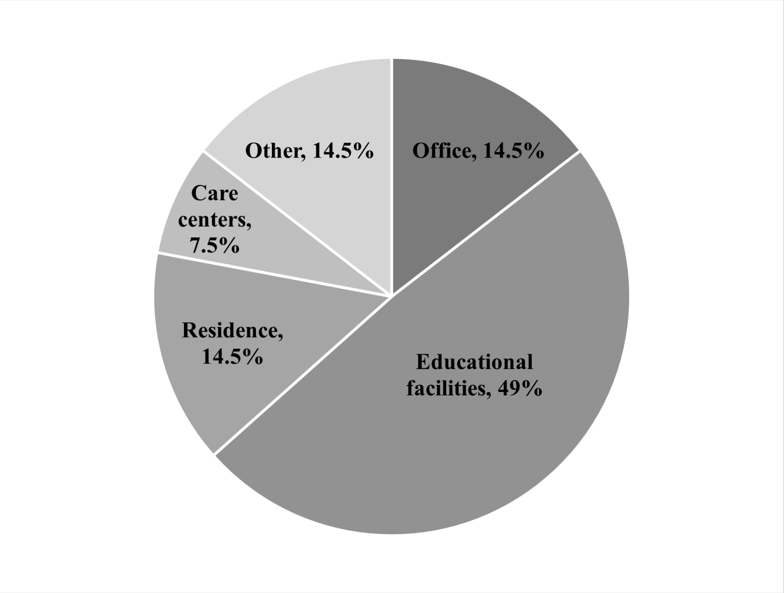

Figure 5. Building type statistics for the selected field measurement studies.

5.2. Measured Parameters

Figure 6 illustrates the percentage of the studies considering each measured parameter as compiled from the data of Table A2. It is evident that the most common parameters measured in the considered field studies are T and CO_2 with 75.6% and 73.2% of the field studies, respectively, followed by RH with 70.7% of the field studies, PM with 56.1% and VOC with 41.5%. On the other hand, the least common parameters are Rn which is considered in just 4.9% of the field studies, SO_2 with 7.3% of the field studies, O_3 with 9.8%, HCHO with 12.2%; while RT, N, and NO_2 were considered in 17.1%, 14.6% and 17.1% of the field studies, respectively. Interestingly, one of the most harmful gases, i.e., radon (Rn), is at the same time the least studied parameter throughout the presented studies. However, one of the largest studies presented in [81] that considers 319 classrooms from 115 schools in Europe has already identified that Rn levels were above recommended in the majority of the field sites. One could thus argue that Rn monitoring and the understanding of its impact in our daily lives is still an under-investigated problem.

5.3. IEQ Influencing Factor

Figure 7 illustrates the IEQ influencing factor statistics compiled from the presented data in Table A3. As expected, the majority of the field measurement studies (i.e., 92.7%) are concerned with the analysis of IAQ while 26.8% consider thermal comfort, and acoustic and visual comfort are considered in 17.1% each. In combination with the percentages of considered parameters we deduce that most of the studies considering IAQ are focused on the analysis of pollutants such as CO_2, PM and VOC, while field studies considering other harmful pollutants are less common. This can be mostly attributed to the availability and cost of sensors for specific pollutants, rather than more generic or cheaper sensors measuring VOCs and CO_2, for example. In addition, our review shows that studies which consider IAQ far surpass the percentage of studies conducted for thermal comfort, which clearly indicates the increased concern over the last two decades for the health impact of various indoor pollutants. It should be noted that for this work special attention was given to field measurement studies focusing on IAQ analysis. It is also worth pointing out, that even that most of the studies that consider IAQ are also collecting measurements for temperature and RH, they are not considering thermal comfort. In fact, the combination of the IAQ measurements, specifically CO_2 with measurements for temperature and humidity could have also been used for analysing the virus transmission risk for these environments (e.g., through the use of the Wells–Riley Equation (1)). However, only a small percentage of 2.4% of the considered field measurement studies are currently performing such an analysis.

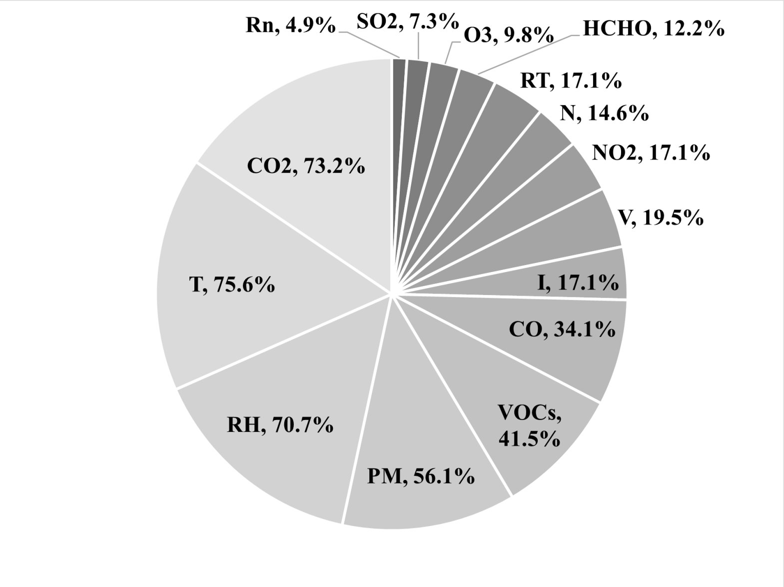

Figure 6. Measured parameter statistics for the selected field measurement studies.

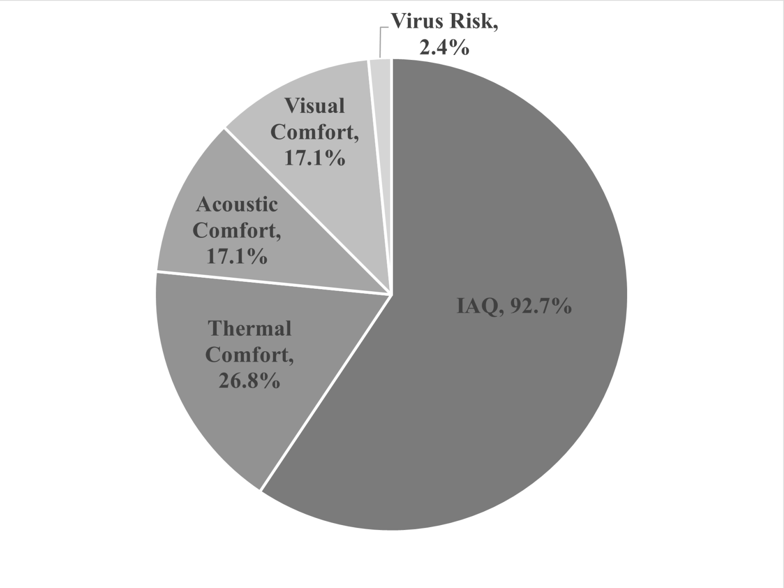

Figure 7. IEQ influencing factor statistics for the selected field measurement studies.

