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Review

Review of Parameters Measured to Characterize Classrooms' Indoor Environmental Quality

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Abstract: As attention to indoor environmental quality (IEQ) grows, a systematic strategy for assessing IEQ in schools needs to be developed. For this purpose, this paper presents a summary of parameters measured in school classrooms to characterize the quality of thermal, acoustic, and visual environments and indoor air quality (IAQ). The summary is based on a review of published literature reporting measurements in schools in Europe and North America in the past ten years. It also summarizes the measurement protocols and measured concentrations. Eighty-eight papers describing measurements in schools were identified and analyzed. No unique standardized measuring method was used in the reviewed studies and different parameters were measured. The most often measured parameters were those describing the thermal environment and IAQ. The former mainly comprised air temperature and relative humidity. The latter mainly comprised concentrations of carbon dioxide, particulate matter, radon, formaldehyde, and some volatile organic compounds. The measured parameters describing acoustic and visual environments mainly comprised noise level, reverberation time, and illuminance. A few studies reported additional measurements of radiant temperature, operative temperature, and speech intelligibility. Measurement protocols from different studies show inconsistency in sampling duration and location and expressed results. Measured concentrations also show high variation between studies, with some pollutants exceeding the threshold values proposed by local and/or international organizations such as the World Health Organization (WHO). This review provides the reference for developing a rating scheme and protocols for uniform characterization of classroom IEQ.

Keywords: IEQ; thermal; acoustic; IAQ; visual; measurement

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1. Introduction

Indoor environmental quality (IEQ) depends on the quality of the thermal environment, acoustic environment, indoor air quality (IAQ), and visual environment [1]. IEQ is a primary concern because people spend a significant portion of their time in buildings [2]. A growing body of studies has shown the influence of IEQ on occupants' health, comfort, and well-being, at homes, offices, and schools [3,4].

In the last twenty years, it has been shown that poor schools' IEQ can affect children's health. The study of Gaffin et al. [5] showed that exposure to a concentration of NO_2 greater than 8 ppb in urban American schools was associated with respiratory airflow obstruction in children. Meanwhile, a growing body of studies showed that low indoor environmental quality in schools can impact children's school performance. The study of Wargocki et al. [6] showed that improved classroom ventilation, as indicated by reduced carbon dioxide (CO_2) concentrations from 2100 to 900 ppm, resulted in improved children's academic performance by 12%, while the performance was increased by 20% when classroom temperatures were reduced from 30 to 20 °C [7]. Most of the work published to date examined the effects of one parameter, and no relationships were created between the quality of the indoor environment and health effects and children's school performance. One reason is the complexity and cost of performing measurements. The other is the lack of a rating scheme for IEQ. The latter is needed to take into account interactions between different parameters and their influence on children.

Recently, Wei et al. [8] reviewed parameters measured to characterize IEQ in offices and hotels. Nearly 100 parameters were identified, but no common rating scheme was identified for IEQ. Consequently, the TAIL (Thermal, Acoustic, IAQ, Lighting) rating scheme was developed including twelve IEQ parameters [9]. Moreover, the method to predict the parameters included in TAIL through simulation was developed and is called predicTAIL [10]. No similar rating exists for schools. In this context, the development of this approach to assess IEQ in school buildings is a relevant issue.

Green Building Certification (GBC) schemes identify some parameters to be monitored to describe IEQ. These are Beam plus [11], BREEAM [12], DGNB [13], Green Globes [14], Green Mark [15], Green Star [16], GREENSHIP [17], HQE [18], KLIMA [19], LEED [20], Lotus [21], Trees [22]. They, however, do not share similar methods or a homogeneous approach. Furthermore, only DGNB, HQE and LEED have a specific section focusing on classrooms and schools. GBC schemes are voluntary, therefore criteria applied in these schemes are not systematically used during measurements in schools. In an attempt to develop an IEQ rating scheme for schools, the present work aimed to review existing measurements of IEQ parameters in schools. Three specific research questions were examined: (1) which IEQ parameters were often measured in schools; (2) what measuring methods were used; and (3) what are the main findings from these measurements?

2. Materials and Methods

The Scopus database was used to search for relevant literature. The following combination of keywords was used: ("indoor environmental quality" OR "IEQ" OR "thermal" OR "acoustic" OR "indoor air quality" OR "IAQ" OR "luminous" OR "visual" OR "lighting") AND ("school" OR "daycare center" OR "nursery" OR "university") AND ("measurement"). To ensure a collection of studies with the latest and up-to-date measurement protocols, the search only covered papers published from 2010 with the following topics: environmental sciences, engineering, social sciences, energy, and multidisciplinary.

A total of 573 papers were identified. A geo-localization filter was applied as only studies in Europe and North America were included to ensure comparability across studies regarding climate conditions, surrounding environment, and building characteristics. Consequently, 324 articles were retained and used for screening. Non-relevant to IEQ measurements in schools, simulation studies, and studies based only on questionnaires were removed. This screening resulted in 79 papers. Nine additional papers were identified and added manually although they did not appear in the initial search. Finally, 88 papers were analyzed in this review. Figure 1 presents a PRISMA flowchart describing the paper selection. It should be noted that 11 studies in university classrooms were included in the review because universities are school environments, even though the students are young adults and no longer children.

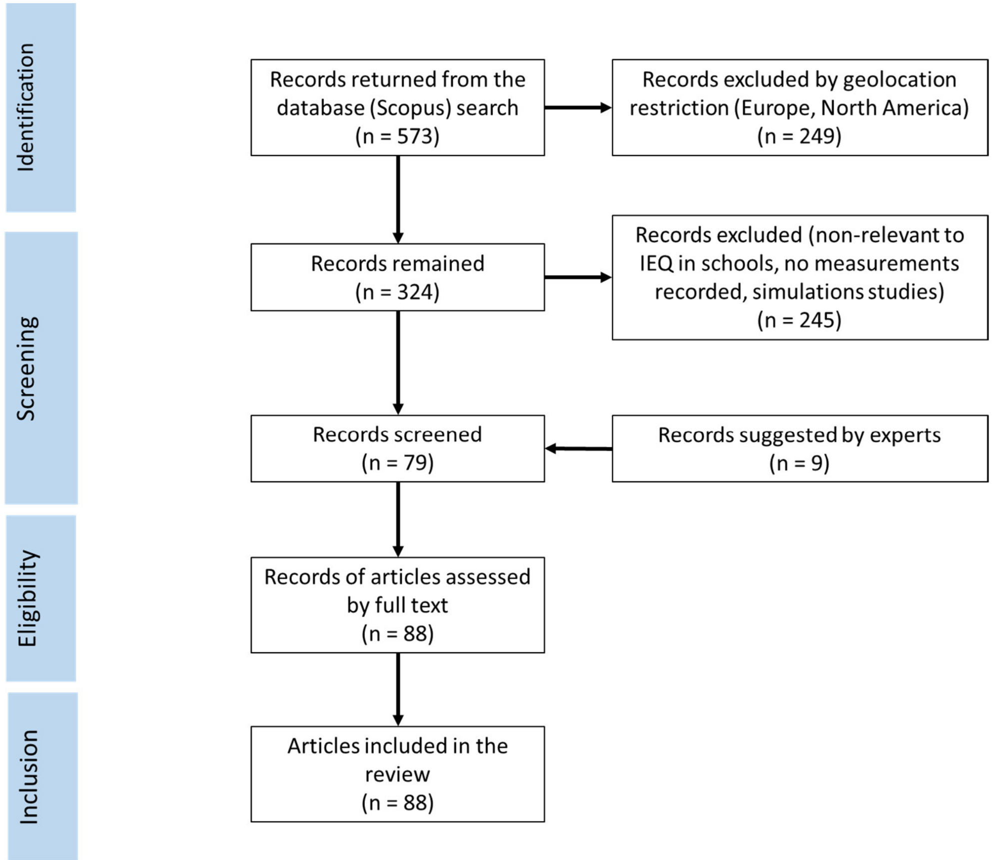

Figure 1. Review flowchart.

