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CRITICAL ANALYSIS OF MONITORING INDOOR AIR QUALITY IN EDUCATION CENTRES

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Abstract. Indoor Air Quality perception in education centres has being a special concern based on their high occupancy and lack of ventilation. This study aims to present an overview of 20 relevant previous studies carried out in the last 5 years regarding monitoring and evaluating Indoor Air Quality in education centres. This analysis focuses on four specific aspects: general description of each study, ventilation typology, indicators measured and the number of locations measured. The results show that 60 % of the studies were located in an urban context, 75 % included primary schools and 75 % included naturally ventilated buildings. Indoor and outdoor was measured in 60 % of the studies. The most measured indicators were CO_2 (60 %), $PM_{2.5}$ (55 %), Temperature (50 %) and Relative Humidity (40 %) all indoor. In 60 % of studies were carried in more than five centres, mostly two rooms were measured and 35 % of studies placed one sensor per room. This can be a major limitation, as the monitored data may differ significantly from the actual situation. In conclusion, the greater correlations found relating to what indicators have been measured, were the ventilation typology and the location of the building, which influences what parameters and concentration can be expected.

Keywords: Indoor Air Quality, monitoring, school, ventilation.

1. Introduction

Indoor air quality (IAQ) is a subject that has been extensively studied, especially because of its impact on health. Most studies focus on office buildings or dwellings, with fewer studies being carried out in educational centres. Some different standards and guidelines limit indoor pollutant concentrations, especially in collective buildings. Several studies have found that the concentration of pollutants in educational centres is very high compared to the recommendations. Most of these studies implement monitoring in multiple classrooms as a methodology to quantify the concentration of pollutants and other variables such as thermal comfort. This study aims to relate air quality monitoring to the main characteristics of the case study. To find if there is a correlation between different characteristics. In recently published studies [1, 2], the most critical aspects when characterising the influence of IAQ in educational institutions are (Figure 1).

External conditions outside the building have a major influence, such as the climate [3] or the location of the school, urban, rural, industrialised, etc. Pollution levels will vary especially concerning road traffic and industry [4, 5]. The ventilation schedule also influences the penetration of pollutants through ventilation inside the building if it is located close to major roads [4]. The permeability of the building is related to the penetration of pollutants inside the building. The more permeable the building, the more energy-efficient it is and, generally, the lower the operating costs are. If the emissions of pollutants are mainly produced outdoors, the higher the permeability, the lower the penetration of pollutants into the building. Conversely, when the emission source is indoors and the permeability is high, this can lead to high indoor concentrations caused by inadequate ventilation.

There are multiple types of ventilation in buildings, which can be classified into three main groups: natural ventilation [6, 7], hybrid [3] and mechanical [4, 8]. These typologies have a major influence on the concentration of indoor pollutants. In the European Union, naturally ventilated classrooms represent the vast majority [3], where it has been shown that can be achieved a good IAQ as with mechanical ventilation systems. The perception of air quality in mechanically and hybrid ventilated classrooms is worse than in naturally ventilated classrooms [1]. The change of seasons also contributes to the concentration of indoor and outdoor pollutants, indirectly in the IAQ because of the different actions performed by the occupants of the centre to achieve mainly thermal comfort [1].

Occupancy is one of the aspects that has the greatest influence on IAQ in educational centres, mainly due to their high occupancy density [3]. Also influences secondary activities such as cooking or cleaning, which without proper ventilation increase the concentration of CO_2, $PM_{2.5}$ and VOCs, they can last until the next day when the teaching activity starts. The maintenance and correct condition of the building is also important [3], so when renovating or improving

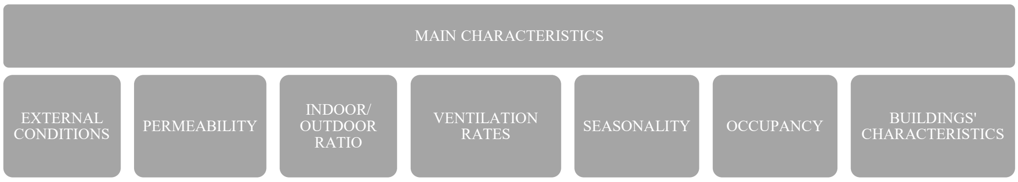

Figure 1. Main schools' aspects that may influence IAQ.