5.4. Data Collection Methods

Figure 8 illustrates the percentages of different methodologies used to collect data for the considered field measurement studies as compiled from the data of Table A2. From the figure, it can be seen that 87.8% of the studies used sensors, 31.7% used passive samplers, while only 29.3% of the studies utilized questionnaires to collect information from occupants. Interesting to note is that considering the studies that utilized sensors as presented in Table A2, approximately 63.4% used Off-The-Shelf (OTS) sensors, 7.3% used Custom Sensors (CS), while 12.2% used a combination of the two. However, only 47% of the studies using sensors, mentioned any form of calibration, either Factory Calibration (FC) or Manual Calibration (MC). These differences in calibration methodologies used, as well as the complete absence of calibration in some cases, could possibly lead to variability between sensors' performance and increase the difficulty of data comparison between the various studies. Ensuring calibration of equipment based on available standards, should be a key cornerstone for future field measurement studies.

Taking a deeper dive and also considering the detailed information presented in Table A4, it can be seen that most field measurement studies collect measurements using either portable loggers or passive samplers, while only four studies used wireless technologies for the transmission of measurements. Data loggers such as those from, TSI Incorporated (Shoreview, MN, USA) [112], GrayWolf Sensing Solutions (Shelton, CT, USA) [113] and Bertin Instruments (Montigny-le-Bretonneux, France) [114] are known to outperform low-cost wireless sensors in terms of accuracy, consistency and performance; however, their high cost prevents large scale massive deployments for extended periods of time. Testament to this is the short measurement duration for the considered field studies, i.e., mostly less than a week for each location and the need of selection of specific seasons, mostly winter and summer. Likewise, passive samplers, while they can produce detailed results for multiple parameters at once, they need to be analysed in a lab following the field trial, hence they keep no information for the time of measurement apart from the start and end times of the measurement period.

Due to these limitations, most of the considered field studies were concerned with the analysis of data assuming no spatial variations within each measured room and assuming uniform distribution of the measured parameters. While this can be an accurate assumption when considering small rooms, for large spaces with increased occupancy, spatial variations need to also be considered. The inclusion of wireless connectivity through a wireless sensor network could significantly improve the monitoring process by allowing multiple simultaneous locations, even within the same room to be monitored, and extending the duration of the field study, something which can significantly enhance the value and impact of the results. As a matter of fact, in the past decade, sensing equipment improvements have increased the availability of IEQ wireless devices for real-time monitoring that can be easily incorporated in such field studies.

5.5. Main Outcomes and Results

Apart from the measured parameters and the instruments used, Figure 9 illustrates the percentages of different IEQ analysis outcomes considered in the examined field studies as compiled from Table A3.

5.5.1. Statistical Analysis and Standards

The majority of the studies (i.e., 87.2%) performed some type of statistical analysis, i.e., correlations between the measured parameters and seasonal variations; while another large portion (i.e., 61.5%) performed a comparison of measurements with existing thresholds and standards. A closer investigation revealed a high variation between the different thresholds and standards considered, which indicates the lack of widely acceptable recommended values for the majority of IEQ parameters and highlights the necessity of establishing unified and comprehensive standards.

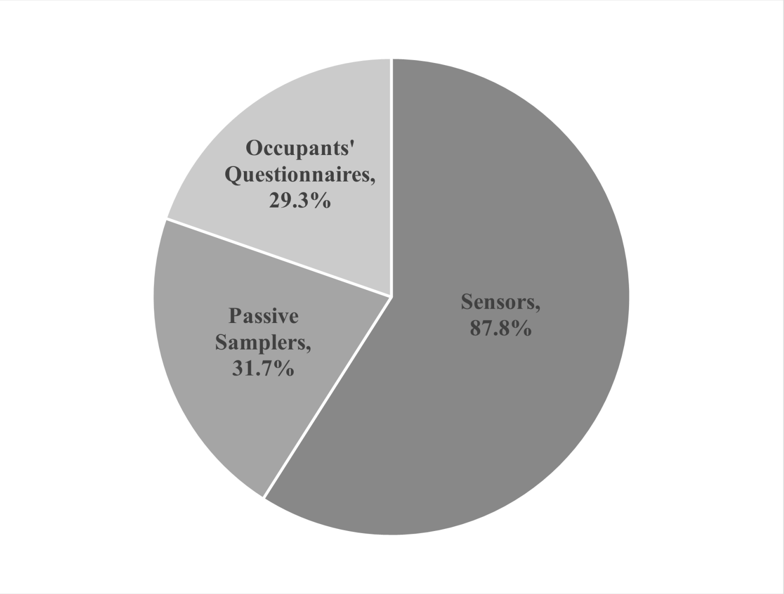

Figure 8. Measuring methods used in the examined field measurement studies.

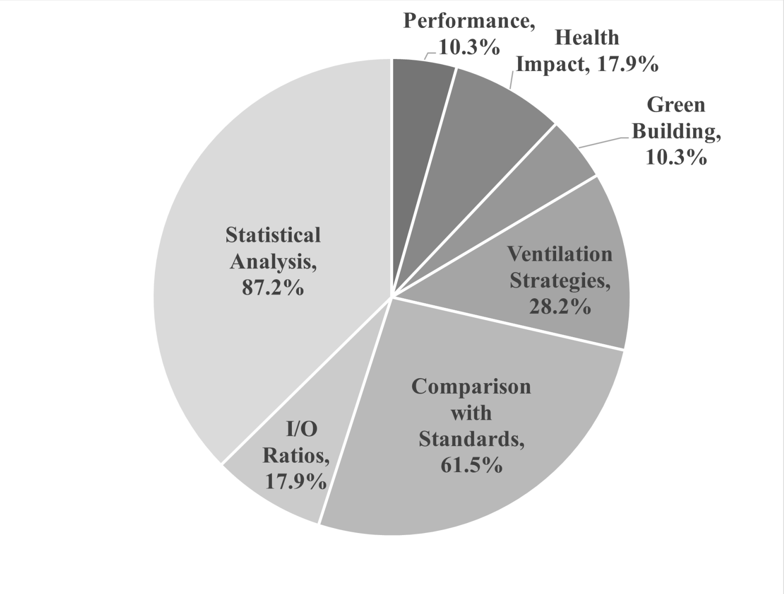

Figure 9. Considered outcomes for the examined field measurement studies.

5.5.2. Ventilation

Ventilation influence and strategies were considered in 28.2% of the field studies that concluded that inadequate ventilation was the major reason for high levels of CO_2, especially in high occupancy environments such as educational facilities. Occupants perception for IEQ was assessed through the use of questionnaires in 12.5% of studies. Interestingly, the results showed that high levels of CO_2 resulted in increased complaints for low comfort and high temperature, which directly indicates the necessity of monitoring and controlling IAQ conditions apart from T and RH to achieve a comfortable indoor environment.