3. Results

Among the 88 articles analyzed in this review, some were issued from the same study. Two articles by Branco et al. [23,24] reported results from a measuring campaign in four nurseries in Porto, Portugal; one focused on CO_2 and comfort, the second one on IAQ pollutants. The report by Csobod et al. [25] on the thermal environment and IAQ and the article by Baloch et al. [26] on the results of the visual environment both reported findings from the SINPHONIE pan-European study. Among the 88 articles, IAQ parameters were measured in 73 studies, thermal parameters in 43 studies, visual parameters in 15 studies, and acoustic parameters in 13 studies. In 40 studies, the parameters describing at least two of the four IEQ components were measured. Only four studies [27–30] measured parameters of the four IEQ components. These studies were carried out in 28 countries (Figure S1 in Supplementary Materials (SM)).

Nine studies were conducted in day-care centers, nine in nursery schools, 40 in elementary schools, 24 in secondary schools, 12 in high schools, and 11 in universities. In 59 studies, schools had no mechanical ventilation system. In eight studies, an HVAC (Heating, ventilation, and air conditioning) system with heat recovery was installed. In nine studies, measurements were performed in both classrooms with no ventilation system and classrooms equipped with a mechanical ventilation system. In three studies, no information on ventilation type was available, and only acoustic and visual measurements were conducted [31–33]. Table 1 summarizes all studies presented in this review. Table 2 summarizes the main findings with the range of results from the 88 articles.

Table 1. Summary of the investigated studies (n = 88 articles).

Study [Reference]	Location	Season	Type of School	IEQ Component
Aguilar et al., 2022 [34]	Spain	Winter	University	Thermal, IAQ
Ahmed et al., 2019 [35]	Finland, Estonia	Winter	Daycare, elementary	Thermal, IAQ
Alves et al., 2013 [36]	Portugal	Winter	Kindergarten, elementary	Thermal, IAQ
Annesi-Maesano et al., 2012 [37]	France	N/A	Elementary	IAQ
Azara et al., 2018	Italy	Spring Summer	Elementary, secondary, high school	IAQ
Baloch et al., 2021 [38]	Europe	Spring Summer	Kindergarten, elementary	Visual
Barmparesos et al., 2018 [39]	Greece	Summer	Elementary	Thermal, IAQ
Becerra et al., 2020 [40]	Spain	Spring	Kindergarten, elementary, secondary, high school	IAQ
Branco et al., 2015 [23]	Portugal	Spring Autumn	Daycare	Thermal, IAQ
Branco et al., 2015 [24]	Portugal	Spring Autumn	Daycare	IAQ
Branco et al., 2016 [41]	Portugal	Year long	Daycare, elementary	IAQ
Brdaric et al., 2019 [42]	Croatia	Spring	Elementary	Thermal, IAQ
Buratti et al., 2018 [43]	Italy	Spring Autumn	University	Thermal, Acoustic, Visual
Canha et al., 2016 [44]	France	Winter	Daycare, elementary	Thermal, IAQ
Cequier et al., 2014 [45]	Norway	Winter Spring	Elementary	IAQ
Chetoni et al., 2016 [46]	Italy	N/A	Secondary, high school	Acoustic
Csobod et al., 2014 [25]	Europe	Spring Summer	Kindergarten, elementary	Thermal, IAQ, Visual
de Gennaro et al., 2013 [47]	Italy	N/A	Elementary	IAQ
De Giuli et al., 2012 [48]	Italy	Spring	Elementary	Thermal, IAQ, Visual
De Giuli et al., 2014 [49]	Italy	Spring	Elementary	Thermal, IAQ, Visual
De Giuli et al., 2015 [50]	Italy	Spring	Elementary	Thermal, IAQ, Visual
de la Hoz –Torres et al., 2022 [29]	Portugal, Spain	Fall	University	Thermal, Acoustic, IAQ, Visual
Dhoqina et al., 2019 [51]	Albania	Spring	Elementary, secondary, high school	IAQ
Erlandson et al., 2019 [52]	United States		University	Thermal, IAQ
Fabbri 2013 [53]	Italy	Fall	Kindergarten	Thermal
Franci et al., 2014 [54]	Italy	Winter	Elementary, secondary, high school	IAQ
Gaffin et al., 2018 [5]	United States	Fall Spring	Elementary, secondary	IAQ
Harcarova et al., 2020 [28]	Slovakia	N/A	Elementary	Thermal, Acoustic, IAQ, Visual
Heracleous et al., 2019 [55]	Cyprus	Winter	Secondary	Thermal, IAQ
Irulegi et al., 2017 [56]	Spain	Spring	University	Thermal
Istrate et al., 2016 [57]	Romania	Summer	High school	Thermal, IAQ
Ivanova et al., 2014 [58]	Bulgaria	Spring	Kindergarten	IAQ
Ivanova et al., 2021 [59]	Bulgaria	Fall Winter	Elementary	IAQ
Jovanovic et al., 2014 [60]	Serbia	Spring	Elementary	Thermal, IAQ
Klatte et al., 2010 [61]	Germany	N/A	Elementary	Acoustic
Kojo et al., 2020 [62]	Finland	Winter Spring	Daycare, Elementary	IAQ
Korsavi et al., 2019 [63]	England	Summer Fall Winter Spring	Elementary	Thermal, IAQ, Visual