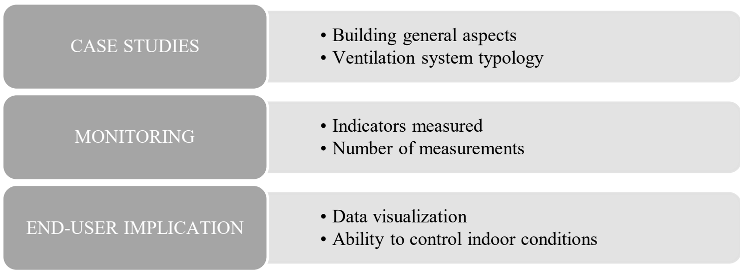

Figure 2. Characteristics analysed in the study.

schools, aslo influences the chosen materialson energy performance, IAQ and occupant comfort in the post-occupancy phases, not only in the design phase.

Several articles have studied IAQ in schools, focusing on the influence of different improvement strategies. They are of particular interest for this research to understand what results can be expected in the different case studies in terms of the implementation of different strategies that use monitoring as part of their methodology.

In the study carried out by Wang et al. [8], is analysed the improvement of air quality and its perception by students in multiple schools in Sweden. The study is conducted over a period of two years and evaluated after the implementation and improvement of mechanical ventilation systems. The study found that the perception of air quality, Subjective Indoor Air Quality, improved when the ventilation ratio, lighting levels and the implementation of new ventilation systems were increased. On the contrary, it worsened with increasing CO_2 or TVOCs concentration, or when the age of the students increased.

In another study, carried out by Pacitto et al. [9], air purifiers are installed in the gymnasiums of two naturally ventilated educational centres located in the urban area of Barcelona. The hourly renewals achieved and the concentration of PM_{1-10}, Black Carbon, CO_2 and NO_2 are measured. As a result, when the windows were completely closed and only air purifiers were applied, the indoor/outdoor ratio decreased the most, up to 95 %. In conclusion, the implementation of air purifiers in school gymnasiums located in environments with high road traffic density is an excellent solution to reduce indoor pollutant concentrations.

Another more accessible strategy is the introduction of a live visualisation system of the monitored data inside the classroom, with a clear protocol for action according to the values displayed. In the study carried out by Wargocki and Da Silva [10], 4 classrooms were monitored for 2 weeks during heating period and 2 weeks in non-heating period, where the data display system was introduced one week and removed the next week. A protocol was established for opening windows and doors according to the CO_2 concentration. Before the intervention, during the non-heating season, there was already adequate window opening to achieve the thermal comfort provided by adequate levels of ventilation. Therefore, the biggest change occurred during heating season, as ventilation was increased which led to an increase in heating consumption.

2. Methods

The aim is to establish whether there is a correlation between different characteristics in previous studies that can be replicated to establish a monitoring strategy in future case studies. After studying the most critical aspects that influence IAQ according to previous literature, those considered to be of special interest have been grouped and selected, relating the construction scale and location of the building with the monitoring strategy carried out.

For the proposed methodology, the first step was to search for scientific publications that dealt with air quality in educational centres and used monitoring as part of their methodology. Subsequently, these articles were classified according to different characteristics (Figure 2) and finally, possible relationships between the different characteristics were analysed.

The following aspects have been classified: at the scale of the study, the year and season in which it was carried out and the country. At the scale of each case study, a general classification of the environment in which the case study is located (urban or rural), what type of educational centre it is (nursery, school or institute) and the ventilation system it has. Per-

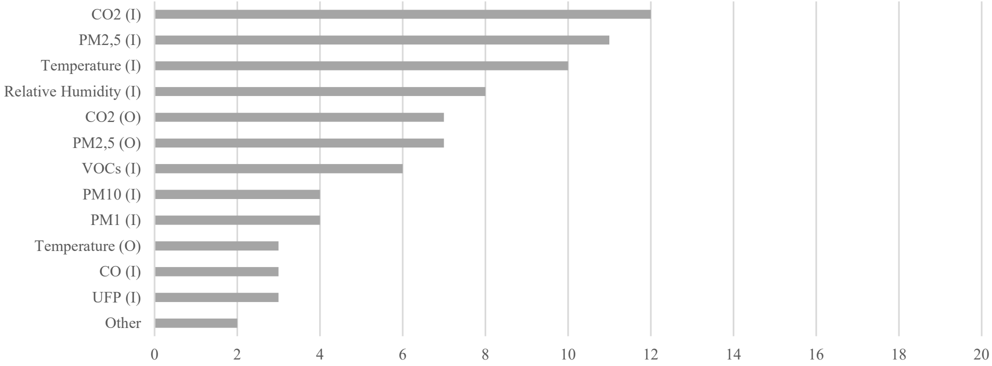

Figure 3. Variables monitored. (I) Indoor; (O) Outdoor.

haps the most relevant feature is which indicators have been measured, especially the most representative ones, and whether they have been measured indoors or outdoors. To categorise the number of measurement points the number of schools, the number of classrooms or locations within the school and the number of sensors per classroom were considered for those that contained this information. Finally, to understand how this monitoring affects the end-user, it has been added whether this data was visible to the users and whether the users can control or change the environmental conditions inside the space they occupy.