5.5.3. Health Impact & Performance

Health impact was investigated in 17.9% of the considered field studies. Interestingly, the virus risk has been found to be positively correlated with low IAQ conditions. In addition, 10.3% of the studies examined the effects of IEQ on productivity, performance and cognitive capabilities, with a focus on high CO_2 concentrations. While the majority of studies considering thermal comfort investigate the differences between female and male occupants in their perception of IEQ, no investigation was performed for possible health impact, productivity or absence rate differences for the two groups. Moreover, statistics derived from these field studies could possibly be used for the generation of quantifiable metrics for the health impact of various IAQ conditions that can be used for the enhancement of monitoring and decision support systems.

5.5.4. Green Buildings

Comparison and assessment of IAQ in new green buildings in comparison with older buildings were included in 10.3% of the investigated studies. It is clear, that the current trends towards energy-efficient and green designs, as well as weatherproofing and passivity concepts, can have a negative impact on IAQ. Thus, there is an increased need for proper monitoring, control and assessment of new and retrofitted buildings, possibly by comparison with older buildings, for the emergence of new methods and design methodologies specifically addressing IAQ-related issues.

5.6. Real-Time Monitoring and Control

The considered field studies focused on the evaluation of IAQ, the comparison of indoor to outdoor concentrations, the identification of sources of indoor pollution and the correlations between the various pollutants. However, directions such as real-time monitoring and control of the indoor environment (e.g., control of the ventilation rate, opening and closing doors and windows) through advanced analytic solutions and data-driven decision support tools are currently unavailable, especially for high-occupancy, high-impact indoor environments such as educational and healthcare facilities. Moreover, as previously mentioned for larger open spaces (e.g., malls, amphitheaters, airports and cruise ships), there is a need for real-time monitoring and control of the IEQ such that proper measures can be taken when dangerous events take place, like the release of a contaminant due to an accident or even a terrorist attack. Under those conditions, it becomes of vital importance to detect and isolate the contaminant source in order to take appropriate measures and ensure the safety of the occupants. The only way to achieve this, is to monitor the IEQ levels in real-time at multiple points and to have in place appropriate intelligent algorithms that can process the sensor data in real time and take the necessart actions through the appropriate decision support systems [115]. Therefore, together with the need for fine-grained real-time field measurement studies, there is also the need to develop more advanced data analytic solutions for sensor placement and contaminant event monitoring like the ones presented in [116–121].

5.7. Standardisation

Considering the presented field studies holistically, a considerable lack of uniformity and standards is revealed for the assessment and categorization of the different parameters for the indoor environment, as well as a lack of consistency of methods used for calibration of the utilized equipment. In addition, none of the studies compared their results with any green-buildings certifications standards (i.e., RESET, LEED etc.). These inconsistencies are mainly attributed to the vast variability of conditions, locations, indoor environment considerations, assumptions of each study, ventilation conditions and IEQ assessment considerations involved in each study. As a result, the one-to-one comparison between the studies is not possible. A wider adoption of standards using formal assessment methods, would ensure that the results of the studies become comparable and useful to the research community, thus adding to the vast amount of existing data and knowledge. New faster communication routes are also needed for conveying these results back to the policymakers responsible for developing the new standards.

6. Conclusions

IEQ is a significant contributor to the occupants' comfort, productivity and well-being. While multiple works exist that investigate or speculate the effects of various indoor environmental conditions on occupants, field measurement studies in real working environments are the only way to truly understand everyday problems, find possible solutions and define new avenues of exploration for future studies.

This paper provides a comprehensive review of selected field measurement studies that have been conducted in various indoor environments during the last two decades, with an emphasis on IAQ-related studies. Moreover, important background information is presented related to the measured parameters and associated indices and standards for thermal comfort, IAQ and the airborne virus transmission risk, which we expect will become a vital component in future IEQ studies. For the considered field measurement studies, insightful statistics are derived with respect to the influencing factors, location selection, measurement acquisition process characteristics, sensing equipment and main outcomes. The derived statistics, along with the identified important research areas and gaps, can serve as an important reference for the designing of field measurement studies in the future.

In particular, there is a need for standardisation and a holistic approach for designing future field measurement studies for the different types of built environments that take into account all the influencing parameters, including the vast range of pollutants. Currently, there is limited information available for pollutants other than CO_2, VOC, and PM. In particular, radon, a proven harmful pollutant at any level above zero, is rarely considered. There is also a need to consider different types of built environments such as hospitals, care centers, gyms, churches, shopping malls, amphitheaters, train stations, cruise ships, and other indoor spaces where people commonly gather in large numbers or for extended periods of time. For these large open spaces, there is a need to design long-term campaigns with multiple sensing points in order to capture the complex indoor environment and the spatial variability. The use of low-cost wireless sensors and technologies can be instrumental in achieving this, however their use remains limited, mainly due to the absence of standards and calibration procedures for validating the collected measurements. In particular, the establishment of universal standards and guidelines for conducting field measurement studies is the most important requirement for increasing the usefulness and facilitating the comparison between the vast amount of collected data. Only then, can useful results be extracted that will lead to corrective measures for improving the IEQ and ensuring the health, comfort, productivity and well-being of the occupants.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. IAQ Recommended Levels and Field Measurement Studies Collective Results

Table A1. Recommended Levels.

Parameter	Recommended Levels
Physical parameters	
T	ASHRAE 55 (residences): [122], 19.5–27.8 °C
RH	• EPA (residences) [123]: 30–60% • ASHRAE 62.1 (residences) [124]: $\leq$65% • ASHRAE (classrooms) [125]: 40–60% (prevention airborne virus transmission)
N	WHO [126]: • Classrooms & Residences: 35 dBA • Bedrooms: 30 dBA
I	EN 12464-1 (Classrooms & Offices) [28]: 500 lux
V	Harvard T.H. Chan (classrooms—(Classroom densities: 25 students/1000 ft^2 for 5–8 years-old)) [69]: • Ideal: 6 ACH • Excellent: 5–6 ACH • Bare minimum: 3–4 ACH • Low: <3 ACH
Chemical parameters	
PM	RESET Air Standard ($PM_{2.5}$) [49]: • Acceptable: <35 μg/m^3 • High performance: <12 μg/m^3 WHO ($PM_{2.5}$) [127]: • Annual mean: 5 μg/m^3 • 24 h mean: 15 μg/m^3 WHO (PM_{10}) [127]: • Annual mean: 15 μg/m^3 • 24 h mean: 45 μg/m^3
CO	WHO [127]: • 24 h mean: 7 mg/m^3 • 8 h mean: 10 μg/m^3 • 1 h mean: 35 mg/m^3 • 15 min mean: 100 mg/m^3 ACGIH (workplaces) [128]: • 8 h TWA: 25 ppm
CO_2	RESET Air Standard [49]: • Acceptable: <1000 ppm • High performance: <600 ppm ECDC [129]: • <800–1000 ppm to ensure sufficient ventilation (prevention airborne virus transmission)