Table 1. *Cont.*

Study [Reference]	Location	Season	Type of School	IEQ Component
Kristiansen et al., 2011 [64]	Denmark	Fall Winter Spring	Secondary	Acoustic
Krugly et al., 2014 [65]	Lithuania	Winter	Elementary	IAQ
Laborda et al., 2020 [66]	Spain	Winter	Secondary	Thermal, IAQ, Visual
Larsson et al., 2017 [67]	Sweden	Spring Fall	Kindergarten	IAQ
Leccese et al., 2020 [31]	Italy	Spring Fall	University	Visual
Liaud et al., 2021 [68]	France	Spring	High school	IAQ
Loreti et al., 2016 [30]	Italy	N/A	Secondary	Thermal, Acoustic, IAQ, Visual
Madudeira et al., 2015 [69]	Portugal	Fall Winter	Elementary	Thermal, IAQ
Mainka et al., 2015 [70]	Poland	Winter	Daycare	IAQ
Mikulski et al., 2011 [71]	Poland	N/A	Elementary	Acoustic
Müllerova et al., 2017 [72]	Hungary, Poland, Slovakia	Fall Winter	Kindergarten	IAQ
Nunes et al., 2016 [73]	Portugal	Spring	Nursery	IAQ
Oldham et al., 2020 [74]	United States	Fall Spring	Elementary	Thermal, IAQ, Visual
Oliveira et al., 2016 [75]	Portugal	Spring	Kindergarten	Thermal, IAQ
Oliveira et al., 2017 [76]	Portugal	Winter Spring	Kindergarten	IAQ
Oliveira et al., 2017 [77]	Portugal	Spring	Kindergarten	Thermal, IAQ
Onishchenko et al., 2017 [78]	Russia	N/A	Kindergarten	IAQ
Papadopoulos et al., 2020 [79]	Greece	Winter	University	Thermal, IAQ
Papazoglou et al., 2019 [80]	Greece	Summer	University	Thermal
Pereira et al., 2014 [81]	Portugal	Spring	Secondary	Thermal, IAQ
Pereira et al., 2015 [82]	Portugal	Spring	Secondary	Thermal, IAQ
Persson et al., 2018 [83]	Sweden	Year long	Kindergarten	IAQ
Poulin et al., 2012 [84]	Canada	Winter	Elementary, secondary, high school	IAQ
Raffy et al., 2017 [85]	France	N/A	Nursery, elementary	IAQ
Ramalho et al., 2015 [86]	France	N/A	Nursery, elementary	IAQ
Rivas et al., 2014 [87]	Spain	Winter Spring Summer	Elementary, secondary	IAQ
Romagnoli et al., 2014 [88]	Italy	Winter Spring Summer	Elementary, secondary, high school	IAQ
Rovelli et al., 2014 [89]	Italy	Winter	Elementary, secondary	IAQ
Rucinska et al., 2020 [33]	Poland	Winter	University	Visual
Russo et al., 2019 [32]	Italy	N/A	Elementary	Acoustic
Sarantopoulos et al., 2014 [90]	Greece	Spring	Elementary	Acoustic
Sarka Langer et al., 2020 [91]	Sweden	Fall Winter Spring	Elementary	Thermal, IAQ
Senitkova et al., 2017 [92]	Czech Republic	N/A	Daycare	Thermal, IAQ
Shield et al., 2015 [93]	England	N/A	Secondary	Acoustic
Simanic et al., 2019 [94]	Sweden	Fall Winter Spring	Elementary	Thermal, IAQ
Sivanantham et al., 2021 [95]	France	Fall Winter Spring	Daycare, Elementary	Thermal, IAQ
Slezakova et al., 2019 [96]	Portugal	Winter Spring	Elementary	IAQ

Table 1. *Cont.*

Study [Reference]	Location	Season	Type of School	IEQ Component
Smith et al., 2019 [97]	United States	N/A	Elementary, secondary	Acoustic
Stamp et al., 2020 [98]	United Kingdom	N/A	Secondary	Thermal, IAQ
Toftum et al., 2015 [99]	Denmark	N/A	Elementary	Thermal, IAQ
Trevisi et al., 2012 [100]	Italy	Year long	Daycare, elementary, secondary	IAQ
Ulla Haverinen-Shaughnessy et al., 2015 [101]	United States	Fall Winter Spring	Elementary	IAQ
Verriele et al., 2016 [102]	France	N/A	Elementary, secondary	Thermal, IAQ
Vilcekova et al., 2017 [27]	Slovakia	Fall	Elementary	Thermal, Acoustic, IAQ, Visual
Villanueva et al., 2018 [103]	Spain	Spring	Elementary	IAQ
Vornanen Winqvist et al., 2018 [104]	Finland	Spring	Secondary	Thermal, IAQ
Vornanen Winqvist et al., 2020 [105]	Finland	Winter	Secondary	Thermal, IAQ
Z.Curguz et al., 2020 [106]	Bosnia and Herzegovina	N/A	Elementary, secondary, high school	IAQ
Zecevic et al., 2018 [107]	Bosnia and Herzegovina	Winter Summer	University	Thermal, IAQ
Zhong et al., 2017 [108]	United States	Winter Spring	Elementary	Thermal, IAQ
Živković et al., 2015 [109]	Serbia	Winter Spring	Elementary, secondary, high school	IAQ

Table 2. Summary of the main results (*n* = 88 articles).

Parameters	Number of Studies	Main Findings	Reference Values
		Thermal environment	
Air temperature (°C)	43	Western Europe: Range: 13 °C to 38 °C with a mean of 22 °C Northern Europe: Range: 12 °C to 26 °C with a mean of 21 °C	22 ± 1 °C (EN 16798-1)
Relative humidity (%)	43	Naturally ventilated classrooms range 22% with a mean air temperature of 23 °C to 78% with a mean air temperature of 25 °C. Mechanically ventilated classrooms, range: 30 to 72%	30–50% (EN 16798-1)
PMV/PPD (derivative)	8	Mean result: ±0.5 from 0 °C	±0.2 °C (EN 16798-1)
Mean radiant temperature (°C)	7	Range: 13 to 24 °C	N/A
Air speed (m/s)	7	All reported results are under 0.1 m/s	N/A
Operative temperature (°C)	5	Range: 19 to 22 °C	N/A
		Acoustic environment	
Background noise level (db(A))	8	Range: 41 to 82 db(A)	<30 db(A) (EN 16798-1)
Reverberation time (s)	8	Range: 0.9 to 1.1 s	0.5 s for small spaces 0.8 for large spaces (EN 16798-1)
Speech intelligibility (%)	7	SNR range: 12 ± 3.6 db STI range: 41–76% C50 range: −6.3 to 5.6 db	N/A

Table 2. *Cont.*

Parameters	Number of Studies	Main Findings	Reference Values
		IAQ	
CO_2 (ppm)	42	Naturally ventilated classrooms, range: 591 to 3494 ppm Mechanically ventilated classroom, all under 1000 ppm	≤550 ppm (concentration above outdoor) (EN 16798-1)
PM (μg/m^3)	22	PM_{10} range: 34 to 2061 μg/m^3 PM_5 range: 31 to 206 μg/m^3 $PM_{2.5}$ range: 1.3 to 106 μg/m^3 PM_1 range: 6.0 to 33 μg/m^3 $PM_{0.5}$ range: 2.1 to 22 μg/m^3	$PM_{2.5} \leq 5$ μg/m^3 (WHO)
Radon (Bq/m^3)	16	Range: 56 to 579 Bq/m^3	100 Bq/m^3 (WHO)
BTEX (μg/m^3)	14	Benzene range: 0.5 to 3.2 μg/m^3 Toluene range: 0.2 to 17 μg/m^3 Ethylbenzene range: <Limit of detection to 9.0 μg/m^3 Xylene range: 1 to 12 μg/m^3	Benzene: <2 μg/m^3
SVOCs (ng/m^3)		Tables S14–S16	N/A
Aldehydes (μg/m^3)	15	Formaldehyde range: 1.4 to 89 μg/m^3	Formaldehyde: <30 μg/m^3
ACR/ VR (h^{-1} or l/s/p)	11	ACR range: 0.1 to 0.4 h^{-1} VR range: 0.8 l/s per person to 3.4 l/s per person	≥10 L/s per person + 2.0 L/s/m^2 floor
VOCs (μg/m^3)	10	Table S12	N/A
NO_2 (μg/m^3)	11	Range: 4.9 to 125 μg/m^3	<10 μg/m^3 (WHO)
Mold inspection (cm^2 or CFU/m^3)	4	Range: 22 to 260 CFU/m^3	<400 cm^2 (Nordic classification and Levels)
		Visual environment	
Artificial illuminance (lx)	4	Range: 241 to 748 lx	500 lx Can be drop to 300 lx for younger children (EN 12464-1)
Total lighting (natural + artificial)	4	Table S19	N/A
Natural lighting	3	Table S19	>5% (EN 17037)

3.1. Thermal Environment

Thermal environment was assessed in 43 studies. The air temperature, radiant temperature, operative temperature, humidity or air speed were measured. Some studies additionally estimated thermal comfort using the model developed by Fanger [110].