3. Results and Discussion

3.1. Search for articles

The search for articles was carried out in the Scopus database in selected journals with the following combination of keywords: "indoor air quality" and "school" and "monitoring". It was also limited to those publications published after 2015. The evolution of the number of publications on this subject has been stable, reaching a higher number of articles in 2020 due to the influence that the pandemic has had on this subject. From a total of 88 articles found related to the search terms, 20 were chosen, those considered most interesting and relevant to this study [4–8, 11–25].

In terms of the motivation of these articles, most of them are part of an international research project [5, 7, 11, 15, 16, 18, 19, 23, 24]. It is worth noting the influence that the health aspect has in this field, as in several articles different health departments have subsidised part of the research [5, 6, 12, 14, 20, 21]. In terms of research content, 6 of these studies are a continuation of previous research done by the same authors [6, 15]. Some of them deal with very innovative topics, such as the study of new technology for ventilation [22] or the study of the impact of shoeless classrooms [16].

3.2. Analysis of the different case studies

The selected articles have been produced in countries with cold or temperate climates, which is a limitation to understand the results that would be obtained in warmer climates. Also, the most monitored period has been winter ([6, 8, 11–15, 17, 18, 20, 21, 23, 25]), being the most vulnerable season, especially in those buildings with natural ventilation, since in general, their users ventilate less to achieve thermal comfort.

Concerning the type of building and age of the pupils, researches are more focused on schools ([4, 7, 8, 11–17, 19, 20, 22, 23, 25]), whose activity is very different from that carried out in kindergartens ([6, 18, 22]) or institutes ([5, 8, 21, 24]). Analysing the location of the schools, 60 % of the studies were located in an urban environment ([4, 5, 7, 11–13, 15, 17, 21, 23, 24, 26]), while the other 40 % were in urban and rural environments ([6, 8, 14, 16, 18, 19, 22, 25]), none studies were found exclusively in rural environments. This may lead to a lack of information and examples for future research that wishes to monitor in rural settings, as the literature comparing urban and rural settings shows a large difference in pollutants from outdoor sources.

In 55 % of the studies analysed, they focus their research on schools with a natural ventilation system ([6, 7, 13–15, 17–21, 25]), while those that study only mechanical ventilation are 25 % ([4, 5, 16, 23, 24]). These can be considered representative values since in the European Union most schools have a natural ventilation system [3].

In 60 % of the investigations, they have monitored both indoors and outdoors ([4–7, 11–15, 17, 18, 23]), most of them using the I/O ratio as an indicator of IAQ. This ratio is a good indicator because the indoor concentration is influenced among others by outdoor sources, but also by indoor sources [7]. As can be seen in Figure 3, The most monitored variables were CO_2 concentration ([4, 7, 8, 13, 17–19, 21–25]), $PM_{2.5}$ ([4–8, 12, 15–18, 22]), temperature ([4, 7, 8, 13, 17, 19, 21, 22, 24, 25]) and relative humidity ([4, 7, 8, 17, 19, 21, 22, 24]), all monitored indoors. Through these variables, information on thermal comfort (temperature and humidity), calculation of classroom air renewals and occupancy (CO_2) and the concentration of pollutants ($PM_{2.5}$) can be obtained.

The most commonly used sensor type was the NDIR

	1	2 to 5	6 to 15	> 15
Number of educational centres	4 [5, 13, 21, 24]	4 [4, 6, 18, 23]	6 [7, 14, 15, 17, 20, 25]	6 [8, 11, 12, 16, 19, 22]
Number of locations within the school	4 [7, 12, 13, 23]	11 [4, 8, 11, 12, 14, 17, 19–21, 24, 25]	0	0
Number of sensors within the classroom	7 [4, 7, 17, 20, 22–24]	3 [12–14]	0	0

Table 1. Number of measurements.

(Non-dispersive infrared sensors) for the measurement of CO_2 [4–6, 11, 12, 14–16, 21, 25]. For the assessment of the suspended particles, gravimetric analysis was used in 6 articles [7, 18, 20, 23–25]. Followed by Negative Temperature Coefficient (NTC) sensors for the measurement of temperature [4, 5, 11, 15]. In terms of connectivity, the most commonly used were wireless sensors with data storage [4, 5, 12, 14–17, 19, 25]. The frequency of measurement has varied from 6 articles where it has been measured every minute, being this the most abundant frequency [5, 12, 14–16, 18, 19], up to where it has been measured every 15 minutes [6, 21]. In some of the articles, this information on which sensors were used was missing. This is an important aspect that will influence the decision-making process as to which technologies are the most widely used and which may be the most suitable for each study.