Table A1. *Cont.*

Parameter	Recommended Levels
SO_2	WHO [127] • 24 h mean: 40 µg/m^3 • 10 min mean: 500 µg/m^3
NO_2	WHO [127] • Annual mean: 10 µg/m^3 • 24 h mean: 25 µg/m^3 • 1 h mean: 200 µg/m^3
O_3	WHO [127]: • 8 h mean (peak season): 60 µg/m^3 • 8 h daily maximum: 100 µg/m^3
VOC	WHO [48]: • Benzene annual mean: 1.7 µg/m^3 ACGIH (workplaces) [128]: • Includes limit values for several chemical substances RESET Air Standard [49]: • Acceptable: <500 µg/m^3 • High performance: <400 µg/m^3
Rn	WHO [130]: • Annual mean: 2.7–8 pCi/L EU [131]: • Annual mean: 8 pCi/L EPA [132]: • Annual mean: 4 pCi/L ICRP [133,134]: • Annual mean: 8 pCi/L

Table A2. Field measurement studies parameters and indices.

Ref.	**Selected Measured Parameters**															**Measuring Methodology**			
	T	**RH**	**RT**	**V**	**N**	**I**	**PM**	**CO**	**CO_2**	**SO_2**	**NO_2**	**O_3**	**VOCs**	**HCHO**	**Rn**	**Sensors**	**Calibration**	**Passive Samplers**	**Occupants' Questionnaires**
Offices																			
[71]							✓				✓	✓	✓	✓				✓	
[72]	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓			OTS	N/A		✓
[73]	✓	✓	✓	✓												OTS, CS	N/A		
[74]	✓	✓			✓	✓	✓	✓	✓				✓			OTS	FC, MC		
[75]									✓							OTS	MC		
[76]							✓									CS	N/A	✓	
Educational facilities																			
[77]	✓	✓							✓							OTS	FC, MC		
[78]	✓								✓							OTS	N/A		✓
[79]	✓	✓							✓							OTS	FC		
[80]	✓	✓	✓	✓		✓			✓							OTS	N/A		✓
[81]	✓	✓					✓	✓	✓				✓		✓	OTS	FC	✓	✓
[82]	✓	✓							✓							OTS	N/A		
[83]	✓	✓							✓							N/A	N/A		
[84]	✓	✓					✓	✓	✓		✓			✓		OTS	MC	✓	
[85]	✓						✓		✓							OTS	N/A		
[86]	✓	✓					✓	✓	✓				✓	✓		OTS	N/A	✓	
[87]	✓	✓	✓	✓												CS	N/A		
[88]	✓	✓	✓	✓	✓				✓							OTS	N/A		
[89]							✓		✓		✓					OTS	N/A	✓	
[90]	✓	✓					✓		✓						✓	OTS	N/A		
[91]	✓	✓					✓	✓	✓							OTS	FC	✓	
[92]							✓			✓	✓		✓					✓	
[93]	✓	✓			✓	✓	✓	✓	✓			✓	✓			OTS	N/A		
[94]	✓	✓					✓						✓			OTS	FC	✓	
[95]	✓	✓				✓		✓	✓							OTS	N/A		
[96]	✓	✓					✓	✓	✓				✓			OTS	FC, MC		

Table A2. *Cont.*

Ref.	**Selected Measured Parameters**															**Measuring Methodology**			
	T	**RH**	**RT**	**V**	**N**	**I**	**PM**	**CO**	**CO_2**	**SO_2**	**NO_2**	**O_3**	**VOCs**	**HCHO**	**Rn**	**Sensors**	**Calibration**	**Passive Samplers**	**Occupants' Questionnaires**
Residences																			
[97]													✓					✓	✓
[98]													✓	✓				✓	✓
[99]	✓	✓	✓	✓												OTS	FC		✓
[100]	✓	✓	✓	✓												OTS	N/A		✓
[101]							✓		✓				✓	✓		OTS	MC	✓	
[102]	✓	✓							✓				✓			CS	N/A		
Care centers																			
[103]	✓	✓		✓	✓	✓	✓	✓	✓							N/A	N/A		✓
[104]	✓	✓			✓	✓			✓							OTS	N/A		✓
[105]	✓	✓							✓							OTS	N/A		✓
Other																			
[106]	✓	✓					✓	✓	✓	✓	✓	✓	✓			OTS, CS	FC		
[107]							✓		✓				✓			OTS	FC, MC	✓	
[108]							✓	✓			✓					OTS, CS	N/A		✓
[109]	✓	✓					✓	✓	✓	✓	✓	✓	✓			OTS, CS	MC		
[110]	✓	✓					✓									OTS	MC		
[111]	✓	✓					✓	✓	✓				✓			OTS, CS	FC		

Sensors: Off-The-Shelf (OTS), Custom Sensors (CS); Calibration: Factory Calibration (FC), Manual Calibration (MC), Not Available (N/A).

Table A3. IEQ Analysis and Influencing factors.

Ref.	**IEQ Analysis**							**IEQ Influencing Factors**				
	Performance	**Health Impact**	**Green Building**	**Ventilation Strategies**	**Comparison with Standards**	**I/O Ratios**	**Statistical Analysis**	**IAQ**	**Thermal Comfort**	**Acoustic Comfort**	**Visual Comfort**	**Virus Risk**
Offices												
[71]							✓	✓				
[72]				✓	✓		✓	✓	✓	✓	✓	
[73]							✓		✓			
[74]					✓		✓	✓	✓	✓	✓	
[75]				✓				✓				
[76]					✓	✓	✓	✓				

Table A3. *Cont.*

Ref.	IEQ Analysis							IEQ Influencing Factors				
	Performance	Health Impact	Green Building	Ventilation Strategies	Comparison with Standards	I/O Ratios	Statistical Analysis	IAQ	Thermal Comfort	Acoustic Comfort	Visual Comfort	Virus Risk
Educational facilities												
[77]		✓					✓	✓				
[78]	✓						✓	✓				
[79]	✓						✓	✓				
[80]		✓						✓	✓		✓	
[81]		✓		✓	✓		✓	✓				
[82]	✓	✓		✓			✓	✓				
[83]		✓						✓				✓
[84]			✓		✓		✓	✓				
[85]			✓	✓	✓	✓	✓	✓				
[86]					✓	✓	✓	✓				
[87]			✓		✓			✓	✓	✓	✓	
[88]				✓	✓		✓	✓	✓	✓		
[89]				✓			✓	✓				
[90]					✓		✓	✓				
[91]					✓	✓	✓	✓				
[92]						✓	✓	✓				
[93]				✓	✓		✓	✓	✓	✓	✓	
[94]	✓	✓			✓		✓	✓	✓			
[95]							✓	✓				
[96]					✓			✓				
Residences												
[97]				✓			✓	✓				
[98]			✓		✓		✓	✓				
[99]							✓		✓			
[100]					✓				✓			
[101]					✓	✓	✓	✓				
[102]							✓	✓				
Care Centers												
[103]		✓					✓	✓	✓	✓	✓	
[104]							✓	✓		✓	✓	
[105]				✓	✓		✓	✓				