3.1.1. Air Temperature

The air temperature was measured in 43 studies; it was often measured simultaneously with relative humidity. Measurements were performed during winter (heating season) in eight studies, during non-heating season, i.e., spring and autumn in 29 studies, during summer in six studies, and seven studies did not provide any information.

Temperature was mainly recorded continuously for the periods of over thirty minutes to three months with a time step ranging from two to ten minutes. In three studies, only spot measurements were carried out. In one study, a combination of continuous measurements over three months and spot measurements four times in each classroom were carried out.

Different numbers of sensors, at various locations in each classroom, were used. Thirty-eight studies used only one sensor for each classroom, and three studies used three sensors per classroom. Laborda et al. [66] measured air temperature in 12 locations in the classroom: six at 0.6 m and six at 1.7 m, divided into two arrays close to the window and next to the entrance doors. Papadopoulos et al. [79] measured air temperature in 11 locations in the classrooms, with their height situated from 0.5 to 2.5 m above the ground to be compliant with the students' breathing zone. Nine studies reported that their sensors were placed at 0.6 m above the ground, and seven other studies placed their sensors from 0.7 to 2 m above the ground. Fabbri et al. [53] measured air temperature at two different heights: 0.6 and 1.3 m. The detailed protocols and results can be found in Table S1 in Supplementary Materials.

Studies from Western Europe (Italy, Spain, Portugal, France, and Greece) measured temperatures ranging from 13 to 38 °C with a mean of 22 °C. Studies from Northern Europe (Sweden and Finland) measured temperatures ranging from 12 to 26 °C with a mean of 21 °C.

3.1.2. Humidity

Relative humidity (RH) was measured simultaneously with air temperature using hygrometer sensor. In one study, absolute humidity was also determined along with relative humidity. Humidity was reported in 43 studies. Findings on the number of sensors, their location, and the duration of measurements are identical to air temperature measurements since the two parameters were always measured together in the reviewed studies. RH ranged between 22% with a mean air temperature of 23 °C and 96% with a mean air temperature of 25 °C. Among the classrooms with mechanical ventilation, the relative humidity varied between 30 and 72%, while the air temperature varied between 21 and 25 °C.The detailed protocols and results can be found in Table S2 in Supplementary Materials.

3.1.3. Mean Radiant Temperature

Mean radiant temperature was measured in 11 studies. In eight studies, the measurements were made using one globe thermometer, placed in the center of the room in each study, with a measurement duration ranging from one to five days. Other studies made spot measurements of the radiant plane temperature to estimate the mean radiant temperature but the monitoring protocol was not detailed and in two studies, air and mean radiant temperature were measured over 24 h. Papadopoulos et al. [79] used a thermal imaging camera to estimate the mean radiant temperature from surface temperatures. The mean radiant temperature measured in the 11 studies ranged between 13 and 24 °C. Table S3 in Supplementary Materials shows the details concerning measuring protocols and results.

3.1.4. Operative Temperature

Operative temperature was reported in six studies based on the measurement of globe temperature, and air velocity. In these studies, a small sample of classrooms (less than ten) was monitored, but the measurements were made at different classroom locations and repeated. In their study in 145 classrooms in Sweden, Simanic et al. [94] assumed that the operative temperature was similar to air temperature, as these schools were well insulated [15].Reported operative temperature from five studies ranged from 19 to 22 °C. Table S3 in Supplementary Materials provides details regarding measuring protocols and results.

3.1.5. Airspeed

Airspeed was measured in 12 studies in schools. These measurements were made to assess thermal comfort. Spot measurements were always made using an anemometer, but its position was never clearly mentioned. The reported results were all under 0.1 m/s.

3.2. Acoustic Environment

Thirteen studies reported measurements of parameters characterizing acoustic environment in schools. Parameters measured included noise level, reverberation time (RT) and speech intelligibility.

3.2.1. Noise Level

The background noise level was the most frequently measured acoustic parameter. It is also a parameter commonly used to assess occupants' long-term noise exposure [111]. Background noise level can be estimated using the variation of the pressure in the air caused by sound waves (sound pressure level-SPL) or the equivalent continuous sound level, e.g., LA_{eq}, defined as the total energy from the sound pressure level during the measurement period [112].

LA_{eq} was measured in nine studies, with one or two sound meters per classroom. The location of the sound meter was mentioned in three studies: Chetoni et al. [46] measured in the center of the room and one meter from the window, Shield et al. [93] also measured at two positions in the classroom, and de la Hoz-Torres et al. [29] only used one sound-meter placed in the center of the room.

Measurements were a spot measurement of one minute or continuous from two hours to two days. In some studies, measurements were made during day without students in the classrooms, while in other studies, measurements were made when the students were occupying the classrooms.

The average measured LA_{eq} in studied classrooms varied between 29 and 82 dB(A). Chetoni et al. [46] used the L_{DAY} indicator, defined as the daily LA_{eq} over the 12 h diurnal period from 7 a.m. to 7 p.m. since this parameter is used in Italy's national regulation for outdoor acoustic. The L_{DAY} ranged between 23 and 63 dB(A). Smith et al. [97] in their study quantified the influence of the different mechanical ventilation systems (single- and multi-zone HVAC systems) on the non-speech noise during occupied periods. The average LA_{eq} was 66 dB(A) for unit ventilators, 67 dB(A) for centralized systems, and 66 dB(A) for systems with decentralized heat pumps. Details on measurement protocol and results can be found in Table S4 in Supplementary Materials.

3.2.2. Reverberation Time

A room reverberation time (RT) expresses the time required for the sound to decay after the sound source has stopped; for example, T_{20} is the time it takes for sound to decay by 20 dB, and T_{60} is the time for a decay of 60 dB, T_{20} as the time for a decay by 20 dB, respectively [112]. There is a linear relationship between T_{20} and T_{60} in the same environment, as the measurement of T_{20} can be used to evaluate T_{60}, which is the case in the study by Loreti et al. [30].

RT was measured in in four studies in Italy [30,32,43,46], one study in Poland [71], one in Denmark [64], one in Germany [61], and one in England [93]; all referred to the measurement methods defined in the ISO 3382 standard [112], using an impulsive response method for a controlled and continuous (white noise) generated by an omnidirectional loudspeaker, blank gun noise, or maximum-length sequence signals. Two to twelve microphones were placed in children's seat positions, i.e., at least 1.1 m of height, and the results were expressed as the average of all these measurements. Mikulski et al. [71] measured the T_{mf} which is the arithmetic mean of RT for 500 Hz, 1000 Hz, and 2000 Hz, as well as the T_{wf} which is the arithmetic mean of RT for 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. The authors specified that measuring T_{mf} alone does not always correspond with the subjective evaluation of the acoustical properties of the room. Other studies, such as the Klatte et al. [61] study, measured the T_{20} averaged from results of octave bands from 250 to 2000 Hz. The measured RT ranged from 0.9 to 1.1 s for T_{60} and 1.1 to 1.4 s for T_{20}. Details on measurement protocol and results can be found in Table S6 in Supplementary Materials.