About the number of measurement points carried out, they have been classified according to the number of schools, the number of locations inside the school and the number of sensors in the classroom (Table 1). The studies in which the number of schools analysed is high, with 3 studies analysing more than 30 schools. And more than half of the studies monitored more than 5 schools. On the other hand, within the same school, the number of classrooms and the number of sensors in the classroom are much lower.

3.3. Users' implication

None of the studies had monitoring data visible, this is because they were studies on the usual behaviour of their users. Previous studies [10] have shown a positive influence on the improvement of air quality when indoor IAQ values are represented with an action protocol according to CO_2 concentration. Nor have the articles referred to the subsequent use of the data obtained to act in schools or possible strategies for action to improve their IAQ.

With most case studies being naturally ventilated, the end-user has limited ability to change indoor conditions solely based on outdoor conditions and the ability to open windows and doors. Whereas, in most mechanical ventilation systems the ability to change indoor conditions is often null because the control is centralised.

3.4. Relation between different aspects

We have studied whether there is a relation between some of the aspects to be taken into account for future monitoring strategies based on the characteristics of the school. When the environment of the school changes (urban or rural) there is no great difference in which variables are monitored. The numbers are similar except when measured both indoors and outdoors, with most schools located in urban environments. This may be generally caused by the fact that road traffic is one of the major emitters of pollutants in urban areas, being lower in rural locations if there are no major roads or industries in the immediate surroundings of the school.

The variables monitored were also related to the type of ventilation in schools. Nor is there a great difference, except in those that monitor CO_2 and temperature outdoors, and CO indoors, with far fewer or even no studies with mechanical ventilation monitoring these variables. The rest of the variables monitored indoors do not vary for each type of ventilation. Although the ventilation system greatly influences the penetration of some pollutants. Mainly due to the filtration process in mechanical ventilation systems, or the number of renewals that can be achieved in uncontrolled ventilation such as natural ventilation.

Regarding the number of measurements and the characteristics of the centre, it has been found that when the case study was schools, the number of sensors is much higher than when the study was carried out in nursery or institutes, varying from an average of 39 measurement locations in schools compared to 4 and 2 in nursery and institutes respectively. As for the number of sensors and the monitored station, no relationship was found between the number of sensors and the monitored station.

3.5. Limitations

Throughout the previous literature overview, different limitations have been detected. Firstly, in the number of sensors used in monitoring, as there have been few sensors in classrooms, and their accuracy and interpretation can vary greatly depending on their location and use.

In the last year, because of the pandemic, information and concern about IAQ have increased. It has influenced classrooms because of their high occupancy density and the vulnerability of their occupants. This has led to the publication of scientific articles, legislation and guidelines to facilitate the incorporation of different measures to reduce the viral load in these indoor spaces. To this end, indoor CO_2 concentration has been commonly used as an indicator of indoor air renewal, trying to prioritise greater ventilation over other parameters such as thermal or acoustic comfort. As well as the correct use of masks in indoor spaces and limiting activities inside classrooms that increase the emission of aerosols.

Other limitation found has been the contradiction between different articles on whether to use CO_2 as an indicator. Most studies have used CO_2 concentrations and thermal comfort as an indicator to measure air quality. As reviewed in previous literature [9] these indicators can be considered insufficient and an oversimplification as most pollutants cannot be predicted based on CO_2 concentration.

The origin of these pollutants must also be taken into account, since those that are produced indoors, as is the case of Radon and VOCs, their behaviour can be similar to that of CO_2, but those gases whose origin is outside, mainly produced by road traffic such as NO_2 or O_3, penetrate the building according to infiltration and the ventilation system used in the building [4].

Although it may be considered limited and insufficient, in the current COVID situation where air renewal is more prioritised than other comforts, CO_2 is a good indicator that allows the calculation of air renewals that occur in the interior space (according to occupancy and physical properties of the building) being easy to implement and easy to take improvement measures according to the concentration values.

4. Conclusions

In conclusion, once the relationships between different variables have been studied when monitoring educational centres, the type of educational centre, its ventilation system and the environment in which it is located have had a special influence. These variables will indicate which pollutants are most likely to be found and the control that can be exercised over indoor conditions, as well as the number of measurements to be taken.

This monitoring can be used to engage users through live visualisation of the values obtained, which is an easily replicable strategy and has been shown to be effective in improving IAQ. It allows users to change their comfort conditions by improving IAQ. However, it is important to be aware of the limitations of some indicators such as CO_2 when extrapolating conclusions about IAQ without knowing the concentration of other pollutants.

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