Table A3. *Cont.*

Ref.	**IEQ Analysis**							**IEQ Influencing Factors**				
	Performance	**Health Impact**	**Green Building**	**Ventilation Strategies**	**Comparison with Standards**	**I/O Ratios**	**Statistical Analysis**	**IAQ**	**Thermal Comfort**	**Acoustic Comfort**	**Visual Comfort**	**Virus Risk**
Other												
[106]					✓		✓	✓				
[107]					✓		✓	✓				
[108]					✓			✓				
[110]				✓	✓	✓	✓	✓				
[109]					✓		✓	✓				
[111]					✓		✓	✓				

Table A4. Field measurement studies information.

Ref.	**Location Info (Ventilation)**	**Measurement Period, Duration, Resolution**	**Sensing Equipment (Measured Parameters)**	**Remarks**
[71]	148 offices from 37 buildings (MV), Europe	2012 and 2013 (summer and winter seasons), 5 days, N/A	Passive samplers: • Radiello diffusion tubes (VOCs, aldehydes, O_3) • Gradko diffusion tubes (NO_2) • Low-volume aerosol sampler with quartz fiber filters (PM)	• Assessment of indoor air pollutants in terms of seasonal variation • Significant seasonal variations observed for all the studied pollutants except for the xylenes
[72]	400 offices from 20 buildings, U.S.	2005–2008 (winter and summer season), 10 min, 15 s	National environmental assessment toolkit (CO_2, CO, PM, VOCs, T, RH) with hand-held sensors (V, RT, N, and I levels)	• Data collection using field measurements and questionnaires • Examine gender differences and relationship between IEQ parameters and occupants' satisfaction • Significant difference in thermal sensation found between male and female workers during summer season • Higher air velocity (air flow rates) contributed to lower CO_2 levels
[73]	Premises of Optoelettronica Italia S.r.l., Far Systems S.p.A., R&D Systems S.r.l. (MV), Italy	July 2013, 3 days, 5 s	Wireless Sensor Network: • SHT25 Sensirion (T, RH) • Thermopile detector T11262-01 Hamamatsu (RT) • Thermal Mass Flow (TMF) sensor (V)	• Custom WSN monitoring system for studying thermal comfort • Almost constant air flow observed when the HVAC system was switched off during the weekend • Temperature variations due to sunlight penetration through windows and the exchange of heat with outdoors • Sharp change observed in both air flow direction and temperature when windows opened

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[74]	1 office and an exit of a car-park (MV), Coventry, UK	N/A, N/A, 10 min	Custom portable IEQ monitoring device: • SHT31 Sensirion (T, RH) • HPMA115S0 Honeywell (PM) • CCS811 AMS (VOCs) • IAQ-Core C AMS (VOCs) • MiCS-VZ-89TE SGX Sensortech (VOCs) • T6713 Amphenol (CO_2) • LLC 110-102 SPEC Sensors (CO) • LLC 110-801 SPEC Sensors (IAQ) • TSL2561 TAOS (I) • Adafruit #1063 (N) (Additional calibration—T, RH and CO_2)	• Proposed portable IEQ monitoring device and custom IEQ indicator • Short term experiments showed the variations in IEQ parameters and their impact on an overall IEQ indicator • Increased VOCs concentration due to the use of air cleaners and different sensitivities between the various VOC sensors
[75]	1 high-rise office building (MV), Hong Kong	Field tests in winter season. Simulation tests for summer and spring, N/A, N/A	• Air flow meters • CO_2 sensors (Calibration using an accurate CO_2 sensor) • Fan power meters	• On-site operation and validation of a CO_2-based controlled ventilation approach • Significant reduction in energy consumption and assurance of good IAQ
[76]	1 office building (MV), Doha, Qatar	April–June 2015 (spring season), 2 months, N/A	Low Volume Sampler LVS16, WB Engineering GmbH (PM)	• Chemical characterisation of indoor and outdoor PMs • PMs concentrations exceeded the WHO and EU daily limit values in 100% of the outdoor measurements • Strong positive correlation between $PM_{2.5}$ and PM_{10} for both indoors and outdoors • Anthropogenic emissions and dust were the main contributors of PM composition • Indoor to outdoor association significantly influenced by infiltration through the HVAC system
[77]	60 classrooms from 30 schools (NV), Scotland	May and June 2010, 1 week, 6 min	Portable data loggers: • Telaire 7001Di CO_2 monitor Edinburgh Instruments Ltd (CO_2) (Factory calibrated and One-point calibrations against CO_2 atmospheric levels/week) • HOBO H08-003-02 IAQ logging instrument Onset, Bourne, MA via Edinburgh Intruments Ltd (T, RH)	• Testing of the hypothesis that CO_2 concentrations are negatively associated to student school attendance and educational performance • Time weighted average (TWA) CO_2 concentrations negatively associated with student school attendance

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[78]	1 primary school (MV), Devon, UK	(summer season), random days/week, N/A	Portable data logger, Telaire 7001 monitor (T, CO_2)	• Impact of low ventilation rate on cognitive function of students • Elevated levels of CO_2 showed a decrement of 5% in power of attention
[79]	2 University classrooms (MV), Malaysia	N/A, 2-h, 5 min	Wireless Sensor Network: • DHT-11 sensor (T, RH) • MG-811 sensor (CO_2)	• Exploration of the impact of environmental parameters on students' concentration during the lectures • Elevated levels of CO_2 over time linked with lower students' performance • Lower IQ tests results at the end of lectures compared to the results at the beginning
[80]	28 classrooms from 7 schools (NV), Venice, Italy	2009 and 2010, 1 day, N/A	• Indoor Climatic Analyser Brüel&Kjaer (T, RH, RT, V) Portable data loggers: • IAQ monitor AirBoxx (CO_2) • Minolta CL200 lux-meter (I)	• Study of students' personal impressions with regard to the indoor environmental conditions in the classrooms by use of questionnaires • CO_2 levels were extremely high in 15 studied classrooms due to insufficient ventilation • Students complained mostly with regard to thermal conditions in warm seasons and poor IAQ
[81]	319 classrooms from 115 schools (NV, MV), Europe	November 2011–March 2012, 1 week, 30 min (CO)	• Radiello diffusive samplers (VOCs) • Gammadata RAPIDOS sampler (Rn) • MS&T area sampler Air Diagnostics and Engineering Inc. (PM) • Neotronics Impulse XP (CO) • CaTec Klimabox data logger (T, RH, CO_2) (Factory calibration/year)	• Association between indoor air pollution, insufficient thermal conditions and children health problems using field measurements and questionnaires • Both positive and negative associations observed between VOCs, PMs, and different diseases • $PM_{2.5}$, Rn, and CO_2 exceeded the air quality guidelines. • Significant association between CO_2, temperature, RH, ventilation rate and symptoms of lower airways • Strong negative association between temperature and both RH and CO_2
[82]	70 schools (MV), U.S.	2008–2009 and 2009–2010, 1 week/school, 5 min (T, RH, CO_2)	Portable data loggers: • QTrak Monitor TSI Incorporated, Shoreview, USA (T, RH, CO_2) • Adenosine triphosphate (ATP) monitoring system • Contact agar plates (RODAC) (bacteria)	• Exploration of different IEQ parameters and their effect on health and academic performance of students • Student's performance associated with both indoor temperature and ventilation rate • Health results associated with both ventilation and culturable bacteria