3.2.3. Speech Intelligibility

Speech intelligibility depends on the spoken language familiarity of the listeners and is limited in children due to a lack of vocabulary and grammar skills [113]. Speech transmission is the physical measurement of the speech intelligibility, which depends on classroom acoustic characteristics such as the RT and the background noise level.

One indicator of speech intelligibility is the signal-to-noise (SNR) ratio. It is defined as the ratio of the signal power to the background noise power and is expressed in decibels. A review on speech intelligibility in school has shown that high background noise levels can mask speech sounds, as the authors stated that a recommended SNR should be greater than +15 dB, and ideally at +25 dB [114]. Sarantopoulos et al. [90] measured the SNR using LA_{90} in an occupied classroom with a teacher talking. LA_{90}, defined as the 90th percentile of LA_{eq} in a one-minute measurement period, was considered as a proxy to background noise during the active teaching period. The SNR was calculated by subtracting the measured teacher's speech noise to the LA_{90}. For 41 teachers in 15 classrooms, the average SNR for teaching was 12.0 $\pm$ 3.6 dB(A), ranging from +6.8 dB(A) to + 21.6 dB(A).

Another indicator of speech intelligibility is the speech transmission index (STI), which ranges between 0 and 100% and represents the transmission quality of speech concerning intelligibility by a speech transmission channel, according to the standard EN 60268-16, 2011 [115]. STI was assessed in four studies in Italy [30,32,43,46], one study in Poland [71], and one in England [93] by emitting a speech-like sound signal and measuring its transmission quantity at another point in the room, referring to the methods described in the standard EN 60268-16, 2011 [115]. Measurements were performed in unoccupied classrooms as students' presence can alter the STI results, and the results ranged from 41 to 76%.

The clarity index is also used to assess speech intelligibility. It is the difference between the emitted sound energy and the later arriving sound energy after a time limit [112], expressed in dB. C_{50} is the clarity index in case of a time limit of 50 ms (ISO 3392-1 standard, 2010). C_{50} was measured simultaneously with STI in the same three studies in Italy [30,32,43], and in one study in England [93]. The results ranged from -6.28 to 5.55 dB in 66% of classrooms. Details on measurement protocol and results of measured SNR, STI, and C_{50} can be found in Table S5 in Supplementary Materials.

3.2.4. Sound Insulation

Sound insulation is the ability of buildings' components to reduce sound transmission through the envelope and the internal walls and floors. Façade insulation measurement can be determined by measuring the airborne sound reduction index between outside and inside the buildings. Different methods exist (ISO 16283-3 standard, 2016 [116]) and aim at assessing either the sound reduction index of an element of the building façade, such as windows, or the reduction of indoor noise levels due to building façade with actual traffic conditions. In some countries, minimum sound insulation level requirements exist in building regulations: at least 38 dB(A) façade insulation in the Italian technical regulation and at least 30 dB(A) façade insulation in the French regulation [116].

Chetoni et al. [46] in Italy determined the total insulation of the school building façade exposed to road traffic and calculated the weighted standardized level insulation ($D_{2m,nT,w}$), following ISO 16283-3 [116]. The study found that the façade insulation index was below the regulatory value of 38 dB in 23 out of 24 classrooms. Different classrooms in the same school had different results, as there are various conditions of poor quality or even damaged windows and doors.

In the same study, airborne sound insulation between two classrooms or between classrooms and corridors was assessed by measuring wall insulation between interior spaces (R'_w). Results showed that in 11 out of 24 classrooms, the R'_w between two classrooms [46] was below the Italian regulatory value of 41 dB [54]. A large variability of R'_w (at a maximum of 18 dB) between the classrooms was observed. It was explained by the different construction technologies, either with load bearing or only with a partition wall.

3.3. Indoor Air Quality (IAQ)

IAQ depends on the concentrations of pollutants having outdoor or indoor origin. Sixty-two studies performed IAQ measurements, including the following parameters: carbon dioxide, different ventilation parameters, formaldehyde and other aldehydes, volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), particulate matter, nitrogen dioxide, bio-contaminants and radon.

3.3.1. Carbon Dioxide (CO_2), Ventilation Rate (VR), and Air Change Rate (ACR)

CO_2 is a marker of ventilation adequacy in the presence of people indoors and is the most prevalently measured parameter in connection with IAQ monitoring [117]. CO_2 was measured mainly with a non-dispersive infrared (NDIR) sensor. The concentrations were determined using spot or continuous measurements, the latter for a period of 30 min to three months with a time interval ranging from two to ten minutes. The number of measurement locations was either one in the center of the room or in multiple locations.

Across 32 studies that measured CO_2 in a naturally ventilated classroom, average mean concentrations ranged between 591 and 3494 ppm. In all naturally ventilated classrooms, CO_2 concentration varied throughout the day depending on children's presence and the frequency of window opening. Studies in classrooms equipped with mechanical ventilation systems showed that CO_2 concentrations did not exceed 1000 ppm.

Details on measurement protocols of CO_2 and results from studies can be found in Table S7 in Supplementary Materials.

The air change rate (ACR) and ventilation rate (VR) can be calculated using the measured CO_2 concentrations. Six studies calculated the ACR using the CO_2 decay rate during the non-occupied period, and one study calculated VR using the CO_2 production rate during the occupied period. The estimated ACR ranged between 0.11 and 0.39 h^{-1} in naturally ventilated classrooms, and between 1.4 and 3.2 h^{-1} in classrooms with mechanical ventilation systems.

In 70 classrooms equipped with either air handling units (17%), fan coil units (21%), or individual unit ventilators (62%) in the USA, VR was calculated using the peak level of measured CO_2 and mean VR was estimated to be 3.6 $\pm$ 2.3 L/s per person. The VR was calculated using measured CO_2 concentrations in 51 classrooms in France (14 classrooms had mechanical ventilation systems and 37 had natural ventilation). Mean VR was estimated to be 4.2 $\pm$ 1.7 L/s per person in mechanically ventilated classrooms and 2.4 $\pm$ 1.4 L/s per person in naturally-ventilated classroom. In the pan-European SINPHONIE study, the mean VR ranged from 0.87 L/s per child in Western Europe to 3.4 L/s per child in Northern Europe.

Detailed protocols regarding ACR/VR can be found in Table S8 in Supplementary Materials.

3.3.2. Formaldehyde and Other Aldehydes

Formaldehyde was measured in 15 studies, while other aldehydes were measured in six studies. A summary of formaldehyde measurements is provided in Table S9 in Supplementary Materials while Table S10 presents the measurements of other aldehydes.

Formaldehyde can be measured using passive (12 studies) or active (three studies) methods. It is sampled on a cartridge containing an organic reagent, such as 2,4-dinitrophenylhydrazine (DNPH), then analyzed with high-performance liquid chromatography (HPLC) and ultraviolet (UV) detection, as recommended in the ISO 16000-4 standard [118] for lightweight aldehydes. One or two passive samplers were deployed per classroom, and their locations were not always reported. The sampling duration for passive samplers ranged from two days to two weeks. The three studies that used active sampling had measured in either spot measurements from one minute [24] and 30 min [108], or 2.5 h [119]. The mean concentration of formaldehyde ranged between 1.4 and 89 $\mu g/m^3$. Summaries of measurement protocols and results of formaldehyde and other aldehydes are provided in Tables S9 and S10 in Supplementary Materials.

3.3.3. Volatile Organic Compounds (VOCs)

The most frequently measured VOCs were BTEX: benzene, toluene, ethylbenzene, and xylenes. Fourteen studies measured BTEX, among which three also measured concentration of total volatile organic compounds (TVOC), and eleven measured a larger number of VOCs. Three studies used a portable analyzer including a photoionization detector with UV to measure organic compounds. The other studies used diffusive passive samplers for a duration of two to four weeks. The location of the samplers was usually in the center of the room with other measurement devices, but in most studies, it was not reported. The mean indoor concentrations ranged between 0.5 and 3.2 $\mu g/m^3$ for benzene, 0.2 and 17 $\mu g/m^3$ for toluene, less than the limit of detection and 9.0 $\mu g/m^3$ for ethylbenzene, and 0.6 to 12 $\mu g/m^3$ for xylenes. A summary of all the measured BTEX compounds and other VOCs, their protocols and results can be found in Table S11 and Table S12 in Supplementary Materials, respectively.

3.3.4. Semi-Volatile Organic Compounds (SVOCs)

SVOCs are less volatile than VOCs and can also be present in the particulate phase in addition to the gas phase. Four groups of SVOCs were measured and reported in eleven studies. They were polycyclic aromatic hydrocarbons, PAH (acenaphthene, anthracene, benzo(a)pyrene), flame retardants (tributylphosphate, polybrominated diphenyl ethers), phthalates (BBP, DBP, DEHP, DEP, DiBP), and synthetic musks (tonalide, galaxolide). Phthalates were the most frequently detected SVOCs in the air. Active sampling on polyurethane foam (PUF) was often used to trap the SVOC gas phase. The samples were then analyzed using GC-MS. The sampling duration ranged from 24 h to one week at one point in the room, with the accurate location not specified. SVOC measurement protocols and concentrations can be found in Tables S14–S16 in Supplementary Materials.

3.3.5. Particulate Matter (PM)

Particulate matter (PM) can originate from indoor (e.g., cooking and heating) and outdoor (e.g., traffic) sources. Twenty-two studies measured PM in classrooms, among which ten measured PM_{10}, 21 measured $PM_{2.5}$, one measured PM_4, two measured PM_1, and one measured $PM_{0 \cdot 1}$.

PM concentrations can be measured using optical and gravimetric methods. Optical PM counters use a laser to count the particles passing a small volume, with results expressed in the total particle count adjusted to the volume. The gravimetric method uses an air pump to drive air through an impactor that collects PM according to their size. Eight studies used an optical counter, and twelve used the gravimetric method to measure PM concentrations. Two studies used condensation particle counters (CPC) that can measure small particles, such as $PM_{0 \cdot 1}$ and $PM_{0.5}$. The sampling duration ranged from eight hours to ten months, with a time interval from one to ten minutes. The sampling locations in the classrooms were not specified.

The measured concentrations ranged from 34 to 2061 $\mu g/m^3$ for PM_{10}, and from 1.3 to 106 $\mu g/m^3$ for $PM_{2.5}$. PM_1 was measured in one study with a mean concentration of 19.2 ± 7.2 $\mu g/m^3$ in two classrooms during school hours. One study measured $PM_{0.5}$ in two classrooms and reported concentrations ranging from 2.1 to 22 $\mu g/m^3$. One study measured the ultrafine particles, with concentrations ranging from 1560 to 16,780 particles/cm^3. The measurement protocols and results can be found in Table S13 in Supplementary Materials.

3.3.6. Nitrogen Dioxide (NO_2)

Nitrogen dioxide (NO_2) is primarily emitted by combustion and mainly comes from outdoors, particularly from traffic. Among eleven studies that measured NO_2, nine conducted long-term (five to fourteen days) passive measurements, and two used a chemiluminescence continuous analyzer for a period of thirty minutes or 24 h. The location of the samplers was usually in the center of the room with other measurement devices, but in most studies, it was not reported. The mean NO_2 concentration ranged from 4.9 to 125 $\mu g/m^3$, with a maximum concentration of 292 $\mu g/m^3$. Details on the measurement protocols and results can be found in Table S17 in Supplementary Materials.

3.3.7. Bio-Contaminants

Dampness and high relative humidity in buildings lead to microbial growth, dust mites and their allergens [120]. Bio-contaminants assessment was reported in three studies in Finland, one in Portugal, and in one pan-European study.

Mold exposure can be assessed either by visual inspection or by measurements of airborne spores. Visual inspection has been reported in one study in Finland, with two out of seventeen schools showing visible mold. For measurements of airborne spores, two studies in Finland measured indoor airborne cultivable microorganisms, and reported an average concentration of 22 to 260 CFU/m^3 of airborne cultivable microorganisms. Finally, the SINPHONIE pan-European study reported that 7% of classrooms had visible signs of mold.

3.3.8. Radon

Radon is a chemically inert gas emitted naturally from underground. It was measured in sixteen studies identified in the present review. Measurements can be made with a passive dosimeter, which was the case in fifteen studies, for a duration ranging from three months to one year. Passive dosimeters were placed on the ground floor or on the lowest floor of the buildings. Only one study used an active measurement device that provided a value every sixty minutes over 24 h. The mean radon concentration ranged from 56 to 579 Bq/m^3. The measurement protocol and the results showing measured radon concentrations are presented in Table S18 in Supplementary Materials.

3.4. Visual Environment

Lighting conditions determine the quality of the visual environment. They include the contributions of both daylight and artificial light emitted by the installed luminaires. Visual environment was investigated in 15 studies; most of them were spot measurement using an illuminance meter placed at students' desks. The number of measurement points varied from one per class to 319. Leccese et al. [31] measured numerous parameters for the purpose of determining the most influential parameters on students' visual comfort.

3.4.1. Daylighting

Daylighting measurements can be made by assessing the daylight factor via simulation or by simply measuring desk illuminance in classrooms with artificial light turned off. Daylight factor (%) is the ratio between the indoor horizontal illuminance at a given location and the outdoor horizontal illuminance measured under the unobstructed sky vault in overcast conditions. One study reported the daylight factor, with a result of 2.2%. Leccese et al. [31] also reported that daylight glare is the most important factor contributing to students' visual comfort.

Five studies reported daylighting by measuring the total illuminance with artificial lighting on students' desk. Rucinska et al. [33] measured the average illuminance in a classroom during two periods: one period with a clear sky and the other period with an overcast sky. This study included the highest number of measurement points per classroom, with 319 points grouped in three different longitudinal rows of tables, i.e., near the windows, in the middle of the room, and next to the entrance door away from the windows. Results showed a 9-fold decrease of mean illuminance in the middle of the room and an 18-fold decrease next to the entrance door, compared to the illuminance on the desks near the windows. In overcast conditions, these ratios were about 3 and 8, respectively. In the other studies, mean measured total illuminance ranged from 303 lx to 1255 lx.

3.4.2. Artificial lighting

Artificial lighting is provided by luminaires installed inside the classroom. Artificial lighting should be able to compensate for an insufficient level of daylight indoors.

The measurement of artificial lighting follows the same principle with the use of an illuminance-meter. To correctly evaluate only artificial lighting, measurements should be done with controlled daylighting, by selecting low daylight timeframe, or simply by closing solar protections if any in the classroom. All performed measurements were spot measurements. Artificial lighting was measured in eight studies. Six out of the eight studies measured only at the center of the classroom, one study reported at least four measurements points and one study measured at six points in the room, additionally reporting the values of the lighting uniformity factors. The illuminance values reported were in the range of 241 lx to 748 lx. Table S19 combines all measurement protocols and results of all studies on lighting conditions.