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[83]	1 University lecture hall (MV), Trondheim, Norway	September 2020, 1-h, 1 min	Manual recording (T, RH, CO_2)	• Quantification of the probability of infection risk of COVID-19 • Very low estimated probability of infection risk (0.098%) which was confirmed with the fact that no one else was infected after attending the lecture in the hall
[84]	3 educational buildings (MV), U.S.	N/A, (fall, winter, and spring season), 48-h and 8-h in each season, 1 min	Custom air sampling station: • SKC Buttons, SKC Incorporated, Eighty Four, USA, SKC parallel particle impactors, BGI GK2.05 (KTL) cyclones Mesa Labs, USA (PM) • UMEx 100 passive samplers SKC Incorporated, Eighty Four, USA (HCHO). • Ogawa passive sampler Ogawa, USA (NO_2) • Q-Trak monitor 7575, TSI Incorporated, Shoreview, USA (T, RH, CO, CO_2)	• Evaluation of the impact of the buildings' construction material, utilization and occupancy status on the IAQ within newly constructed, retrofitted and traditional buildings in a campus setting • Average outdoor levels of PMs significantly higher than indoors • Average $PM_{2.5}$ significantly differ between various building zones (classrooms/common areas/outdoors) and occupancy levels • Highest levels of PMs and formaldehyde were observed in the newly constructed buildings
[85]	4 primary schools (NV), Taiwan, China	November–December 2016, 3 weeks, N/A	Portable data loggers: • DUSTTRAK monitor 8530 TSI Incorporated, Shoreview, USA (PM) • BRAMC-SMART-126 detector (PM) • HTV-M detector PPM Company, UK (T, CO_2)	• Association between ambient air pollution, IAQ, building defects and indoor activities • Average indoor PMs and CO_2 exceeded the recommended values • Indoor temperature did not meet the thermal comfort standards • Main source of indoor PMs was outdoors during unoccupied periods and indoors during occupied • Building users' activities and the buildings air-tightness affect indoor PMs
[86]	55 schools, classroom, computer room and laboratory/school (NV), Korea	July–December 2004 (summer, autumn and winter season), 1-day, N/A	• TSI Incorporated, Shoreview, USA 8762 non-dispersive (NDIR) analyser (CO, CO_2) • Airmetrics PAS 201 MiniVol portable air samplers (PM) • Biotest air sampler RCS (TBC), Tenax-TA tubes (VOCs) • Supelco LPDNPH S10 air sampler (HCHO)	• Characterisation of indoor air pollutants concentration in relation to the age of school buildings • Emissions of chemical compounds from building materials or furnishings and inadequate ventilation identified as main contributors of poor IAQ • High concentrations of CO, TVOCs, and HCHO occurred at schools constructed within 1 year • Indoor TBC levels were significantly higher during summer and autumn than winter season

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[87]	26 classrooms from 1 University Campus (MV), Salerno, Italy	May 2019, N/A, N/A	N/A	• Data collection using questionnaires and subjective evaluation of the IEQ and way-finding. • Main students complaints were attributed to poor ventilation conditions and the presence of stale air in classrooms while over 50% of students had orientation difficulties within the campus.
[88]	18 classrooms, from 9 schools in urban, suburban and rural areas (NV, MV), England	2006 and 2007 (winter season), 1 week, 5 min (CO_2), 1 s (T, RH, V)	Portable data loggers: • Quest Technologies AQ5001Pro monitors (T, RH) • Telaire 7001 monitor (CO_2) Thermal comfort analysers: • VAISALA capacitive sensor (RH) • DANTEC heated thermocouple sensor (V) Sound level analyser: • B&K 2260D Investigator with Qualifier type 7830 • Omni Power sound source 4296	• Investigation of the effect of ventilation rates on IAQ, thermal comfort and sound quality in classrooms • 6 naturally ventilated classrooms exceeded the daily CO_2 average of 1500 ppm • Highest ventilation rates observed in the naturally ventilated classrooms • In most of the classrooms the PPD (thermal comfort) was lower than 15% • Cold draughts from the ventilation systems were observed in both the mechanical and mixed mode ventilated classrooms
[89]	18 classrooms from 17 schools (NV), Netherland	2010–2012 (2 winter seasons), 3 weeks, 4 min	Data logger: • GRP-300 Pro or ATV-IAQ set ATAL B.V., Purmerend, The Netherlands (CO_2) Portable passive sampler: • Electrostatic dust collector (EDC) (endotoxin, β(1,3)-glucan) • Harvard impactor Air Diagnostics and Engineering Inc, Harrison, ME, USA (PM) • Ogawa passive sampler OGAWA & Company Inc., Pompano Beach, FL, USA (NO_2)	• Investigate the impact of increased ventilation on IAQ in classrooms • Increased ventilation led to a significant decrease in endotoxin, β(1,3)-glucan and PM_{10} levels