4. Discussion

This review highlighted that out of the 88 reviewed articles, all four components of IEQ were measured only in four studies [27–30]. Identical parameters were measured in these four studies (air temperature, RH, CO_2, illuminance, noise level), with a sample size of less than five classrooms in three studies. The study by de la Hoz–Torres et al. [29] measured IEQ parameters in 15 classrooms in six buildings in Portugal and Spain. As shown in Figure 2, eight studies measured at least three out of the four IEQ components—seven studies measured IAQ, visual and thermal parameters [25,48–50,63,66,74], and one study measured visual, thermal and acoustic parameters [43].

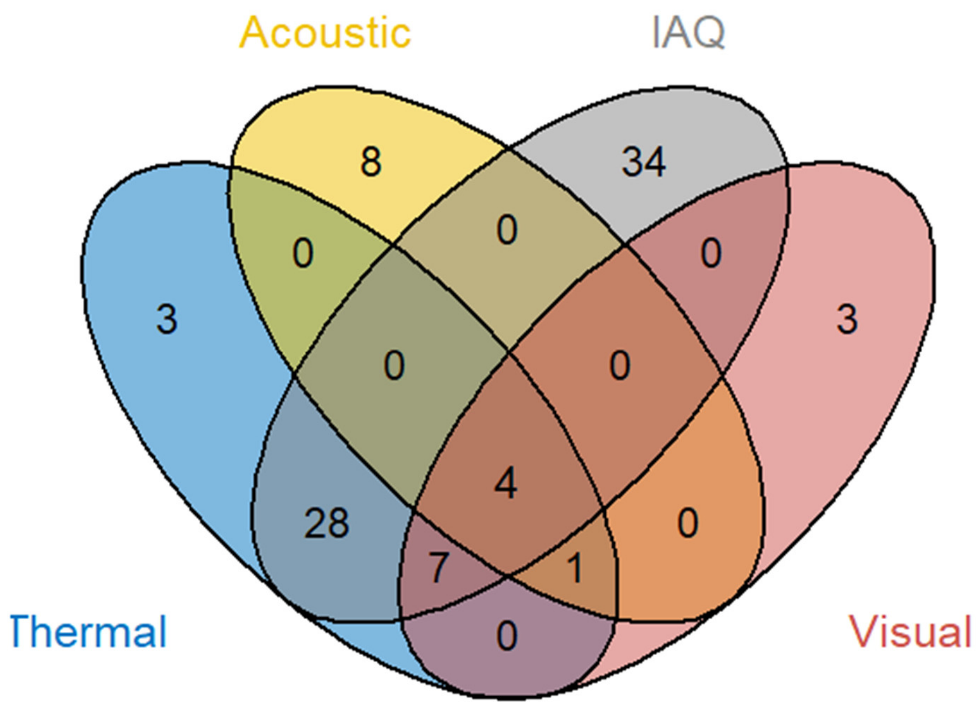

Figure 2. Number of studies according to the IEQ components measured (n = 88 articles).

As shown in Figure 3, most studies had a small sample size; the median was six schools and 17 classrooms. Twenty-six studies only measured IEQ parameters in one school, and thirteen of them only instrumented one classroom. In 19 out of these 26 studies, there were at least two IEQ components measured including three studies that measured all four IEQ components [27,28,30]. In 11 studies that targeted more than 100 schools, only three performed measurements of more than one IEQ component, including the pan-European SINPHONIE study, which measured thermal, IAQ, and visual parameters in 114 schools and 342 classrooms across 23 countries [25,38]. One study had the largest sample size of 1000 classrooms in 438 schools but only radon was measured with passive dosimeters [100]. Overall, it was seldom that many parameters were measured when the study included many classrooms and schools.

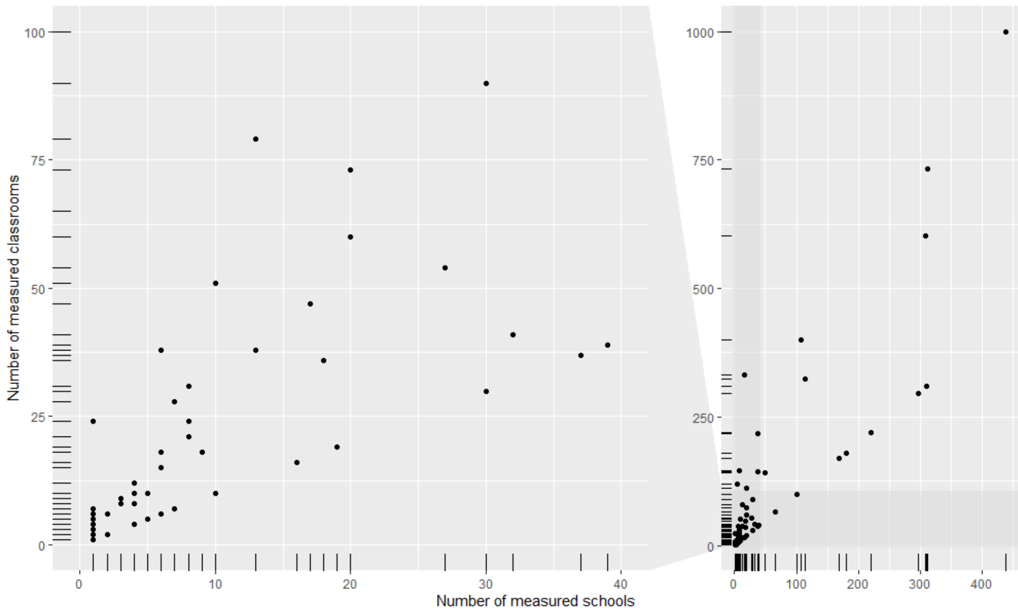

Figure 3. Number of schools and classrooms per study where the measurements were made. Each dot represents a study with the number of measured schools on the x-axis and the number of measured classrooms on the y-axis.

Among the different aspects retrieved from the reviewed studies (sampling location, type of sampling, duration, etc.), the measured parameters were the first point of interest of the review. Targeted parameters varied between studies depending on their objective and their capabilities in terms of equipment, safety considerations, and cost. Whilst most parameters could be used to characterize IEQ or evaluate children's pollutant exposure and comfort, some parameters show limitations. Indeed, to characterize thermal environment, air temperature was measured in all studies. However, this measurement may not be sufficient to characterize children's thermal sensations which depends also on other parameters such as relative humidity, airspeed, and mean radiant temperature [53,121]. Operative temperature is based on the measurement of air temperature with a temperature thermocouple sensor, air velocity with an anemometer, and mean air radiant temperature with a globe thermometer. It requires advanced measurement systems which are complex and expensive to implement in a large sample of classrooms over a long period [94]. We stipulate that it was the reason why it was measured only in five studies and in two of them as spot measurements before the monitoring week due to the safety considerations [27,81]. In these studies, the differences between mean radiant temperature and air temperature were always below 3 °C, suggesting that the choice of measuring air temperature is somewhat justified. In 145 classrooms of six schools in Sweden, air temperature was measured from May to October and the difference between operative temperature and air temperature was below 1 °C because the schools were well insulated; this provides additional justification for using only air temperature measurements [94].

The second discussion point deals with the measurement protocols. Measuring protocols for some parameters have shown significant differences in sampling strategies and statistical indicators. The sampling strategies were inhomogeneous concerning the position, the height, the duration of the measurements in the classrooms, the sampling frequency, and the devices 'accuracy' were not systematically mentioned in many studies including calibration. This variability was observed for the four IEQ components, especially for the numerous IAQ parameters. For example, particles were monitored with optical or gravimetric methods, with various sampling strategies during occupancy or non-occupancy periods. These variations were also observed for the background noise level, which was measured either when children were in the classrooms or not in the classrooms. These differences led to inhomogeneity in results, metrics, and difficulty to interpret the results. Many measuring methods and indicators were complex and trained field technicians were needed to perform measurements. This mainly concerns parameters of acoustic and visual components. For example, speech intelligibility, essential for providing an adequate learning environment for children, was measured in five studies using three different indicators: SNR, STI, and C_{50}, RT, which is also an essential factor for acoustic quality in classrooms [122], was measured with different protocols, especially for the generation of the noise, but always followed the standard ISO 3382 [112]. For the visual environment, many parameters, including illuminance, uniformity, luminance distribution, glare, effects of temporal light modulation such as flicker and the stroboscopic effect, and color temperature, should be considered to have well-balanced lighting in classrooms essential for health, well-being, and learning. Illuminance on desks was measured in all the studies dealing with visual environment. It is the less complex parameter to assess using a lux-meter. Other indices, such as glare indices, have been shown to have more impact on students' perception but are based on equations correlating luminance values in the occupant's field of view and human' sensation. These parameters were only measured one time, in one lighting's specific study in one classroom, demonstrating its difficulty to implement them in a large sample of schools [31]. The factors that primarily influence occupant visual comfort were daylight glare and luminance, which are not commonly measured as previously mentioned.

Finally, main results from the reviewed studies provide an overall picture of IEQ in schools within the scope of our review. Most IEQ parameters identified in this review have reference values in the regulations, standards, and guidelines from WHO and the governments or GBC. Table 2 presents the summary results for each IEQ parameter from 88 retrieved papers and their reference values. IAQ parameters have fewer guideline values compared to other parameters, especially for VOCs and SVOCs. While a growing body of studies on IAQ parameters in schools has shown associated risks to children's health, well-being, and cognitive performance, further development and future studies are still needed to highlight the relationship between children' exposure to air pollutants and health outcomes, for the purpose of establishing their reference values. For acoustic and visual components, some parameters are regulated in European countries and the USA for school buildings, such as façade insulation, sound insulation between two rooms, and RT. The illuminance-regulated value has been mentioned in the labor code in France. This review highlighted that many parameters in the four components exceeded threshold values [123].

This review creates the background for developing an IEQ rating scheme in schools by listing the measured parameters and assessing their respective prominence, limitation, and applicability to the school environment. The most measured parameters for the four IEQ components are air temperature and relative humidity for thermal, concentrations of carbon dioxide, particulate matter, radon, formaldehyde, and some volatile organic compounds for IAQ, noise level, and reverberation time for acoustic and illuminance for visual environments. The popularity of these parameters in studies indicates their pertinence in characterizing the IEQ parameters in schools. However, a consensus measurement protocol of all IEQ parameters must be set to facilitate inter-comparison between measurements at different schools. Another question can be raised on whether and how occupant perception can be used to assess the IEQ, as studies have shown limitations of some parameters when evaluating children's comfort. Future works should propose harmonized protocols and define the threshold values for each parameter to ensure children can spend time at school without harming their health, well-being, and cognitive performance.

5. Conclusions

This review provides an overview of IEQ parameters measured in schools in Europe and North America since 2010 and compares different monitoring protocols and results in 88 articles. This review aims to provide an overview of IEQ parameters often measured in schools, their measuring methods, and the main findings from these measurements. These studies mainly focused on individual IEQ components in small samples of schools (median of six schools). Twenty-two parameters or families of parameters were reviewed. Measurement protocols, including the number and position of samples and the sampling duration, did not present a consensus between studies, which leads to the difficulty in comparing the results. Some parameters also present limitations in the current schools' environment and need further developments to be adapted to the school's environment and children's exposure. Air temperature and relative humidity for thermal, concentrations of carbon dioxide, particulate matter, radon, formaldehyde, and some volatile organic compounds for IAQ, noise level, and reverberation time for acoustic and illuminance for visual environments can be defined as adequate parameters for the purpose of characterizing IEQ in schools.

Overall, a holistic approach to quantifying IEQ in schools is needed with a set of measurable parameters for the four components with consensus on measurement protocols, and threshold values that reflect children's pollutant exposure and comfort perception.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13020433/s1, Figure S1: Distribution of studies per country (n = 88); Figure S2: Types of ventilation in reviewed studies; Table S1: Measurements of air temperature (°C) in schools in Europe and North America since 2010; Table S2: Measurement of relative humidity in schools across Europe and North America from 2010; Table S3: Thermal comfort assessment in schools in Europe and North America since 2010; Table S4: Measurements of background noise level (dB) in schools in Europe and North America since 2010; Table S5: Measurement of clarity index in schools across Europe and North America from 2010; Table S6: Measurements of reverberation time in schools across Europe and North America from 2010; Table S7: Measurements of carbon dioxide (CO_2) in schools in Europe and North America since 2010; Table S8: Calculation of air exchange rate/ ventilation in schools across Europe and North America from 2010; Table S9: Measurements of formaldehyde in schools in Europe and North America since 2010; Table S10: Measurements of aldehydes in schools across Europe and North America from 2010; Table S11: Measurements of BTEX in schools across Europe and North America from 2010; Table S12: Measurements of volatile organic compounds in schools across Europe and North America from 2010; Table S13: Measurements of particulate matter (PM) in schools in Europe and North America since 2010; Table S14: Measurements of flame retardants (SVOCs) in schools across Europe and North America since 2010; Table S15: Measurements of polycyclic aromatic hydrocarbons (SVOCs) in schools across Europe and North America since 2010; Table S16: Measurements of phthalates and musks (SVOCs) in schools across Europe and North America since 2010; Table S17: Measurements of NO_2 in schools across Europe and North America since 2010; Table S18: Measurements of radon in schools across Europe and North America since 2010; Table S19: Measurements of illuminance (Lux) in schools in Europe and North America since 2010.

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Nomenclature

Abbreviation	Signification
IEQ	Indoor environmental quality
IAQ	Indoor air quality
CO2	Carbon dioxide
TAIL	Thermal, Acoustic, IAQ, Lighting
GBC	Green building certification
SM	Supplementary material
HVAC	Heating, ventilation, and air conditioning
PMV	Perceived mean vote
PPD	Percentage person dissatisfied
VOCs	Volatile organic compounds
BTEX	Benzene, toluene, ethyl-benzene, xylene
SVOCs	Semi-volatile organic compounds
PM	Particulate matter
ACR	Air change rate
VR	Ventilation rate
NO2	Nitrogen dioxide
CFU	Colony forming unit
RH	Relative humidity
LAeq	Background noise equivalent level
RT	Reverberation time
SNR	Speech to noise ratio
STI	Speech transmission index
HPLC	High-performance liquid chromatography
UV	Ultra violet
TVOC	Total volatile organic compounds
DNPH	2,4-dinitrophenylhydrazine
PAH	Polycyclic aromatic hydrocarbons
BBP, DBP, DEHP, DEP, DiBP	Phthalates
PUF	Polyurethane foam

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