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[90]	4 University classrooms (NV), Turkey	September–May 2018, 2 days/week, 10 min	Portable data loggers: • Extech portable IAQ CO_2 meter • AlphaGUARD PQ 2000 PRO (Rn) • Lighthouse Handheld 3016 IAQ (T, RH, PM)	• Determination of IAQ and comparison with ASHRAE, EU, WHO and Hong Kong standards • Average indoor CO_2, $PM_{2.5}$, and PM_{10} concentration were higher than standards • Average indoor temperature was slightly lower than standards • Average indoor Rn and RH levels were within acceptable limits
[91]	32 classrooms from 16 schools in urban areas (MV), Qatar	December 2015 -March 2016 (winter season), school-hours, 1 min	Portable data loggers: • Q-Trak Indoor Air Quality monitor 7575-X TSI Incorporated, Shoreview, USA (T, RH, CO, CO_2) (Factory calibrated) Portable passive samplers: • Marple $PM_{2.5}$ and PM_{10} 200 Personal Environmental Monitor (PEM) MSP Co., Minneapolis	• Investigation of IAQ • Indoor CO_2 and PM concentration exceeded the ASHRAE, and US-EPA standards • Main contributors of CO_2 in classrooms were indoor sources • High indoor PM levels were observed and attributed mainly to outdoor levels
[92]	27 schools in urban and suburban areas (NV), Antwerp, Belgium	December 2002 and Jun 2003, 5 days, N/A	• MS&T Area Sampler Air Diagnostics and Engineering (PM) • Radiello diffusion tubes (SO_2, NO_2, O_3)	• Assessment of the exposure of children to indoor air pollutants • Average indoor $PM_{2.5}$ levels were higher than outdoor in almost all schools • Different elemental composition of indoor $PM_{2.5}$ than outdoor $PM_{2.5}$ • Re-suspension of dust from carpets was possibly the main contributor indoors • NO_2, SO_2, O_3, and BTEX mainly from outdoor sources • High concentrations of benzene present for classrooms located at lower levels
[93]	16 schools in urban and rural areas (MV), Dubai and Fujairah, UAE	April 2012–Feberary 2013, 8-h daily, 30 s (PM), 15 min (T, RH, CO, CO_2, O_3, VOC)	Portable data loggers: • TSI Optical Particle Sizer 3330 TSI Incorporated, Shoreview, USA (PM) • GrayWolf Direct Sense IAQ-IQ probe 610 (T, RH, CO, CO_2, O_3, VOCs) • SL 130G EXTECH Sound Level Alert with Alarm • HD450 EXTECH Data logging Light Meter	• Investigation of IEQ in UAE classrooms in respect to IEQ standards • Average indoor values of TVOCs, CO_2, and PMs exceeded the standards • High levels of PM_{10} observed during a sandstorm event • High occupancy level contributed to high indoor CO_2 levels • Thermal conditions for T and RH met the recommended limits • Average indoor sound level and lighting levels greater than the recommended limits

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[94]	42 schools (NV, MV), Nicosia, Limassol, Larnaca, Pafos, Cyprus	May–July 2021, 2 days/week, N/A	• PurpleAir sensors, Draper, Utah, USA, (PM) • Radiello passive samplers, Pavia, Italy (Benzene, Toluene, Ethylbenzene, Xylenes) • mcf88 LoRaWAN Indoor Environmental Sensor (T, RH, bVOCs)	• Investigation of indoor and outdoor air quality for primary schools in Cyprus • Data collection using field measurements and questionnaires
[95]	2 classrooms from 1 Polytechnic Institute, Guarda, Portugal	2015, 3 months, N/A	Wireless Sensor Network • SHT10 sensor (T, RH) • MQ7 sensor (CO) • T6615 sensor (CO_2) • LDR 5 mm sensor (I)	• Proposed WSN air quality monitoring system • System implementation and evaluation in an indoor environment • Low cost sensor modules and open-source technologies developed for IAQ monitoring in real time
[96]	1 University, main entrances of the building, laboratories, restroom (MV), Korea	2018, N/A, N/A	• Laser dust sensor PM2007 Cubic Optoelectronics Co. • GSBT11-P110 sensor Ogam Technology (VOC) • GSET11-P110 sensor Ogam Technology (CO) • CM1103 sensor (CO_2) • DHT11 OSEPP Electronics (T, RH)	• A web-based IAQ monitoring platform • Additional calibration and reliability tests with certified devices • Tested and accredited as reliable for IAQ monitoring by the Korean Ministry of Environment
[97]	622 flats, living room/flat (NV, MV), Leipzig, Germany	(summer and winter season), 16 months, N/A	Passive samplers: • Organic Vapor Monitors 3M, OVM 3500 (VOCs)	• Identification of the sources and patterns that describe indoor VOCs • Large sample size ($N = 2242$) • Flats strongly influenced by ventilation occupant activities, furnishings, natural processes or a combination of these factors
[98]	169 energy—efficient residences, bedroom/residence (NV), Switzerland	September 2015, 7 days, N/A	Passive samplers: • Carbon molecular sieve, Anasorb 747 TOXpro SA Switzerland (VOCs) • 2.4—dinitrophenylhydrazine impregnated silica gel TOXpro SA Switzerland (HCHO)	• Investigation the effect of building characteristics on indoor VOCs levels • Higher levels of TVOC at residences with attached garages • Increased levels of formaldehyde, toluene, and butane caused by interior thermal renovation and absence of mechanical ventilation • Chronic exposure limits for formaldehyde exceeded for 90% of studied residences

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[99]	274 households (NV), Jogjakarta, Indonesia	April–June 2001 and November–January 2002 (summer and winter season), one and a half months (06:00-24:00), N/A	Sensor probes and data loggers mounted on a tripod: • Digital thermometer (T) • Electronic psychrometer (RH) • 150mm diameter black painted globe thermometer (RT) • Omni directional hot wire anemometer (V)	• Investigation of thermal comfort for tropical regions • PMV index predicted warmer thermal perception compared to what occupants actually felt • Occupants living in tropical regions showed preference to cooler temperatures (26 °C) as compared to what the neutral (comfort) temperature (29.2 °C) showed • They seemed to prefer higher air movement by opening the windows to make their indoor environment more thermally comfortable
[100]	1944 residences (NV), Hainan, China	Mar.–April (spring and early summer), 2 months, 10 min (outdoor)	Data loggers: • HOBO U12-011 America Onset (Outdoor T, RH) • DT-321S Hygrometer & Thermometer China Hua shengchang (Indoor T, RH) • AZ8778 Black-bulb thermometer Tai wan hengxin, • TESTO 405-v1 Anemomeer German (V)	• Investigation of thermal comfort in tropical island areas • Analysis of gender differences in terms of thermal comfort • Data collection using field measurements and questionnaires • People living in tropical climates expected a cooler environment • Females were more sensitive to changes of air temperature than males
[101]	6 households, living room and kitchen/ household (NV, MV), Hong Kong	July–October 1999, 8-h (CO_2, PM), 1 day (HCHO), 1 min (PM)	Portable data loggers: • Q-Trak monitor 8551 TSI Incorporated, Shoreview, USA (CO_2) • DustTrak air monitor 8520 TSI Incorporated, Shoreview, USA (PM) Passive samplers: • SKC formaldehyde monitoring kit SKC Incorporated, Eighty Four, USA, Mass flow controller FC4104CV-G Autoflow Inc. (VOCs) Bio-aerosol sampler: • Burkard single stage impactor Burkard Manufacturing Co. Ltd. (Additional calibration)	• Investigation of IAQ and indoor emission sources at residential buildings • Higher average CO_2 and PM_{10} concentrations observed in almost all kitchens than living rooms • Insufficient ventilation in the kitchens was the main contributor for elevated CO_2 • Average indoor airborne bacteria levels in kitchens higher than living rooms and outdoors • Significant correlation between airborne bacteria and number of occupants in both kitchens and living rooms • Elevated VOCs concentrations due to cooking with LPG fuel
[102]	living room, bedroom, office, and kitchen	Feb.–Mar 2016, 1 month, N/A	Wireless Sensor Network: • Air quality sensor Winsen Electronics Technology Co., Ltd (CO_2, NO_x, NH3, C6H6) • Winsen Electronics Technology Co., Ltd (RH) • LM 35 Sparkfun (T)	• Proposed WSN air quality monitoring system • System implementation and evaluation in an indoor environment • Poor IAQ observed in the kitchen due to the cooking activities

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[103]	12 care centres bedrooms/centre (NV), Taiwan	January 1994, 24-h, N/A	N/A	• Identification of the significant negative factors on the indoor environment of care centres • Data collection using field measurements and questionnaires • Noise and RH levels found to be the most significant negative factors among all the studied physical parameters
[104]	15 rooms from 1 nursing home (NV, MV), Hefei, China	September 2019, 2 weeks, 10 min	Wireless Sensor Network	• Identification of the main contributors on IEQ acceptance in nursing homes • Development of an IEQ assessment model based on data from field measurements and questionnaires • Temperature determined the most significant parameter on IEQ acceptance • Mean radiant temperature was not measured to compute thermal comfort
[105]	3 social housing apartments, living room, and bedroom/apartment (NV), Spain	Mar.–April & December–January (spring and winter season), 2 days, 2 min	Portable data logger: • Delta OHM HD 21ABE17 (T, RH, CO_2) • Outdoor government meteorology station (CO_2)	• Characterisation of indoor environmental conditions in social housing with elderly people • Data collection using field measurements and questionnaires • Unhealthy levels of CO_2 and low indoor temperatures due to the ventilation patterns of the building users • Decreased levels of CO_2 obtained in the bedrooms with door open during sleeping periods
[106]	1 office and 1 living room (MV), Florida, US	September 2021, 1 week, 10 min	Internet of Things(IoT) enabled sensors: • Aosong Electronics, DHT22 sensor (T, RH) • Nova Fitness, SDS011 sensor (PM) • SPEC sensors (DGS- NO_2 968-043, DGS-SO2 968-038, DGS-CO 968-034, DGS- O_3 968-042) • Senseair K-30 CO_2Meter • Ohmetech.io, uThing: VOCTM • Bosch BME680 air quality sensor (Factory calibrated)	• Proposed IAQ monitoring system • Average indoor $PM_{2.5}$, PM_{10}, CO_2 and O_3 concentrations were higher in the residential apartment compared to the office space • Average NO_2, SO_2, TVOC concentration were relatively similar at both sites • Strong positive correlation between SO_2 and PM concentrations at both sites • RH level was significantly higher in the office compared to the apartment

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[107]	2 offices and 1 educational facility (MV), Delhi, India	June–July 2015, 8-h in a daily basis, 5 days/week, 5 min	Portable passive sampler: • SKC Air pump 224-PCXR8 with PEM impactor SKC Incorporated, Eighty Four, USA (PM) • UltraRAE3000 RAE Systems, USA (VOCs) (Factory calibrated) Portable data logger: • Q-Trak Indoor Air Quality monitor 7575 TSI Incorporated, Shoreview, USA (CO_2) (Additional calibration of all samplers by an electronic calibrator)	• Investigation of IAQ in non-residential buildings and calculation of Total Hazard Ratio Indicator (THRI) • Average indoor CO_2 concentrations can vary due to sampling location, occupancy level or the proximity to a major pollutant outdoor source such as a busy road • Elevated levels of $PM_{2.5}$ due to ductless air conditioning systems and inefficient air circulation • Elevated VOCs due to large number of office equipment such as copier machines and computers
[108]	1 Shopping mall (MV), Hong Kong, China	October 2017, 1 week, 1 min	• Aerocet 831 Handheld Particle Counter and model 212 Ambient Particulate Profiler Met One, Grants Pass, OR, USA (Outdoor, indoor PM) • NO_2-B4, CO-B4 Alphasense Ltd., Great Notley, UK (Outdoor, indoor NO_2 and CO) (Lab and field perfomance tests)	• Quantification of the effect of outdoor air pollution on IAQ and investigation of the spatial heterogeneity of indoor air pollutants. • Increased impact of outdoor air pollution on IAQ observed during mall opening hours. Specifically 75% of $PM_{2.5}$, 53% of PM_{10}, and 59% of NO_2 were estimated to had infiltrated into the mall. • Increased concentrations of $PM_{2.5}$ and CO were observed during the dinner period. • Considerable spatial variations were observed for PMs and NO_2 near major entrances and dining areas.
[109]	1 classroom, 1 living room, and 1 church (MV), Korea	(fall and winter season), N/A, N/A	Wireless Sensor Network • DHT11 sensor (T, RH) • GP2Y1010AU0F, sensor(PM) • GSNT11 sensor (NO_2) • SO_2-AF sensor • T6613 sensor (CO_2) • TGS5042 sensor (CO) • MiCS-2610 sensor (O_3) • TGS2602 sensor (VOCs)	• Design and implementation of a WSN indoor air quality monitoring system based on US-EPA standard • Algorithms development in relation to smoothing, calibration and data aggregation • On-site experiments for the assessment of the prototype system performance in 3 different indoor environments: living room, classroom, and church • Possible influencing factors on IAQ were location, airflow, the people density, size of room, and different room materials • Significant changes in temperature and RH led to the need for calibration

Table A4. *Cont.*

Ref.	Location Info (Ventilation)	Measurement Period, Duration, Resolution	Sensing Equipment (Measured Parameters)	Remarks
[110]	Stadium, hotel, shopping centre, research centre, commercial office, apartment, detached villa (MV), Beijing, China	Feb.–March 2014, 1 h, 10 min	• TSI 8530 TSI Incorporated, Shoreview, USA (Outdoor, indoor PM) • TSI 9545 TSI Incorporated, Shoreview, USA (Outdoor, indoor T, RH) (Additional calibration—T, RH and PM)	• Comparison of indoor and outdoor concentrations of $PM_{2.5}$ • Study the effects of the ventilation systems and air cleaners on $PM_{2.5}$ concentrations • Ventilation systems with air cleaning methods removed approximately 90% of the outdoor $PM_{2.5}$ • Elevated indoor $PM_{2.5}$ concentrations were observed in public buildings compared to residential buildings • Outdoor $PM_{2.5}$ concentrations were the main contributor of increased indoor $PM_{2.5}$ both in public and residential buildings
[111]	One double storey building, Malaysia	N/A, N/A, 1 min	Wireless Sensor Network • Figaro gas sensor (CO, CO_2, VOC, CH4, chlorofluoro carbons, O_2) • GP2Y1010 optical dust sensor Sharp (PM) • HSM-20G sensor (T, RH)	• A web-based monitoring system for indication of IAQ parameters in real time • High concentration of VOCs observed at the chemical's lab due to the release of different chemical compounds into the room air

Ventilation: Natural Ventilation (NV), Mechanical Ventilation (MV).

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